AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2014WR015572

Key Points:
- Water marketing arrangements interact with existing institutions
- Conjunctive administration redistributes profit and alters land-use patterns
- Water banking offsets profit losses from drought and conjunctive administration

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Citation:
Ghosh, S., K. M. Cobourn, and L. Elbakidze (2014), Water banking, conjunctive administration, and drought: The interaction of water markets and prior appropriation in southeastern Idaho, *Water Resour. Res.*, *50*, doi:10.1002/2014WR015572.

Received 12 MAR 2014
Accepted 1 AUG 2014
Accepted article online 5 AUG 2014

Water banking, conjunctive administration, and drought: The interaction of water markets and prior appropriation in southeastern Idaho

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Abstract Despite recognition of the potential economic benefits and increasing interest in developing marketing instruments, water markets have remained thin and slow to evolve due to high transactions costs, third party effects, and the persistence of historical institutions for water allocation. Water banks are a marketing instrument that can address these obstacles to trade, allowing irrigators within a region to exchange water in order to mitigate the short-term effects of drought. Water banks coexist with the institutions governing water allocation, which implies that rule changes, such as adoption of a system of conjunctive surface water-groundwater administration, carry implications for the economic impacts of banking. This paper assesses and compares the welfare and distributional outcomes for irrigators in the Eastern Snake River Plain of Idaho under a suite of water management and drought scenarios. We find that water banking can offset irrigators' profit losses during drought, but that its ability to do so depends on whether it facilitates trade across groundwater and surface water users. With conjunctive administration, a bank allowing trade by source realizes 22.23% of the maximum potential efficiency gains from trade during a severe drought, while a bank that allows trade across sources realizes 93.47% of the maximum potential gains. During drought, conjunctive administration redistributes welfare from groundwater to surface water producers, but banking across sources allows groundwater irrigators to recover 88.4% of the profits lost from drought at a cost of 2.2% of the profit earned by surface water irrigators.

1. Introduction

Economic studies widely document the potential gains associated with water markets, which allow for the reallocation of water from low-value to high-value uses, thereby maximizing allocative economic efficiency. Despite recognition of the potential economic benefits, and increased interest in developing marketing instruments, water markets have remained thin and slow to evolve in response to increasing water scarcity driven by population growth and reduced water supplies [*Carey and Sunding*, 2001; *Howitt and Hansen*, 2005; *Hansen et al.*, 2008; *Libecap*, 2011]. Economists have argued that transactions costs, third party effects, and the persistence of historical institutions for water allocation form barriers to the development of new water marketing arrangements, especially across the western United States [*Chang and Griffin*, 1992; *Gisser and Johnson*, 1983; *Lefkoff and Gorelick*, 1990; *Libecap*, 2011].

Water marketing can be accomplished with a variety of instruments, one of which is water banks, which often facilitate the short-term leasing of water between water users [*Burke et al.*, 2004; *Griffin*, 2006; *Howe et al.*, 1986; *Lefkoff and Gorelick*, 1990]. Water banks have been established in most states in the western United States, though the structure of the banks varies widely and trading in many states remains limited. Relatively more active banking programs in the region are those administered by Idaho, California, and Arizona [*Clifford et al.*, 2004]. Idaho's water banking program, the longest-running of the state programs, was legally formalized in 1979 but has only recently become an active platform for water exchange. The number of trades realized through Idaho's water banks increased significantly over the past two decades. In 1995, 0.16 million m^3 of water was exchanged through the banks; by 2012, banks facilitated the trade of 70.69 million m^3 [*Clifford et al.*, 2004; *Idaho Department of Water Resources*, 2013].

Table 1. Management and Administration Scenarios[a]

Management Scenarios	Administration Scenarios: PA: Administer SW and GW Rights Separately	Administration Scenarios: CA: Administer SW and GW Rights Conjunctively
NTR: No water trade	NTR-PA	NTR-CA
BK: Trade of water allowed through state banks		
BKS: Banking by source, SW users trade with SW users, GW users trade with GW users	BKS-PA	BKS-CA
BKX: Banking across sources, SW users may trade with SW and/or GW users, GW users may trade with SW and/or GW users	BKX-PA	BKX-CA
OPT: Economically optimal water allocation	OPT	

[a]Institutional scenarios do not apply when determining the economically optimal water allocation; all water may be freely allocated across farm boundaries.

Water marketing arrangements, such as water banks, often coexist with the long-standing institutional rules that govern the allocation of water across users [*Howe et al*., 1986; *Lefkoff and Gorelick*, 1990]. Therefore, the form of these institutions may influence trading activity. A significant change in institutional structure, such as the implementation of conjunctive surface water-groundwater rights administration, is likely to influence the efficiency gains obtained with water exchange through banks. The objectives of this paper are to examine how different institutional arrangements influence individuals' decisions to trade water through a regional water bank and to quantify the interactive effect of banking and institutional rules on the economic welfare of agricultural irrigators during drought.

To do so, we develop an empirical programming model and apply it to the Teton Water Banking area located in the Eastern Snake River Plain of Idaho, an area which has seen a marked increase in water banking activity in recent years. We rely on a detailed geospatial data set of individual water rights to simulate the water diversion, land allocation, and water banking decisions of heterogeneous irrigators. Irrigators in the region are heterogeneous along a number of margins that influence their incentives to exchange water through water banks. The novel source of heterogeneity considered in this analysis arises due to differences in water rights ownership. The water right(s) owned by an irrigator differ in source (surface water and/or groundwater) and priority date. The source of water affects an irrigator's costs of diversion, but the importance of source and priority extend beyond these costs. Both source and priority are key determinants of whether an irrigator receives their water allocation during drought, where the relationship between source, priority, and water receipts depends on the way in which water rights are administered according to institutional rules.

With the programming model, we consider a suite of water management and water rights administration scenarios when simulating irrigator behavior. These scenarios are outlined in Table 1. The water management scenarios include: no water trade (NTR), the economically optimal seasonal allocation of water across irrigators (OPT), and short-term (seasonal) water trade through a regional bank. For water banking, we consider two scenarios: one in which banks facilitate trade by water source (BKS) and one in which banks allow trade across water sources (BKX). The economically optimal scenario (OPT) is the allocation of water that maximizes aggregate producer welfare with no constraints on the movement of water across farm boundaries. The economically optimal scenario thus sets an upper bound on the profit earned by irrigators. Although the OPT scenario is not a realistic policy option, it provides a benchmark against which the water banking scenarios may be evaluated. The no-trade scenario (NTR), on the other hand, does not allow any movement of water across farms. This scenario places a lower bound on the profit earned by irrigators. The water banking scenarios allow for some movement of water across farms, but water is traded at a fixed price and is subject to transactions costs. The banking scenarios therefore fall between the NTR and OPT bounds. The question for this study is where the water banking scenarios fall relative to the worst-case (NTR) and best-case (OPT) scenarios.

The answer to this question depends importantly on the institutional rules governing the allocation of water across irrigators. We consider two institutional scenarios: one in which surface water and groundwater rights are administered separately (PA) and one in which surface water and groundwater rights are administered conjunctively (CA). The former approach has long been used for water rights administration in the western United States and may be an appropriate approach if surface and groundwater resources are hydraulically disconnected. However, the hydrologic literature has established that surface water and groundwater resources are hydraulically connected in many regions [e.g., *Jones and Mulholland*, 2000; *Kollet and Zlotnik*, 2003; *McCallum et al*., 2014; *Sophocleous*, 2002; *Winter et al.*, 1998]. In recognition of this fact, many states in the western United States have adopted conjunctive administration (CA), which involves merging surface water and groundwater rights into a single administrative framework in hydraulically connected areas.

In Idaho, CA is defined as the legal and hydrologic integration of the diversion and use of water under water rights from surface and groundwater sources. As currently practiced, CA allows for the doctrine of prior appropriation to be applied across surface water and groundwater rights, so that water rights are fulfilled in order of priority date, regardless of source. This approach allows the state to curtail junior groundwater rights to increase surface water availability when surface and groundwater resources are hydraulically connected, as they are in much of southeastern Idaho [*Cosgrove and Johnson*, 2005; *Miller et al*., 2003]. This system of CA has been shown to generate important welfare and distributional effects for surface water and groundwater users, both in cases when water trade is allowed [*Elbakidze et al*., 2012] and when it is not [*Snyder and Coupal*, 2005].

In this study, we compare irrigator behavior in the no trade and water banking management scenarios under PA and CA. Though CA is already implemented in the State, a comparison of the two cases provides new insight into how a system of water banking interacts with institutional rules to influence producer behavior and economic outcomes. This type of information is critical in understanding how marketing arrangements might be designed to maximize economic efficiency, the ways in which institutional change affects water marketing and the consequences for adaptation by irrigators to changing climatic conditions.

This study also extends the literature by considering the way that institutional rules affect water diversion decision making at the level of the individual irrigator. Modeling individual decision makers allows us to consider the way in which water rights ownership and water rights administration affect the incentives of irrigators to trade water through a bank. When there is no trade or when there are transactions costs associated with water trade, differences in water rights ownership matter because they imply that irrigators face differing constraints on water diversions. As a result, the marginal value of water used in irrigation differs across producers, which creates the potential for economic gains to be realized from water trade, even within a local area. Water rights administration determines which rights are fulfilled (or not) during a water shortage, and thus plays a fundamental role in determining the water diversion constraints facing each irrigator.

Understanding the gains from local or intraregional trade is important given that there are often barriers to interregional trades due to large transactions costs and third party effects. Water banks that operate within a region offer a means of circumventing these obstacles by limiting the scope of trade and are becoming an increasingly important tool to facilitate the exchange of water among irrigators. This paper thus provides a complement to studies on water markets that focus on basin-scale optimization problems [e.g., *Gohar and Ward*, 2011; *Howitt et al*., 2012]. Models that aggregate across irrigators within a region are most appropriate when agricultural decision makers are homogeneous. This analysis demonstrates that water rights ownership constitutes an important source of heterogeneity among irrigators within a basin. These differences imply that water rights administration influences the ability of agricultural irrigators to protect themselves from economic losses during drought by exchanging water through banks.

2. Background on Water Banking

Though their form varies widely in practice, water banks are defined generally as "an institutional mechanism that facilitates the legal transfer and market exchange of various types of surface, groundwater, and storage entitlements" [*Clifford et al*., 2004]. Banks perform a variety of functions, including setting a price for water, determining who may rent and lease water, and defining between whom exchange can occur. Exchanges through a bank sometimes involve the permanent transfer of a water right between parties, but more often involve the short-term (seasonal) transfer of water without a change in the right's ownership. An important function of banks is to reduce the transactions costs associated with trade [*O'Donnell and Colby*, 2010].

