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# THE GRAVITY OF WATER: WATER TRADE FRICTIONS IN CALIFORNIA

CHARLES REGNACQ, ARIEL DINAR, AND ELLEN HANAK

It is relatively well accepted that costs associated with transfers weigh upon water markets and deter some exchanges. But few studies explicitly address such costs and their impacts on trading behavior. In this article we fill this gap, using a tool from the international trade literature called the gravity equation. We first develop a theoretical model to assess the micro-foundation of this approach in a water market context. The model distinguishes between variable and fixed costs of trade, which allows us to disentangle the decision to enter into the water market (extensive margin) and the decision on the quantity of water to be transferred (intensive margin). We then test the theoretical predictions using water transfer data among California water districts over a 17-year period. We approximate transfer costs by distance and institutional factors. Results validate the theoretical predictions and show the importance of distance and institutional impediments in the decision to trade.

*Key words:* Water markets, gravity equation, transaction costs.

*JEL codes:* Q5, Q25.

As water scarcity increases in many regions, decentralized management of this resource using market-based institutions (Msangi and Howitt 2007) has been of growing interest among policy makers (Easter, Rosegrant, and Dinar 1998; Easter and Huang 2014). For more than three decades, water markets have been developed in many water-scarce regions such as Chile, Australia, and western U.S. states, each within different institutional settings (Bjornlund and McKay 2002). In line with traditional trade theory, the transfer of property rights to water among users is seen as an efficient reallocation mechanism for this resource, enabling it to move from lower- to higher-value uses (Brown 2006). In California, where most water rights were allocated decades ago, trading enables flexible reallocation that can benefit the overall economy (Hanak 2015).

Interest in the market as a reallocation tool in California grew in the late 1970s, in the wake of an acute drought that created significant water scarcity in both the urban and agricultural sectors. Two official reports (Governor's Commission to Review California's Water Law 1978; Phelps, Moore, and Graubard 1978) strongly endorsed water trading to support the growth of the Californian economy. Legislation was enacted in the early 1980s to facilitate trading, but the market did not take off until the next severe drought (1987–1992)—particularly as of 1991, when the state established and ran a drought water bank (Hanak 2015). This water bank mobilized nearly 820,000 acre-feet of water from Northern California for resale in Southern California during a year when water deliveries were severely cut back (California Department of Water Resources 1991). The total negative economic impacts in the selling regions outweighed the positive impacts in the buying regions (Dixon, Moore, and Schechter 1993).

But as a general observation, neither in California nor in other western U.S. states have water markets emerged as a major reallocation mechanism (Hanak 2015; Brown 2006; Hansen, Howitt, and Williams, 2015).

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For example, while water trading in California has grown significantly since the early 1990s, trading volumes by the late 2000s were only roughly 3 to 5 percent of total water use in the urban and agricultural sector (Hanak 2015). As a point