Water banking exists in some form in most of the states in the western United States, but banks are most active in California, Arizona, and Idaho. In 1991, California introduced the Drought Water Bank as a mechanism to allow water users to mitigate drought losses with the temporary exchange of water. Transfers through the

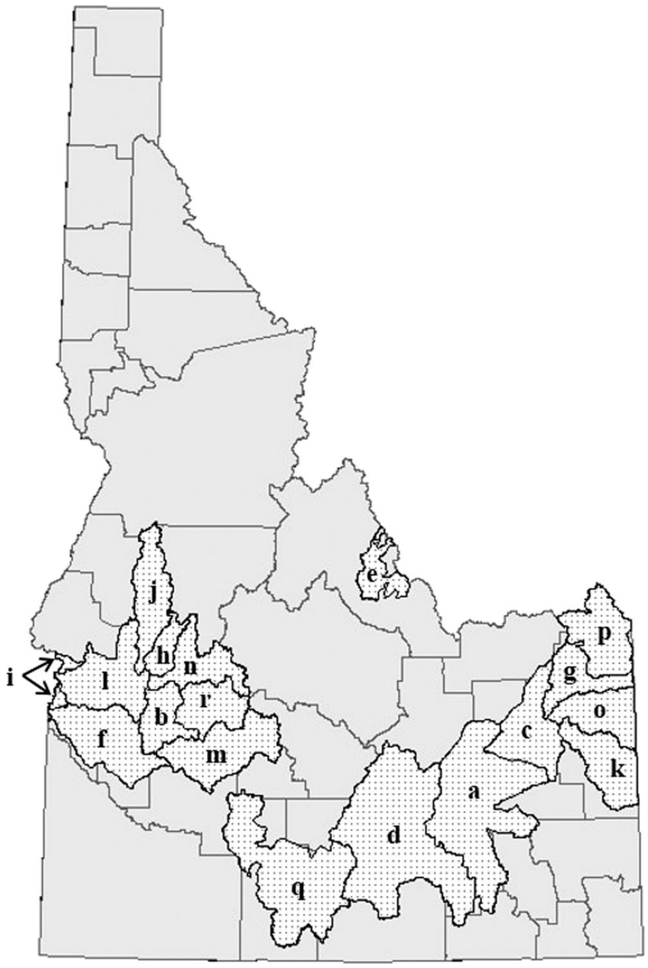

Figure 1. Water banking areas in Idaho. The water banking areas are as follows: (a) American Falls, (b) Boise-Mores, (d) Idaho Falls, (e) Lake Walcott, (e) Lemhi, (f) Lower Boise, (g) Lower Henrys, (h) Middle Fork Payette, (i) Middle Snake-Payette, (j) North Fork Payette, (k) Palisades, (l) Payette, (m) South Fork Boise, (n) South Fork Payette, (o) Teton, (p) Upper Henrys, (q) Upper Snake-Rock, (r) North and Middle Fork Boise. The study area coincides with water banking area (o).

Drought Water Bank have since been instrumental in supplying water to farmers and public agencies during dry years. For example, in 2009, the Bank bought water from users' associations and irrigators upstream of the San Joaquin Delta to provide water to the local water systems that were expected to face shortfalls in the subsequent year. The Arizona Water Banking Authority, started in 1996, stores excess water from the Colorado River for intrastate and interstate trade. Water storage in Arizona's banks has steadily increased in recent years [*Fabritz-Whitney*, 2012, 2013].

Idaho maintains the state Water Supply Bank, which is operated to "make use of and obtain the highest duty for beneficial use from water, provide a source of adequate water supplies to benefit new and supplemental water uses, and provide a source of funding for improving water user facilities and efficiencies" [*Idaho Administrative Code*, 2004]. Idaho's Water Supply Bank specifies a fixed fee per unit of water traded through the bank, with 90% of the fee paid by a renter (buyer) to the lessee of a right (seller), and 10% allocated to administrative costs. The Bank is divided into 18 water banking areas spanning the southern portion of the state, as illustrated in Figure 1. They specify the area over which the exchange of water can transpire, with the objective of minimizing the generation of third party effects (M. van Bussum, IDWR, personal communication, September, 2012). To that end, the banking areas generally coincide with USGS hydrologic units.

The exchange of water through Idaho's banks has increased substantially over the last 5 years [*Idaho Department of Water Resources*, 2013]. In 2008, the bank rented out 14.47 million m^3 of water and generated \$78,365 in revenue. In 2012, the bank rented out 70.68 million m^3 and generated \$542,700 in revenue. The majority of rental agreements in 2012 (72%) transferred water between irrigators. Both surface water and groundwater banking have been prevalent in Idaho: In 2008, 36 groundwater rights and 22 surface water rights were exchanged. The escalating level of revenue and number of trades through the bank over the last 5 years suggests that the banks provide a viable means for irrigators, in particular, to exchange water on a seasonal basis.

3. Economic Model and Management Scenarios

The focus of this analysis is on the water use decisions of agricultural irrigators, the sector that has accounted for the majority of banking activity to date in Idaho. To examine the economic impacts of water banking, we develop a numerical, nonlinear optimization model that simulates the water diversion, land allocation, and water banking decisions made by heterogeneous irrigators under each of the management-administration scenarios in Table 1 and under a range of drought (water availability) conditions.

Heterogeneity among irrigators arises from several sources. As discussed in the introduction, irrigators differ in their water rights, which specify water source and priority. Irrigators in the model also differ with respect to the size of their land base and the productivity of their land (in terms of crop yields per unit land area).

In the model, we assume that irrigators operate under certainty, which implies that they can anticipate the severity of a drought and whether their water right(s) will be curtailed in each management-administration scenario. Uncertainty is prevalent in both economic and hydrologic systems and is therefore a potential element of any hydro-economic model. Surface water availability, in particular, constitutes an important source of uncertainty for irrigators [*Bredehoeft and Young*, 1983; *Gemma and Tsur*, 2007; *Knapp and Olson*, 1995; *Provencher and Burt*, 1994; *Tsur and Graham-Tomasi*, 1991; *Young and Bredehoeft*, 1972]. We choose to abstract from uncertainty in this analysis in order to sharpen the focus on the way in which water rights administration interacts with water banking to affect irrigators' decision making. In the sensitivity analysis, we explore a model variant that incorporates stochasticity in surface water flows. The analysis demonstrates that including stochasticity alters the magnitudes of the economic outcomes for irrigators slightly, but that the combination of water rights administration and management scenario exerts a much larger effect on irrigator profit. In this analysis we focus on the difference in outcomes *across* scenarios, which are unchanged by assuming certainty.

The model focuses on irrigator decision making during a single growing season, a time period consistent with the short-term nature of leasing and rental activity through Idaho's water banks. The model thus focuses on short-run responses to drought, rather than long-run changes such as the purchase or sale of water rights and/or land. Idaho expressly prohibits the storage of water from 1 year for use in the next, which eliminates dynamic storage concerns. Analyzing water marketing decisions within a growing season is also interesting given that multiyear water transactions have been rare to date relative to single-year transactions [*Clifford et al*., 2004]. One source of dynamics that is potentially important, and that we do not consider, concerns the effect of changing groundwater pumping on surface water flows in future years [*Elbakidze et al*., 2012; *Kuwayama and Brozovic*, 2013]. Water banking areas in Idaho are small enough in spatial extent, and the transmissivity of the aquifer sufficiently high, that abstracting away from this concern is reasonable. There are always some third party effects associated with a change in surface water or groundwater use. However, Idaho's water banking areas are specified based primarily on hydrogeologic properties so that these externalities are small enough that they should not impede transfers.

3.1. No Trade Management Scenario (NTR)

An individual grower chooses their land allocation and water diversions to maximize the returns over the variable costs of production for a growing season:

$$\max_{w_{uks},l_{uk}} \pi_u = \sum_k \left\{ \left[(p_k - nwc_k) y_{uk} \left(l_{uk}, \sum_s w_{uks} \right) - \sum_s wc_s w_{uks} \right] l_{uk} \right\} \tag{1}$$

where $u=1,\ldots,U$ indexes the grower, $k=1,\ldots,K$ indexes the crop, and $s=sw, gw$ indexes the water source (surface water or groundwater). In equation (1), p_k is the price for each crop per unit yield, nwc_k are the nonwater costs of production per unit yield, y_{uk} is the crop yield per hectare, l_{uk} is the amount of land allocated to crop k, w_{uks} is the amount of water per hectare diverted (withdrawn) from source s and allocated to crop k, and wc_s is the cost of water diversions by source and per unit diverted. A crop's yield depends on the amount of land allocated to the crop and the total amount of water diverted to irrigated the crop, which is given by $\sum_s w_{uks}$, the sum of diversions from surface water and groundwater sources. In general, crop yield declines as more marginal land is brought into production and increases with water diversions (up to a point). The yield function in equation (1) may include deficit irrigation as a short-term response to changes in water availability or yield may be modeled using fixed proportions in land and water, which precludes the use of deficit irrigation [*Ward and Pulido-Velazquez*, 2012; *Gohar et al*., 2013]. Dryland crop yields are given by $y_{uk}(l_{uk}, 0)$.

In management scenario NTR, the objective function is maximized subject to constraints on land availability and water diversions. The constraint on land availability is:

$$\sum_k l_{uk} \leq L_u \tag{2}$$

Constraint (2) limits the total land allocated across all crops to the irrigator's total arable land area, L_u. The constraint on water diversions is:

$$\sum_k w_{uks} l_{uk} \leq D_{us} \quad (3)$$

Constraint (3) ensures that total water diversions by grower and source do not exceed the total water that each grower is permitted to divert from each source, D_{us}.

The grower and source-specific diversion limit on the right-hand side of constraint (3) depends on the water rights owned by each grower, the total amount of water available for diversion in the region (seasonal water availability), and the way in which the state administers water rights. These three factors combine to determine whether a grower's water rights will be fulfilled or curtailed during a growing season, and thus the total amount of water that a grower may divert for irrigation.

To specify which rights are fulfilled in a growing season, we consider two water administration scenarios. Under both scenarios, rights are administered using the doctrine of prior appropriation, under which the state water agency allocates available water in order of priority date (seniority), starting with the oldest water right and continuing down the list until the available water supply in the region has been exhausted. Once the available supply has been allocated, all remaining rights are curtailed. In the first scenario that we consider (PA), surface water and groundwater rights are administered separately. In the second scenario (CA), surface water and groundwater rights are administered conjunctively. The next two subsections describe how water rights are administered in each of these scenarios and the derivation of the right-hand side of constraint (3).

3.1.1. Water Rights Administration Scenario PA

Water rights are denoted wr_{is}, where i indexes individual rights and s indexes source. Every water right has a priority date and an associated diversion limit. The diversion limit, denoted $\overline{div}_{is}$, is the maximum entitlement for water right wr_{is}, and is not necessarily the quantity of water that the water right is awarded in a growing season. For administration scenario PA, we partition the set of all water rights into a subset of surface water rights and a subset of groundwater rights, $\{wr_{1s}, \ldots, wr_{N_s s}\}$, where N_s is the total number of rights to divert water from source s. Each subset is ordered based on priority date, so that the first right in the set, wr_{1s}, is the most senior (oldest) water right for source s and the last right in the set, $wr_{N_s s}$, is the least senior (youngest) water right for source s.

At a regional level, the total amount of water available for diversion from each source is $\bar{W}_s$. For surface water and groundwater rights separately, the state allocates water in the quantity div_{is} to right i from source s according to the rule:

$$div_{is} = min\left\{\overline{div}_{is}, \bar{W}_s - \sum_{j=1}^{i-1} div_{js}\right\} \text{ for } i=1,\ldots,N_s, \; s=sw, gw$$

As long as $\bar{W}_s$ exceeds $\overline{div}_{1s}$, the most senior water right from source s is awarded its full entitlement, i.e., $div_{1s} = \overline{div}_{1s}$. The amount of water available to allocate to the second most senior water right is whatever is left over after allocating water to the most senior right, or $\bar{W}_s - div_{1s}$. If that quantity exceeds $\overline{div}_{2s}$, then the second most senior right will receive its full entitlement, i.e., $div_{2s} = \overline{div}_{2s}$. This process continues until the amount of water left to allocate to a right does not exceed its entitlement. Suppose that this holds for the fifth most senior water right from source s. The quantity of water allocated to that right is given by $div_{5s} = \bar{W}_s - \sum_{j=1}^{4} div_{js}$. All remaining water rights will be curtailed so that $div_{6s} = \ldots = div_{N_s s} = 0$.

Irrigators may own multiple water rights from different sources so that the total number of rights may exceed the number of growers. Each irrigator owns a subset of the region's water rights from each source, which we denote R_{us}. Based on the allocation of water to each right, the diversion limit by grower and source for constraint (3) is:

$$D_{us} = \sum_i div_{is} \text{ if } wr_{is} \in R_{us}$$

Drought reduces surface water availability, $\bar{W}_{sw}$, which results in the curtailment of junior surface water rights under PA. Though groundwater administered under PA is conceptually allocated in the same way, it is difficult in practice to determine a seasonal limit on groundwater availability that depends on drought severity. In fact, one of the benefits of groundwater access is that it can buffer irrigators from variation in surface water availability because groundwater availability is relatively stable across seasons [*Tsur and Graham-Tomasi*, 1991]. When groundwater and surface water are administered separately, the only constraint on groundwater use is the limit imposed by the exogenously specified maximum rate of diversion for each groundwater right, i.e., $\bar{W}_{gw}=\sum_{i=1}^{N_{gw}} div_{igw}$, where $div_{igw}=\overline{div}_{igw}$. This is consistent with water allocation rules in Idaho prior to the implementation of CA. Even since the implementation of CA, curtailing groundwater rights has been relatively rare, though the incidence of groundwater curtailments in southern Idaho has escalated in recent years.

3.1.2. Water Rights Administration Scenario CA

Administration scenario CA is similar to scenario PA, except that prior appropriation is administered across all rights, regardless of source. Instead of partitioning water rights by source, we order all water rights based on priority date. The ordered set of rights is $\{wr_1, \ldots, wr_N\}$, where wr_1 is the most senior right from any source and wr_N is the least senior right from any source (and $N=N_{sw}+N_{gw}$).

The total amount of water available for diversion from both sources is given by $\bar{W}=\bar{W}_{sw}+\bar{W}_{gw}$. Under CA, junior rights from any source will not be fulfilled unless there is sufficient water to fulfill all senior rights, regardless of source. The state allocates water to right i in the quantity div_i according to the rule:

$$div_i=min\left\{\overline{div}_i, \bar{W}-\sum_{j=1}^{i-1} div_j\right\} \text{ for } i=1, \ldots, N$$

Let R_{us} continue to denote the subset of the region's water rights owned by irrigator u from source s. We map individual water rights, wr_i, into the subsets R_{us} to obtain the grower and source-specific diversion constraint in (3) as:

$$D_{us}=\sum_i div_i \text{ if } wr_i \in R_{us}$$

Drought reduces total water availability by reducing $\bar{W}_{sw}$. Groundwater availability is sufficient to satisfy all groundwater rights, but the state may curtail junior groundwater rights during a water shortage in order to satisfy senior surface water rights. The implementation of CA therefore involves a substantial change from PA: in administrative scenario PA, drought affects the amount of water available for surface water irrigators only; in administrative scenario CA, drought affects water availability for surface and groundwater irrigators alike. This difference in the two scenarios represents an *institutional change* that may be applied in any region in which surface and groundwater are hydraulically connected.

Under CA, when a total water availability constraint is applied across rights regardless of source, we assume that irrigators continue to withdraw their allocated water from the source(s) for which they hold a water right. The substitution of groundwater for surface water thus occurs in the water agency's accounting ledger, not at the field. Opportunities for substitution between sources at the field are likely to be limited because some growers have access to surface water conveyance infrastructure, while others may only have access to groundwater wells, and because existing irrigation technology is often tailored to a specific water source. In the long run, producers may invest in conveyance infrastructure, drill wells, or modify their irrigation technology. However, because we are considering short-run water trading, this type of decision making is outside of the scope of this study.

3.2. Water Banking Management Scenarios (BKS, BKX)

With water banking, the administrative scenarios PA and CA determine which rights are fulfilled and which are curtailed based on total water availability. If a right is not curtailed, a grower may choose to lease (sell) water to the water bank for a single season. A curtailed right may not be exchanged through the bank until the curtailment call is removed. The leased water is eligible to be rented (bought) by another grower for a single season. The rental price and administrative costs are often fixed by a state's water agency. In the model, a renter pays a fixed price per unit of water rented and the lessee receives a payment for the leased water equivalent to the rental price less administrative costs. Each producer's objective function becomes:

$$\max_{w_{uks},l_{uk}} \pi_u - rf\sum_s rw_{us} + (1-\delta)rf\sum_s lw_{us} \quad (4)$$

where π_u is given by equation (1). The second term in objective function (4) captures the cost of renting water, with exogenous rental fee rf per unit of water. Water rented by grower u from source s is denoted rw_{us}. The third term captures the revenue earned from leasing water into the bank, where lw_{us} is water leased by grower u from source s. The parameter $\delta \epsilon [0,1]$ represents the administrative fee that is exogenously specified as a proportion of the rental price.

For this scenario, constraint (2) applies, but constraint (3) must be modified to include leases and rentals:

$$\sum_k w_{uks} l_{uk} \leq D_{us} + rw_{us} - lw_{us}$$

In addition, a constraint must be added to ensure that rentals out of the bank and leases into the bank balance. We consider two variants of this constraint, which correspond to the banking scenarios BKS and BKX. In the first, exchange is allowed by water source only (scenario BKS), such that groundwater leases must equal groundwater rentals and surface water leases must equal surface water rentals:

$$\sum_u rw_{us} = \sum_u lw_{us} \text{ for } s = sw, gw$$

In the second variant of the constraint (scenario BKX), exchange is allowed across sources such that total water leases equal total water rentals:

$$\sum_u \sum_s rw_{us} = \sum_u \sum_s lw_{us}$$

The first constraint is consistent with current water banking practice in Idaho. The second variant is included as a hypothetical scenario. This is included because it is consistent with the underlying premise that if a region is hydraulically connected such that groundwater rights can be curtailed to increase surface water availability (or vice versa), then the exchange of water across sources should also be feasible.

In Idaho, there is a cap on the total quantity of water that may be rented from the bank, which is proportional to the total amount of land in an individual irrigator's land base (M. Ciscell, IDWR, personal communication, November, 2012). We denote this proportion γ and impose the constraint:

$$\sum_u \sum_s rw_{us} \leq \gamma L_u$$

The final constraint included in the model is:

$$\left(\sum_s rw_{us}\right)\left(\sum_s lw_{us}\right) = 0$$

which requires that an irrigator does not simultaneously lease and rent water through the bank.

3.3. Economically Optimal Management Scenario (OPT)

In this scenario, water and land are allocated according to their highest and best use within a growing season. This scenario chooses the land allocation and water diversions for each grower, crop, and water source to maximize aggregate producer profit with no constraints on individual water use. The objective function is:

$$\max_{w_{uks},l_{uk}} \sum_u \pi_u$$

where π_u is given by equation (1). Constraint (2) continues to apply in this management scenario. A new water availability constraint ensures that aggregate water diversions do not exceed aggregate water availability:

$$\sum_u \sum_k \sum_s (w_{uks} l_{uk}) \leq \bar{W}$$

No other constraints on the water used by individual irrigators apply, save for the assumption that growers divert water only from their current water source(s). In OPT, administration scenarios PA and CA are irrelevant because the initial allocation of water to each producer does not affect the optimal allocation of water across producers.

The allocation of water obtained in this scenario represents the best possible outcome for the region in terms of aggregate economic efficiency, and places a lower bound on the profit losses experienced under drought (or, equivalently, an upper bound on aggregate profit). This is equivalent to the allocation under a water market with an endogenously determined price for water and zero transactions costs. We use the results of this scenario to examine the relative economic efficiency of the other management scenarios.

4. Study Region, Data, and Calibration

Agriculture in Idaho contributes nearly $5.9 billion, or 6%, to the state's GDP, and Idaho ranks third in the United States in terms of the amount of water withdrawn for agricultural irrigation [*Kenny et al*., 2009]. Statewide, water is applied to 1.34 million hectares of agricultural land, over 0.81 million of which are located in the Eastern Snake River Plain [*Frey*, 2012]. The Eastern Snake Plain Aquifer is an important source of irrigation water in the Plain, providing roughly one third of the total amount of water used in irrigation.

Because surface water and groundwater are hydraulically connected throughout the Plain, implementing the conjunctive administration (CA) of surface and groundwater has been a policy and water management focus in the state for the last two decades. In 1994, the state established a system of conjunctive administration that applies the doctrine of prior appropriation across surface water rights and groundwater rights, so that junior groundwater rights may be curtailed during a shortage to increase water availability for senior surface water rights in hydraulically connected areas. As a result of the implementation of CA, numerous groundwater curtailment calls have been filed in recent years. Examples for 2014 include the Rangen call, which curtails groundwater rights in the Magic Valley with priority dates junior to 13 July 1962, and the Surface Water Coalition call to curtail groundwater rights in the Eastern Snake Plain with priority dates junior to 31 May 1989.

The study region selected is Administrative Basin 22, which closely corresponds to the Teton Water Bank area and the Teton Basin (*USGS HUC* 17040204) within the Upper Snake Basin. The study region, depicted in Figures 1 and 2, overlaps with Madison, Fremont, and Teton Counties. This study region was selected on the basis of the amount of water exchanged through the regional water bank in recent years, and based on expert insight into the prospects for future water transfers through the bank (R. Allen, University of Idaho, and D. Tuthill and H. N. Anderson, Idaho Water Engineering, personal communication, September, 2012). The region falls within the overlap between Henry's Fork (a tributary of the Teton River) and the Eastern Snake Plain Aquifer. The Idaho Department of Water Resources (IDWR) has established that the aquifer and Teton River are hydraulically connected at points throughout the study region. Thus, Idaho's CA rules can legally be applied within the bounds of the study area [*Baker*, 1991].

At present, the rental price for water through the bank is \$0.014 per m^3 and the administrative costs to be collected by the IDWR equal 10% of the gross rental fees collected. The administrative cost rate is codified, but the rental price is not. The Idaho Water Resources Board (IWRB) determines the rental fee, which is set in accordance with the rental charges for stored water specified as part of the Snake River Water Rights Agreement of 2004. This agreement, which was a resolution to a long-running dispute over the claims of the Nez Perce Tribe to Snake River flows, provides for the Bureau of Reclamation to rent water from the state bank to augment surface water flows. The agreement specifies a rental fee of \$0.011 per m^3 for 2006–2012, \$0.014 per m^3 for 2013–2017, \$0.016 per m^3 for 2018–2022, and \$0.019 per m^3 for 2023–2030.

The IDWR maintains a geospatial water rights data set that describes, for every right in the state, the right's ownership, place of use (the land base over which water can be spread), point of diversion (source, listed as either groundwater or a specific surface water body), season of use, and the maximum rate at which water can be diverted. Within Administrative Basin 22, there are a total of 4547 unique water rights, 1697 of which are for use in irrigation. Of the rights for irrigation, 64% are for diversions from surface water sources; the remaining are for groundwater. The median priority year for surface water irrigation rights in the Basin is 1900; for groundwater irrigation rights it is 1974. The distribution of priority dates by source for Basin 22 is illustrated in Figure 3.

We model decision making by a random sample of representative irrigators, which includes five canal companies, an irrigation district, and six individual water rights owners. We limit the model to a subset

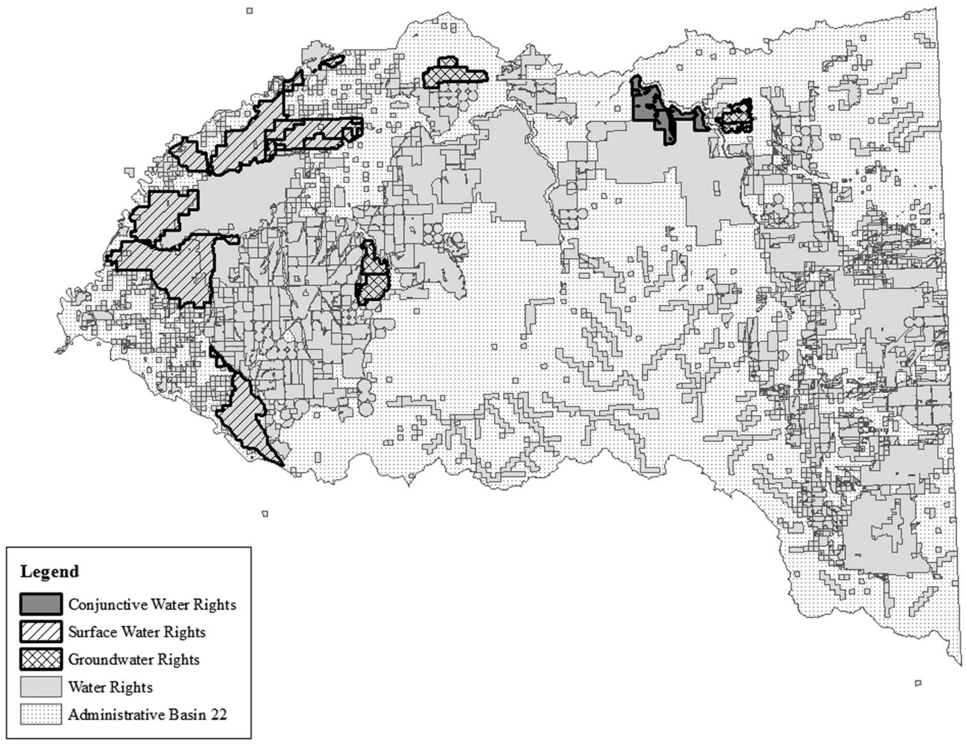

Figure 2. Study region and sampled water rights by source. Water rights are represented with their georeferenced place of use, or the area over which water allocated to that right can be applied.

of irrigators in the region because of the difficulties associated with quantifying an individual's diversion limits. Quantifying the amount of water that an individual decision maker may divert, and the land base over which that water may be applied, is nontrivial. Individual water rights may be "stacked," which occurs when multiple rights, generally of different priorities and potentially from different sources, are used for the same purpose and overlie the same place of use. For irrigators with stacked rights, the IDWR specifies a combined diversion limit for all rights in the stack that is not necessarily equal to the sum of the diversion limits associated with each right (M. Ciscell, personal communication, 2012). Furthermore, individual agents may own multiple water rights with a shared diversion limit. In this case, the same diversion limit is recorded multiple times in the geospatial database, so that summing across rights with a shared limit would generate a misleading diversion constraint. To account for stacked rights and multiple ownership, we retrieve paper water rights from the IDWR, manually determine which rights are associated with each grower, and modify the place of use polygons for each grower's rights accordingly.

We treat canal companies and irrigation districts as individual decision makers because each irrigator within their service area owns shares in water rights that are owned by the group. A curtailment order for a right held by the group is absorbed in proportion to the number of shares owned by each member of the group. Because of this ownership structure, the transfer of water between irrigators within a canal company or irrigation district is far more flexible than between individual water rights owners outside of service areas, and is often accomplished informally, via ads posted on bulletin boards. It is therefore more appropriate to aggregate across irrigators within a district or canal company than to model each individual grower.

Table 2 describes the sample irrigators. Together, the sampled owners cultivate 13,956 ha or 12% of the total irrigated agricultural land area in the Basin. The mix of surface water and groundwater irrigators in the sample is representative of the Basin, within which surface and groundwater irrigators are evenly split. Surface water irrigators in the region draw water primarily from the Upper Teton River, Henry's Fork, and the Upper Snake River. In the sample, six irrigators rely on surface water, five use groundwater and one holds surface water and groundwater rights for the same place of use. The median priority date for surface water rights in the sample

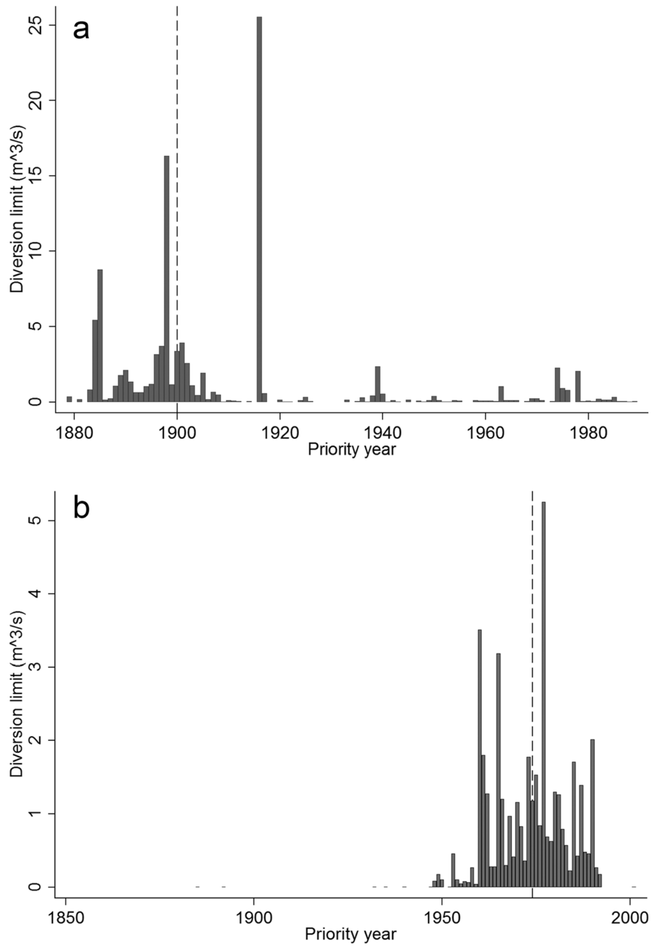

Figure 3. Total permitted diversions for the study region, by source and priority year. (a) Surface water rights. (b) Groundwater rights. Median priority year shown with vertical dashed line. Total volume is the sum over all rights with the same source and priority year.

is 1888; for groundwater it is 1971. Surface water users tend to rely on a single water right, while groundwater owners tend to hold two to three water rights for the same place of use. Most of the groundwater irrigators are private owners, while surface water rights are owned by canal companies and irrigation districts. Based on the USDA Cropland Data Layer for 2011, 31.1% of the land cultivated by sampled irrigators is in alfalfa, 31.7% is in barley, 25.6% is in wheat, and 11.6% is in potatoes. This land allocation is representative of observed agricultural land allocation across the Basin from 2009 to 2011.

For each management-administrative scenario, we consider three drought scenarios: no drought, in which there is sufficient water to fulfill all rights held by the sample irrigators; moderate drought, a reduction in surface water availability of 10%; and severe drought, a reduction in surface water availability of 30%. These reductions are based on the USDA-NRCS projections in the Idaho Water Supply Outlook for 2013 for the Upper and Lower Snake River Basins. According to this report, the average water supply availability is projected to fall by 25–35% during drought seasons for most rivers in these basins. The chosen drought scenarios are also consistent with summary statistics provided by the USDA-NRCS for reservoir and streamflow for the years 2006–2013 in the Teton River Basin. Over that time span, water shortages ranged up to a maximum of 35% of historical average flows, with a mean shortage of 13%.

To calibrate the model, we employ the positive mathematical programming (PMP) methodology [*Howitt*, 1995]. The PMP methodology offers a means of accounting for unobserved sources of nonlinearity in an optimization problem, such as heterogeneity in land quality or unobserved agronomic or socio-economic constraints. Following *Dagnino and Ward* [2012], we use a fixed irrigation requirement per ha to estimate the yield for each crop, by irrigator, as a function of the amount of land allocated to that crop. Yield functions are of the form: $y_{uk}=\beta_{0uk}+\beta_{1uk}l_{uk}$, where the coefficients β_{0uk} and β_{1uk} are estimated as described in Appendix A.

Studies by *Ward and Pulido-Velazquez* [2012] and *Gohar et al*. [2013] also assume a fixed proportion of water per unit of land for the purposes of basin-level optimization modeling. Water use per unit of land varies through the crop water coefficient, which depends upon the evapotranspirative demand for water. The proportion of applied water that is consumed via evapotranspiration depends on the irrigation technology used [*Marques et al*., 2005]. Within a single growing season, the time frame considered for this study, changes in irrigation technology are rarely seen. Furthermore, *Maneta et al*. [2009] and *Medellin-Azuara et al*. [2010] suggest that the importance of deficit irrigation, an adjustment at the intensive margin of water use, is minor

Table 2. Description of Sample Irrigators[a]

Owner		Water Rights SW	Water Rights GW	Diversion Limit (m^3/s)	Observed Land Allocation (ha) Alfalfa	Barley	Wheat	Potatoes	Total Land
1	Irrigation district	5/1884		0.068	381.6	518.4	255.4	108.5	1263.8
2	Canal company	6/1884		2.203	484.8	325.4	390.9	97.5	1298.6
3	Canal company	6/1885		0.453	182.1	15.4	79.7	0.8	278.0
4	Canal company	6/1888		0.750	933.2	157.0	124.2	4.9	1219.3
5	Canal company	4/1898		1.855	530.5	333.5	749.9	16.6	1630.5
6	Canal company	1/1901		2.832	411.2	140.8	259.0	55.0	866.0
7	Private		4/1960	0.065	0.4	7.3	53.4	48.2	109.3
8	Private		12/1960	0.045	9.3	127.1	225.4	155.8	517.6
			3/1969	0.074					
			6/1977	0.113					
9	Private		4/1966	0.198	0.8	189.8	28.3	121.8	340.7
			1/1986	0.008					
10	Private		2/1969	0.125	4.5	156.2	80.5	194.7	435.8
			5/1970	0.142					
			4/1985	0.147					
11	Private		7/1972	0.178	6.5	193	159.4	117.8	476.7
			8/1985	0.150					
12	Private	9/1976		0.028	9.7	854.7	25.1	182.1	1071.6
			8/1977	0.379					
			4/1986	0.283					
Total				10.109	2573	3019	2431	1104	9508

[a]SW denotes surface water; GW denotes groundwater.

as a means of mitigating drought losses, relative to changes along the extensive margin of water use, namely changes in the crop mix or irrigated land area.

Hence, we follow the approach taken by *Dagnino and Ward* [2012] and *Gohar et al*. [2013], using a quadratic production function with crop-specific irrigation depth requirement. Growers may respond to drought through a change in crop mix and/or total irrigated land area (and total water use). As a sensitivity test, we consider a scenario in which producers may allocate land to the dryland production of a subset of crops that can feasibly be produced without irrigation in the study region. The parameters used in the model are reported in Table 3.

5. Results and Discussion

Table 4 reports the land and water allocation for each management-administration and drought scenario. Table 5 summarizes profit outcomes for surface water, groundwater, and conjunctive irrigators for all scenarios. Table 6 summarizes banking activity for scenarios BKS and BKX.

5.1. No Trade Management Scenario (NTR)

In scenario NTR-PA with no drought, no water rights are curtailed. A total of 65.99 million m^3 of water are diverted, with 76% as surface water and the remainder as groundwater. This is consistent with observed withdrawals for the region based on USGS water use data [*Kenny et al*. 2009]. Alfalfa occupies the largest portion of the agricultural land base, 34.0%; barley and wheat account for 26.7 and 27.1%; and potatoes account for 12.2%. By incorporating unobserved constraints on production, the PMP calibration prevents corner solutions in which all of the land base is allocated to the most profitable crop(s). A total of 9045 ha of land are allocated to crop production, compared with an observed land allocation of 9508 ha. Potatoes earn the highest average return at $1834 per ha. Wheat, alfalfa, and barley garner returns of $583, $484, and $133 per ha, respectively.

The change in land allocation and water diversions associated with a drought depends on whether conjunctive administration (CA) is implemented. In scenario NTR-PA, junior surface water rights are the first to be curtailed during a water shortage. Under moderate drought, 6.8% of the land cultivated under the baseline is fallowed. The majority of that land is taken out of alfalfa, which declines by 11.7%. Land allocated to barley and wheat declines by 4.8 and 5.3%. Land in potatoes declines by 0.6%. The same pattern holds under

Table 3. Parameters Used in the Simulation Model[a]

	Units	Symbol	Value			
			Alfalfa	Barley	Wheat	Potatoes
Crop-Specific Parameters						
Price	USD/unit yield	p_k	140.00	7.20	7.70	10.00
Nonpumping variable cost	USD/unit yield	nwc_k	75.57	6.40	3.92	6.87
Average yield	unit yield/ha	$\bar{y}_k$	8.80	182.73	166.23	601.43
Water requirement	m^3/ha	λ_k	2.26	1.51	1.66	1.51
Other Parameters						
SW cost	USD/m^3	wc_{sw}				
GW cost	USD/m^3	wc_{gw}	0.014			
Max. total SW diversions	million m^3	$\bar{W}_{sw}$	50.18			
Max. total GW diversions	million m^3	$\bar{W}_{gw}$	18.26			
Rental fee	USD/m^3	rf	0.01			
Administrative fee	proportion	δ	0.10			
Rental limit	scalar	γ	2.77			

[a]Average yield and the water requirement are used in the PMP calibration described in Appendix A. Yield for alfalfa is in tons, barley and wheat are in bushels (bu), and potatoes are in hundredweight (cwt). All prices and costs are in 2011 dollars. Data for crop-specific parameters are from Idaho Crop Enterprise Budget Sheets, USDA-NASS Idaho crop data, and the Idaho Water Resources Research Institute.

severe drought: total cultivated land declines by 19.9%, with the largest reduction in alfalfa (25.8%) and the smallest in potatoes (5.1%).

Under moderate drought in scenario NTR-PA, surface water diversions fall by 9.94% and groundwater diversions increase slightly relative to the no-drought case. Groundwater diversions may increase because the groundwater diversion constraint for the conjunctive irrigator is not binding in the no-drought scenario. When that irrigator's surface water right is curtailed under moderate drought, the irrigator shifts to groundwater. Under moderate drought, producers suffer a profit loss of 4.33%, relative to no drought. Under severe drought, surface water diversions fall by 27.54% relative to no drought (Table 4), and profit losses amount to 14.46% (Table 5). In the PA scenarios, surface water irrigators bear the majority of those profit losses.

In scenario NTR-CA, groundwater rights are curtailed prior to most surface water rights. Under moderate drought, the decline in water availability is small enough that only a few of the most junior groundwater rights are curtailed. In this scenario, surface water diversions are unchanged, but groundwater diversions fall from 15.81 to 11.61 million m^3. Under severe drought, the decrease in water availability is large enough to require that all groundwater rights and some surface water rights are curtailed. With severe drought, no groundwater is diverted and surface water diversions decrease by 1.4%.

The land allocation change during drought in scenario NTR-CA differs substantially from that in NTR-PA. Under moderate drought, the total amount of cultivated land falls by 7.6%, a slight increase over NTR-PA. However, the majority of the reduction is driven by a decline in land in barley, which falls by 26.2%. Land in potatoes decreases by 2.4%, and land in alfalfa and wheat decreases by 0.3 and 0.6%, respectively. Under severe drought, total land in production falls by 29.0%, an increase of 1.5 times the amount of land fallowed under severe drought in scenario NTR-PA. Curtailing groundwater rights in NTR-CA results in a shift out of barley and potatoes, while land in alfalfa is maintained at nearly its no-drought level. This is in contrast to NTR-PA, which results in a shift in the crop mix toward potatoes and away from alfalfa.

Under moderate drought, CA is beneficial in aggregate, as total profit increases from $5.242 million to $5.407 million (Table 5). However, when drought is severe, profit declines to $3.574 million in NTR-CA, as compared to $4.687 million in NTR-PA. Because yield is declining in the amount of land allocated to each crop by each irrigator, curtailing all groundwater irrigators in NTR-CA involves removing from production land with a much higher marginal net benefit than land remaining in production by surface water irrigators. This result is consistent with that found by *Elbakidze et al.* [2012]: heterogeneity in the productivity of the agricultural land base can play a significant role in determining the optimal spatial pattern of water use when there is a water shortage in this region.

Table 4. Land and Water Allocation by Management-Administration and Drought Scenario[a]

	Scenario NTR-PA			Scenario OPT		
Drought Scenario	None	Moderate	Severe	None	Moderate	Severe
Land Allocation (ha)						
Alfalfa	3071	2712	2280	3152	3021	2655
Barley	2416	2300	2016	2610	2157	1274
Wheat	2450	2321	1895	2454	2384	2208
Potatoes	1108	1101	1051	1111	1094	1072
Total	9045	8434	7243	9327	8656	7209
Water Diversions (million m^3)						
Surface Water	50.18	45.19	36.36	57.2	54.28	45.81
Groundwater	15.81	15.90	15.90	10.76	9.15	7.58
Total	65.99	61.09	52.25	67.96	63.43	53.39
	Scenario NTR-CA					
Drought Scenario	None	Moderate	Severe			
Land Allocation (ha)						
Alfalfa	3071	3062	3008			
Barley	2416	1783	1259			
Wheat	2450	2436	1873			
Potatoes	1108	1081	285			
Total	9045	8362	6425			
Water Diversions (million m^3)						
Surface Water	50.18	50.18	49.48			
Groundwater	15.81	11.61				
Total	65.99	61.79	49.48			
	Scenario BKS-PA			Scenario BKX-PA		
Drought Scenario	None	Moderate	Severe	None	Moderate	Severe
Land Allocation (ha)						
Alfalfa	3001	2835	2374	2998	3073	2759
Barley	2287	2090	1532	2072	2048	1261
Wheat	2416	2354	2180	2373	2416	2258
Potatoes	1107	1104	1097	1093	1095	1075
Total	8810	8384	7182	8534	8631	7354
Water Diversions (million m^3)						
Surface Water	50.18	45.20	36.36	53	49.93	43.98
Groundwater	14.14	15.99	15.99	9.61	13.52	10.64
Total	64.32	61.18	52.35	62.61	63.45	54.62
	Scenario BKS-CA			Scenario BKX-CA		
Drought Scenario	None	Moderate	Severe	None	Moderate	Severe
Land Allocation (ha)						
Alfalfa	3001	2935	2804	2998	2998	2526
Barley	2287	2150	1457	2072	2072	911
Wheat	2416	2389	1810	2373	2373	2141
Potatoes	1107	1104	462	1093	1093	1062
Total	8810	8577	6534	8534	8534	6640
Water Diversions (million m^3)						
Surface Water	50.18	50.18	49.48	53	52.79	42.64
Groundwater	14.14	12.51		9.61	9.82	6.84
Total	64.32	62.69	49.48	62.61	62.61	49.48

[a]NTR, OPT denote no water trade and economically optimal management scenarios. PA denotes separate surface water and groundwater rights administration, CA denotes conjunctive surface water-groundwater administration. BKS, BKX denote water trade in state banks by source and across sources, respectively.

5.2. Water Banking Management Scenarios (BKS, BKX)

Water banking allows water to move from uses with a low marginal net benefit for water to uses with a higher marginal net benefit for water. However, the extent to which this is possible depends on whether CA is enforced and whether the bank allows irrigators to trade within or across water sources.

When the exchange of water is restricted by source in scenario BKS-PA, and there is no drought, surface water irrigators exchange 1.67 million m^3 of water through the bank (Table 6). Under moderate and severe drought, the quantity of surface water exchanged through the bank in this scenario increases to 4.19 and

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Table 5. Summary of Drought Losses by Management and Drought Scenario

	Profit (million USD)					
	SW	GW	CW	Total	Percent Loss[a]	Relative Gains[b]
Scenario NTR-PA						
No drought	3.582	1.493	0.405	5.479		
Moderate drought	3.352	1.493	0.398	5.242	4.33	
Severe drought	2.797	1.493	0.398	4.687	14.46	
Scenario NTR-CA						
No drought	3.582	1.493	0.405	5.479		
Moderate drought	3.582	1.493	0.332	5.407	1.32	
Severe drought	3.574			3.574	34.77	
Scenario BKS-PA						
No drought	3.584	1.493	0.405	5.482		3.33
Moderate drought	3.509	1.493	0.402	5.404	1.44	55.86
Severe drought	3.274	1.493	0.402	5.169	5.71	72.59
Scenario BKS-CA						
No drought	3.584	1.493	0.405	5.482		3.33
Moderate drought	3.582	1.505	0.392	5.479	0.06	57.60
Severe drought	3.567		0.402	3.969	27.61	22.23
Scenario BKX-PA						
No drought	3.584	1.517	0.407	5.508		32.22
Moderate drought	3.516	1.516	0.426	5.458	0.90	74.48
Severe drought	3.381	1.513	0.420	5.314	3.52	94.43
Scenario BKX-CA						
No drought	3.584	1.517	0.407	5.508		32.22
Moderate drought	3.584	1.514	0.407	5.505	0.05	78.40
Severe drought	3.506	1.341	0.388	5.235	4.96	93.47
Scenario OPT						
No drought	3.587	1.493	0.489	5.569		
Moderate drought	3.569	1.483	0.480	5.532	0.66	
Severe drought	3.445	1.455	0.452	5.351	3.91	

[a]Percent loss is relative to the no drought case for each scenario.
[b]Relative gains are calculated as the difference between total profit for the banking scenario and NTR, divided by the difference between the total profit for OPT and NTR. NTR denotes no water trade; BKS, BKX denote water trade in state banks by source and across sources, respectively; OPT denotes economically optimal management scenarios. PA denotes separate surface water and groundwater rights administration; CA denotes conjunctive surface water-groundwater administration. SW, GW, and CW denote surface water irrigators, groundwater irrigators, and conjunctive water irrigators.

8.74 million m^3, respectively. This exchange in water alters the land allocation relative to scenario NTR-PA. The majority of the reduction in crop acreage in BKS-PA comes out of barley, rather than alfalfa (Table 4). Under severe drought, the change in land allocation follows a similar pattern.

When the exchange of water across sources is allowed in scenario BKX-PA, and there is no drought, surface water irrigators continue to exchange 1.67 million m^3 of water, but another 2.82 million m^3 of water is exchanged from groundwater to surface water irrigators. When drought severity increases, the amount of groundwater transferred to surface water irrigators increases. In BKX-CA, less water is transferred from groundwater irrigators to surface water irrigators because groundwater rights are curtailed. Under severe drought, when all groundwater rights are curtailed, the direction of exchange reverses such that water is exchanged from surface water to groundwater irrigators.

Across management-administration and drought scenarios, allowing banking across sources (BKX) introduces flexibility in water exchange that improves producer welfare outcomes relative to the case when exchange is restricted to within sources (BKS). In BKX-PA with no drought, profit is $5.508 million, which exceeds $5.482 million in BKS-PA, and $5.479 million in NTR-PA. The same pattern applies with moderate or severe drought: BKX-PA outperforms BKS-PA, which improves upon NTR-PA. For example, in severe drought irrigators lose 3.52% (relative to the no drought level) in BKX-PA, 5.71% in BKS-PA, and 14.46% in NTR-PA. A similar patterns holds for the CA scenarios: under severe drought irrigators lose 4.96% in BKX-CA, 27.61% in BKS-CA, and 34.77% in NTR-CA. These outcomes demonstrate that in severe drought, the relative performance of banking across sources over banking by source is far more pronounced when CA is used than when surface and groundwater rights are administered separately. When CA is enforced during severe drought, all groundwater irrigators are curtailed. Their only recourse is to rent water from the bank, an option that is only available if water can be transferred from surface water irrigators whose rights are fulfilled to groundwater irrigators whose rights are curtailed.

Table 6. Banking Activity by Scenario[a]

	Scenario BKS-PA			Scenario BKX-PA		
Drought Scenario	None	Moderate	Severe	None	Moderate	Severe
Land Fallowed (ha)						
SW Irrigators	235	661	1863	235	14	827
GW Irrigators				275	198	424
CW Irrigators					202	440
Leases (million m³)						
Surface Water	1.67	4.19	8.74	1.67	0.20	3.78
Groundwater				2.82	4.73	7.62
Rentals (million m³)						
Surface Water	1.67	4.19	8.74	4.48	4.93	11.40
Groundwater						
Rental fees (USD)	22,996	57,808	120,451	61,799	68,001	157,127
Lease payments (USD)	20,696	52,027	108,406	55,619	61,201	141,414
Administrative fees (USD)	2300	5781	12,045	6180	6800	15,713
	Scenario BKS-CA			Scenario BKX-CA		
Drought Scenario	None	Moderate	Severe	None	Moderate	Severe
Land Fallowed (ha)						
SW Irrigators	235	405	687	235	235	1444
GW Irrigators		16	1700	275	275	630
CW Irrigators		47	124			331
Leases (million m³)						
Surface Water	1.67	2.92	4.47	1.67	1.67	10.05
Groundwater		1.00		2.82	2.61	
Rentals (million m³)						
Surface Water	1.67	2.92	4.47	4.48	4.28	3.20
Groundwater		1.00				6.84
Rental fees (USD)	22,996	53,940	61,593	61,799	58,966	138,449
Lease payments (USD)	20,696	48,546	55,433	55,619	53,070	124,604
Administrative fees (USD)	2300	5394	6159	6180	5897	13,845

[a]BKS, BKX denote water trade in state banks by source and across sources, respectively. PA denotes separate surface water and groundwater rights administration, CA denotes conjunctive surface water-groundwater administration. SW, GW, and CW denote surface water irrigators, groundwater irrigators, and conjunctive water irrigators respectively. Land fallowed is calculated relative to scenario NTR with no drought.

5.3. Economically Optimal Management Scenario (OPT)

The economically optimal allocation of land and water varies with drought severity. With no drought, it is optimal to reallocate water across irrigators in such a way that the cultivated land area increases by 282 ha. Most of that increase is in barley and alfalfa, which increase by 194 and 81 ha. The total amount of water used in irrigation increases slightly as a result, from 65.99 to 67.96 million m^3. This increase can occur because the groundwater diversion constraints for some groundwater rights owners are not binding under NTR-PA with no drought. Under the optimal allocation, water is redistributed from groundwater irrigators, whose diversions decline by 5.05 million m^3, to surface water irrigators, whose diversions increase by 7.02 million m^3. The increase in total water diversions allows for an increase in aggregate profit of $0.09 million (from $5.479 in NTR-PA to $5.569 in OPT), all of which accrues to surface water and conjunctive irrigators.

During drought, it is optimal to reduce groundwater diversions in order to maintain surface water diversions. This result is in driven by differences in the marginal productivity of land for surface and groundwater irrigators and by differences in the marginal cost of diverting surface water and groundwater. Under moderate drought, groundwater diversions fall by 15.0% and surface water diversions fall by 5.1%. Under moderate drought, the loss in aggregate profit in OPT is 0.66%, as compared to a loss of 4.33 or 1.32% in NTR-PA and NTR-CA, respectively. Under severe drought, groundwater and surface water diversions decline by 29.6 and 19.9%. The reduction in profit losses under severe drought is 3.91% in OPT versus 14.46 or 34.77% respectively in NTR-PA and NTR-CA.

Comparing the profit obtained in banking scenarios BKS and BKX with that under the bounding scenarios NTR and OPT allows us to comment on the relative economic efficiency of water banking. The maximum potential improvement in profit over the baseline in each management-administration and drought scenario is given by the difference between OPT and NTR. We express the performance of each banking scenario by reporting the increase in profit over NTR as a percentage of the maximum potential improvement. These are reported as relative gains in the last column of Table 5.

If surface and groundwater rights are administered separately, banking by source (BKS-PA), obtains 55.86% of the maximum potential improvement over NTR under moderate drought and 72.59% of the maximum potential improvement over NTR under severe drought. Banking across sources (BKX-PA), increases those levels to 74.48 and 94.43%, respectively. If surface and groundwater rights are administered conjunctively, banking by source (BKS-CA) obtains 57.60 and 22.23% of the maximum potential improvement under moderate and severe drought. Banking across sources (BKX-CA) improves upon the aggregate outcome, increasing those levels to 78.40 and 93.47%.

In OPT, surface water and groundwater irrigators share in the losses realized under drought. In NTR-PA, BKS-PA, and BKX-PA, profit losses from drought are absorbed almost entirely by surface water irrigators. In NTR-CA, BKS-CA, and BKX-CA, groundwater irrigators absorb some drought losses, but the magnitude of those losses depends on whether the water bank restricts trade by source or allows trade across sources. The worst-case scenario for groundwater irrigators occurs with severe drought in scenarios NTR-CA or BKS-CA, both of which result in a complete loss of water. The greatest difference between BKS and BKX is realized under severe drought and conjunctive administration, when all of the region's groundwater irrigators are curtailed, but surface water rights are fulfilled.

5.4. Sensitivity Analysis

We conduct a variety of sensitivity analyses with respect to the model's parameters and assumptions. For brevity, we focus our discussion on the effect of changes in the water bank's rental fee, the introduction of dryland crop production as a short-run response to drought, and the inclusion of variability in surface water flows. Additional sensitivity analysis results, such as those for changes in the marginal cost of groundwater pumping or crop prices, are available from the authors upon request.

We vary the rental fee from zero to \$1.05/m^3 and simulate the effect on irrigation decision making. An increase in the rental fee reduces the amount of water exchanged between irrigators, as illustrated in Figure 4, which displays the total amount of water exchanged through the bank in scenarios BKS-CA and BKX-CA. A larger amount of water is exchanged under BKX-CA for any rental fee. In both scenarios, the quantity of water exchanged through the bank increases most rapidly as the price falls below \$0.4/m^3. For prices above that level, the quantity of water exchanged is relatively insensitive to price changes. However, prices in this range are substantially higher than the (nominal) prices set by the IWRB through the year 2030.

Table 7 presents the profit and relative gains under each banking scenario as the rental fee varies from a low of \$0.011/m^3 to a high of \$0.019/m^3, which is consistent with the range of prices set for 2006–2030 by the Idaho Water Resources Board (IWRB). The baseline price in the model is \$0.014/m^3. Within each drought scenario, an increase in the rental fee reduces aggregate profit and the relative gains from water banking. Compared to the difference between management-administration and drought scenarios, the impact of a change in rental price within each scenario is relatively small. Under BKX-CA, for example, the amount of water exchanged during a severe drought is 10.09 million m^3 when the fee is \$0.011/m^3, 10.05 million m^3 when the fee is \$0.014/m^3, and 9.957 million m^3 when the fee is \$0.019/m^3.

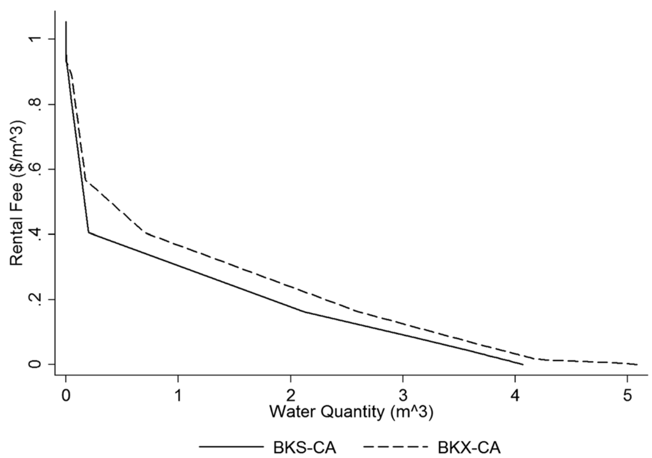

Figure 4. Quantity of water exchanged through water banks under moderate drought in scenarios BKS-CA and BKX-CA, as a function of the rental fee. BKS, BKX denote water trade in state banks by source and across sources, respectively. PA denotes separate surface water and groundwater rights administration, CA denotes conjunctive surface water-groundwater administration.

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Table 7. Sensitivity Analysis, Rental Fee[a]

	Scenario BKS-PA		Scenario BKX-PA	
	Profit (m. USD)	Relative Gains	Profit (m. USD)	Relative Gains
Rental Price: $0.011/m^3$				
No drought	5.483	4.44	5.509	33.33
Moderate drought	5.405	56.21	5.459	79.20
Severe drought	5.171	72.89	5.316	93.58
Rental Price: $0.014/m^3$ (Baseline)				
No drought	5.482	3.33	5.508	32.22
Moderate drought	5.404	55.86	5.458	74.48
Severe drought	5.169	72.59	5.314	22.23
Rental Price: $0.019/m^3$				
No drought	5.482	3.33	5.506	30.00
Moderate drought	5.402	55.17	5.456	73.79
Severe drought	5.165	71.99	5.308	22.12
	Scenario BKS-CA		Scenario BKX-CA	
	Profit (m. USD)	Relative Gains	Profit (m. USD)	Relative Gains
Rental Price: $0.011/m^3$				
No drought	5.483	4.44	5.509	33.33
Moderate drought	5.480	58.40	5.506	79.20
Severe drought	3.970	22.28	5.237	93.58
Rental Price: $0.014/m^3$ (Baseline)				
No drought	5.482	3.33	5.508	32.22
Moderate drought	5.479	57.60	5.505	78.40
Severe drought	3.969	22.23	5.235	93.47
Rental Price: $0.019/m^3$				
No drought	5.482	3.33	5.506	30.00
Moderate drought	5.477	56.00	5.503	76.80
Severe drought	3.967	22.12	5.230	93.19

[a]Relative gains are calculated as the difference between total profit for the banking scenario and NTR, divided by the difference between the total profit for OPT and NTR. NTR denotes no water trade; BKS, BKX denote water trade in state banks by source and across sources, respectively; OPT denotes economically optimal management scenarios. PA denotes separate surface water and groundwater rights administration; CA denotes conjunctive surface water-groundwater administration.

Dryland farming is not currently practiced in the study region, though we consider the possibility that producers may introduce dryland production as a short-run response to drought. On average, dryland yield varies between one fourth to one half of the irrigated yield of alfalfa, barley, and wheat in southeastern Idaho. Potatoes cannot be produced without irrigation. To incorporate dryland yield into the model, we specify a yield function similar to that for irrigated yield. Because dryland production has not been practiced in the study region, we lack the data necessary to calibrate dryland yield functions. Instead, we assume that the yield functions have the same slope as for irrigated yield, but that the intercept is one fourth of the irrigated level.

Table A1 in Appendix A describes the changes in land allocation, water diversions, and aggregate profit when dryland crops are incorporated into the model for scenarios NTR-CA, BKX-CA, and OPT. In all scenarios, producers allocate some land to dryland production. In scenario NTR-CA, dryland production occupies 12% of the land base under no drought, 13% under moderate drought, and 17% under severe drought. The outcome in scenarios BKX-CA and OPT are similar, with dryland occupying 10–11% of the land base under moderate drought and up to 24% under severe drought. Though the land allocation can differ significantly from that in the model that does not allow dryland farming, the maximum aggregate improvement in profit for any scenario from introducing dryland cropping is 4.3%.

To incorporate variability in surface water flows into the model, we use data from the *USGS National Water Information System* on annual average surface water flows for 1891–2013 through USGS surface water gauge 13055000 (Teton River near St. Anthony). Flows through this gauge are representative of the magnitude and variability of surface water availability for the irrigators in our model. The distribution of annual average surface water flows is approximated well by a normal distribution with a mean of 23.39 m^3/s and a standard deviation of 6.82 m^3/s. For each management-administration scenario, we generate 100 realizations for surface water flows. Among the 100 random draws, 53% result in a water shortage (defined as insufficient water to satisfy all surface water rights), with a mean shortage of 10.4%. The uncertainty case includes the moderate and severe drought scenarios among the stochastic realizations in proportion to their likelihood of occurrence.

Table A2 in Appendix A reports the mean and standard deviation of irrigator profit across surface water realizations for each management-administration scenario. When surface and groundwater rights are administered separately, BKX-PA outperforms BKS-PA, which outperforms NTR-PA, both in terms of the mean and variance of irrigator profit. When surface and groundwater rights are administered conjunctively, either banking scenario outperforms NTR-CA, though the difference between BKX-CA and BKS-CA is negligible. Although BKX-CA substantially outperforms BKS-CA under severe drought conditions, those conditions occur rarely enough that the average level of irrigator profit across stochastic realizations is similar between the two scenarios. Scenario OPT consistently yields the highest mean and the lowest variance for irrigator profit among the management-administration scenarios.

The results in Table A2 indicate that the implementation of CA affects the relative variance in profit for surface water irrigators and groundwater irrigators. Under PA, groundwater irrigators are relatively insulated from risk. Shifting to CA increases profit variability for groundwater irrigators, while substantially reducing profit variability for surface water irrigators. Across management scenarios, increased flexibility in water marketing increases irrigator profit, as it does in the model that assumes certainty, but it also reduces variability in profit. These results indicate that management and administration scenarios are likely to carry important implications for the risk faced by irrigators. A more comprehensive examination of questions related to risk is outside of the scope of this analysis, but is an interesting avenue for future exploration.

6. Conclusion and Policy Implications

Water marketing in the western United States has been a widely researched topic in the economic literature but few studies have analyzed water banks. Water banks are a marketing instrument that can address some of the obstacles to water marketing or trade, allowing irrigators within a region to exchange water in order to mitigate the short-term effects of drought. This paper quantifies and compares the effect of water banking on the level and distribution of irrigator profit under a range of drought conditions. In addition, it assesses how institutional arrangements, namely the separate versus conjunctive administration of surface water and groundwater rights, impact the efficiency of water banking as a means of reallocating water across irrigators.

The outcomes for each management scenario differ depending upon whether CA is enforced or not. With no water trade, the enforcement of CA during a severe drought results in a decline in aggregate profit of 34.77% relative to the no-drought case. CA shifts the burden of drought losses from surface water irrigators to groundwater irrigators. Allowing for water banking across sources (BKX) mitigates drought-related losses substantially, reducing aggregate profit losses to 4.96% during severe drought. In this scenario, groundwater irrigators are able to recover 88.4% of their profits under no drought at a cost of 2.2% of the profits earned by surface water irrigators under no drought. When water exchange through banks occurs only within sources, there is no means of redistributing water from surface water irrigators to groundwater irrigators who are curtailed during drought. Surface water calls against groundwater pumpers in the Eastern Snake River Plain are becoming more prevalent. The injury that these calls are expected to inflict upon groundwater irrigators have provided an incentive for the State to find ways to allow groundwater pumpers to fulfill senior surface water rights through means other than curtailing pumping. This analysis suggests that when CA is implemented in a hydraulically connected region, designing a regional water bank to facilitate trade across sources may be an effective mechanism to do so.

In this analysis, we present a simplified model that allows us to focus on the way in which water rights administration interacts with different management scenarios to influence economic outcomes for agricultural producers. One modeling choice that we make is to abstract from uncertainty in the production environment. Given that surface water flows are highly variable year-to-year, there are likely to be important risk implications associated with different water rights administration and management scenarios. The results of our sensitivity analysis indicate that conjunctive administration reduces variability in profit for surface water irrigators, but that it increases aggregate variability in profit substantially. By offering a means of stabilizing water availability, water banking is likely to provide additional economic value over that estimated here [*Tsur and Graham-Tomasi*, 1991]. The stabilization value of water banking is likely to be larger under CA than under PA, but the affected irrigators differ in each case. Incorporating risk and uncertainty is a logical extension to this work and is likely to be important to consider in analyses that attempt to estimate the costs and benefits of water-related projects or describe the optimal extraction path for groundwater [*Gemma and Tsur*, 2007].

Future efforts may also expand the model presented here to a dynamic setting. We develop a static model because our focus is on short-term responses to water marketing arrangements that apply for a single season at a time. But even if water marketing decisions are made on an annual basis, water diversion decisions affect water availability in future years. This is particularly relevant when implementing CA because the effects of groundwater pumping on surface water availability are attenuated over time in accordance with the physical characteristics of the region (e.g., aquifer transmissivity) and distance [*Elbakidze et al.*, 2012; *Kuwayama and Brozovic*, 2013; *Sophocleous*, 2002]. In this analysis, we consider the case in which groundwater that is not diverted is immediately available for use by surface water irrigators. However, curtailing groundwater rights at different points in space will not yield the same benefit in terms of increasing surface water flows. If curtailing a pumper provides little or no additional surface water, then the state will not curtail that right. In this context, CA will yield outcomes that sit between the PA and CA scenarios considered in this analysis. Coupling a hydrologic model of groundwater-surface water interactions with an economic model of the type presented in this paper would allow future analyses to answer questions about, for example, whether CA is optimal, over what geographic scope water banks should facilitate water trade, and how institutional arrangements affect the availability of water to support ecosystem services.

Appendix A

For the Positive Mathematical Programming (PMP) calibration, we assume that there is a fixed proportion of irrigation water used per ha of land for each crop and that the yield of the crop depends upon the land allocation decision. Specifically, following *Dagnino and Ward* [2012], the crop-specific yield per ha for each irrigator is given by:

$$y_{uk}=\beta_{0uk}+\beta_{1uk}l_{uk} \tag{A1}$$

where $u=1,\ldots,U$ indexes the irrigator, $k=1,\ldots,K$ indexes the crop, and l_{uk} represents the land allocation. The coefficients β_{0uk} and β_{1uk} are determined by the PMP calibration. This functional form is consistent with the Ricardian theory of rent which states that yield declines as more marginal land is brought into production, with other inputs held constant.

An irrigator takes the water requirement per unit of land in each crop as given and maximizes profit by choosing the land allocation and implied water allocation. Let the quantity of water required per acre for crop k be given by λ_k. Then total water use by irrigator u on crop k is:

$$w_{uk}=\lambda_k l_{uk} \tag{A2}$$

The total profit for irrigator u is:

$$\pi_u=\sum_k\left[(p_k y_{uk}-c_k)l_{uk}-p_w w_{uk}\right] \tag{A3}$$

where p_k is the price for each crop per unit yield, c_k denotes the nonwater costs of production per unit of land allocated to crop k, and p_w is the price of irrigation water.

Substituting (A1) and (A2) into (A3), we can express profit as a function of water use:

$$\pi_u=\sum_k\left\{\left[p_k\left(\beta_{0uk}+\beta_{1uk}\frac{w_{uk}}{\lambda_k}\right)-c_k\right]\frac{w_{uk}}{\lambda_k}-p_w w_{uk}\right\}$$

Taking the first-order necessary conditions for a maximum yields:

$$\frac{2p_k\beta_{1uk}w_{uk}+\lambda_k p_k\beta_{0uk}-\lambda_k c_k}{(\lambda_k)^2}-p_w=0 \ \text{ for } \ k=1,\ldots,K \tag{A4}$$

Using (A4), (A1), and (A2), we solve for β_{1uk} as:

$$\beta_{1uk}=\frac{\lambda_k p_w-(p_k y_{uk}-c_k)}{p_k l_{uk}}.$$

The parameter β_{1uk} is estimated using the observed water price, crop price, recommended irrigation depth for the crop, variable production costs per unit of land (from cost of production studies for the study

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Table A1. Sensitivity Analysis, Model With Dryland Cropping[a]

	No Drought		Moderate Drought		Severe Drought	
	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Dryland
Scenario NTR-CA						
Land Allocation (ha)						
Alfalfa	2940	394	2931	394	2910	395
Barley	1979	350	1357	360	917	418
Wheat	2327	418	2314	418	1780	435
Potatoes	1099		1072		282	
Total	8346	1161	7674	1172	5888	1248
Water Diversions (million m^3)						
SW	46.03		46.03		45.85	
GW	15.23		11.10			
Total	61.26		57.13		45.85	
Profit (m. USD)	5.59		5.51		3.69	
Scenario BKX-CA						
Land Allocation (ha)						
Alfalfa	2938	397	2929	407	2498	764
Barley	2110	215	2094	228	959	733
Wheat	2327	419	2324	425	2133	617
Potatoes	1101		1100		1065	
Total	8476	1031	8447	1060	6654	2114
Water Diversions (million m^3)						
SW	51.81		51.64		42.39	
GW	10.24		10.20		7.09	
Total	62.05		61.84		49.48	
Profit (m. USD)	5.66		5.66		5.66	
Scenario OPT						
Land Allocation (ha)						
Alfalfa	2941	393	2941	393	2614	692
Barley	2129	197	2129	197	1349	620
Wheat	2329	417	2329	417	2192	581
Potatoes	1101		1101		1077	
Total	8500	1007	8500	1007	7232	1894
Water Diversions (million m^3)						
SW	51.95		51.95		45.32	
GW	10.25		10.25		8.07	
Total	62.20		62.20		53.39	
Profit (m. USD)	5.76		5.76		5.57	

[a]NTR denotes no water trade; BKX denote water trade in state banks across sources; OPT denotes economically optimal management scenarios. PA denotes separate surface water and groundwater rights administration; CA denotes conjunctive surface water-groundwater administration.

Table A2. Sensitivity Analysis, Variability in Surface Water Flows[a]

	Profit (m. USD)			
Management-Administration Scenario	SW	GW	CW	Total
NTR-PA	3.217	1.493	0.403	5.113
	(0.509)		(0.001)	(0.510)
NTR-CA	2.510	1.118	0.248	4.876
	(0.182)	(0.606)	(0.194)	(0.908)
BKS-PA	3.388	1.493	0.403	5.284
	(0.312)		(0.001)	(0.313)
BKS-CA	3.570	1.234	0.293	5.097
	(0.064)	(0.535)	(0.178)	(0.716)
BKX-PA	3.393	1.498	0.413	5.303
	(0.299)	(0.009)	(0.006)	(0.287)
BKX-CA	3.570	1.235	0.293	5.097
	(0.064)	(0.535)	(0.178)	(0.716)
OPT	3.567	1.487	0.484	5.538
	(0.053)	(0.013)	(0.013)	(0.078)

[a]NTR denotes no water trade; BKS, BKX denote water trade in state banks by source and across sources, respectively; OPT denotes economically optimal management scenarios. PA denotes separate surface water and groundwater rights administration; CA denotes conjunctive surface water-groundwater administration. SW, GW, and CW denote surface water irrigators, groundwater irrigators, and conjunctive irrigators. Standard deviations are in parentheses.

region), the average yield for crop k in the study region, denoted $\bar{y}_k$, and the observed land allocation to crop k by irrigator u. The parameter β_{0uk} is derived from (A1) using average yield by crop, the observed land allocation, and the estimated value of β_{1uk}.

Acknowledgments
This work was supported by funding from the Idaho EPSCoR Program and the National Science Foundation under award number EPS-0814387. All data used in this analysis are publicly available, with sources as cited in the text. The authors will provide a copy of the programming code upon request.

References

Baker, S. J. (1991), *Effects of Exchange Wells on the Teton River in the Rexburg-Teton Area, Madison and Fremont Counties*, Idaho, Idaho Dep. of Water Resour., Boise, Idaho.

Bredehoeft, J. D., and R. A. Young (1983), Conjunctive use of groundwater and surface water for irrigated agriculture: Risk aversion, *Water Resour. Res.*, *19*, 1111–1121.

Burke, S. M., R. M. Adams, and W. W. Wallender (2004), Water banks and environmental water demands: Case of the Klamath Project, *Water Resour. Res.*, *40*, W09S02, doi:10.1029/2003WR002832.

California's Drought: Water Conditions & Strategies to Reduce Impacts.

Carey, J. M., and D. L. Sunding (2001), Emerging markets in water: A comparative institutional analysis of the Central Valley and Colorado-Big Thompson Projects, *Nat. Resour. J.*, *41*, 283–328.

Chang, C., and R. C. Griffin (1992), Water marketing as a reallocative institution in Texas, *Water Resour. Res.*, *28*, 879–890.

Clifford, P., C. Landry, and A. Larsen-Hayden (2004), *Analysis of Water Banks in the Western States*, Wash. Dep. of Ecol. publication number 04-11-011, Olympia, Wash.

Cosgrove, D. M., and G. S. Johnson (2005), Aquifer management zones based on simulated surface-water response functions, *J. Water Resour. Plann. Manage.*, *131*(2), 89–100.

Dagnino, M., and F. A. Ward (2012), Economics of agricultural water conservation: Empirical analysis and policy implications, *Int. J. Water Resour. Dev.*, *28*(4), 577–600.

Elbakidze, L., X. Shen, G. Taylor, and S. Mooney (2012), Spatio temporal analysis of prior appropriations water calls, *Water Resour. Res.*, *48*, W00L07, doi:10.1029/2011WR010609.

Fabritz-Whitney, S. A. (2012), Arizona water banking authority annual plan of operation 2013, Arizona Water Banking Authority, Phoenix, Ariz. [Available at www.azwaterbank.gov.]

Fabritz-Whitney, S. A. (2013), Arizona water banking authority annual plan of operation 2014, Arizona Water Banking Authority, Phoenix, Ariz. [Available at www.azwaterbank.gov.]

Frey, M. R. (2012), Assessing climate change impact on water rights on the Eastern Snake River Plain, Master's thesis, Idaho State Univ., Pocatello, Idaho.

Gemma, M., and Y. Tsur (2007), The stabilization value of groundwater and conjunctive water management under uncertainty, *Appl. Econ. Perspect. Policy*, *29*(3), 540–548.

Gisser, M., and R. N. Johnson (1983), Institutional restrictions on the transfer of water rights and the survival of an agency, in *Water Rights: Scarce Resource Allocation, Bureaucracy, and the Environment*, edited by T. L. Anderson, pp. 137–165, Ballenger Publ. Co., Cambridge, Mass.

Gohar, A. A., and F. A. Ward (2011), Gains from improved irrigation water use efficiency in Egypt, *Water Resour. Dev.*, *27*(4), 737–758.

Gohar, A. A., F. A. Ward, and S. A. Amer (2013), Economic performance of water storage capacity expansion for food security, *J. Hydrol.*, *484*, 16–25.

Griffin, R. C. (2006), *Water Resource Economics: The Analysis of Scarcity, Policies, and Projects*, MIT Press, Cambridge, Mass.

Hansen, K., R. E. Howitt, and J. Williams (2008), Valuing risk: Options in California water markets, *Am. J. Agric. Econ.*, *90*, 1336–1342.

Howitt, R. E., and K. Hansen (2005), The evolving western water markets, *Choices*, *20*, 59–63.

Howitt, R. E. (1995), Positive mathematical programming, *Am. J. Agric. Econ.*, *77*, 329–342.

Howitt, R. E., J. Medellín-Azuara, D. MacEwan, and J. R. Lund (2012), Calibrating disaggregate economic models of agricultural production and water management, *Environ. Model. Software*, *38*, 244–258.

Howe, C. W., D. R. Schurmeier, and W. D. Shaw Jr. (1986), Innovative approaches to water allocation: The potential for water markets, *Water Resour. Res.*, *22*, 439–445.

Idaho Administrative Code (2004), *Water Supply Bank Rules, IDAPA 37*, title 02, chap. 3, pp. 1–8, Dep. of Water Resour., Boise, Idaho.

Idaho Department of Water Resources (2013), Water Supply Bank: 2013 Report for the Board's Water Supply Bank, Idaho Water Resource Board, Boise, Idaho. [Available at http://www.idwr.idaho.gov/WaterManagement/WaterRights/WaterSupply/ws_default.htm.]

Jones, J. B., and P. J. Mulholland (2000), *Streams and Ground Waters*, Academic Press, San Diego, Calif.

Kenny, J. F., N. L. Barber, S. S. Hutson, K. S. Linsey, J. K. Lovelace, and M. A. Maupin (2009), Estimated use of water in the United States in 2005, *U.S. Geol. Surv. Circ.*, *1344*, 52 pp.

Knapp, K. C., and L. J. Olson (1995), The economics of conjunctive groundwater management with stochastic surface supplies, *J. Environ. Econ. Manage.*, *28*(3), 340–356.

Kollet, S. J., and V. A. Zlotnik (2003), Stream depletion predictions using pumping test data from a heterogeneous stream-aquifer system (a case study from the Great Plains, USA), *J. Hydrol.*, *281*(1-2), 96–114.

Kuwayama, Y., and N. Brozovic (2013), The regulation of a spatially heterogeneous externality: Tradable groundwater permits to protect streams, *J. Environ. Econ. Manage.*, *66*(2), 364–382.

Lefkoff, L. J., and S. M. Gorelick (1990), Benefits of an irrigation water rental market in a saline stream-aquifer system, *Water Resour. Res.*, *26*, 1371–1381.

Libecap, G. D. (2011), Institutional path dependence in climate adaptation: Coman's "Some unsettled problems of irrigation," *Am. Econ. Rev.*, *101*, 64–80.

Maneta, M. P., M. O. Torres, W. W. Wallender, S. Vosti, R. Howitt, L. Rodrigues, L. H. Bassoi, and S. Panday (2009), A spatially distributed hydroeconomic model to assess the effects of drought on land use, farm profits, and agricultural employment, *Water Resour. Res.*, *45*, W11412, doi:10.1029/2008WR007534.

Marques, G. F., J. R. Lund, and R. E. Howitt (2005), Modeling irrigated agricultural production and water use decisions under water supply uncertainty, *Water Resour. Res.*, *41*, W08423, doi:10.1029/2005WR004048.

McCallum, A. M., M. S. Andersen, G. C. Rau, J. R. Larsen, and R. I. Acworth (2014), River-aquifer interactions in a semiarid environment investigated using point and reach measurements, *Water Resour. Res.*, *50*, 2815–2829, doi:10.1002/2012WR012922.

Medellin-Azuara, J., J. J. Harou, and R. E. Howitt (2010), Estimating economic value of agricultural water under changing conditions and the effects of spatial aggregation, *Sci. Total Environ.*, *408*, 5639–5648.

Miller, S. A., G. S. Johnson, D. M. Cosgrove, and R. Larson (2003), Regional Scale Modeling of Surface and Ground Water Interaction in the Snake River Basin, *J. Am. Water Resour. Assoc.*, *39*(3), 517–528.

O'Donnell, M., and B. Colby (2010), *Water Banks: A Tool for Enhancing Water Supply Reliability*, Univ. of Arizona Dep. of Agric. and Resour. Econ., Tucson, Ariz.

Provencher, B., and O. Burt (1994), Approximating the optimal groundwater pumping policy in a multi aquifer stochastic conjunctive use setting, *Water Resour. Res.*, *30*, 833–843.

Snyder, D. L., and R. H. Coupal (2005), Assessment of relative economic consequences of curtailment of eastern Snake Plain Aquifer Ground Water Irrigation Rights, Report to the Idaho Legislature, 0205, Boise, Idaho.

Sophocleous, M. (2002), Interactions between groundwater and surface water: The state of the science, *Hydrogeol. J.*, *10*, 52–67.

Tsur, Y., and T. Graham-Tomasi (1991), The buffer value of groundwater with stochastic surface water supplies, *J. Environ. Econ. Manage.*, *21*(3), 201–224.

Ward, F. A., and M. Pulido-Velazquez (2012), Economic costs of sustaining water supplies: Findings from the Rio Grande, *Water Resour. Manage.*, *26*, 2883–2909.

Winter, T. C., J. W. Harvey, O. L. Franke, and W. M. Alley (1998), Groundwater and surface water: A single resource, *U.S. Geol. Surv. Circ.*, *1139*, 79 pp.

Young, R. A., and J. D. Bredehoeft (1972), Digital computer simulation for solving management problems of conjunctive groundwater and surface water systems, *Water Resour. Res.*, *8*, 533–556.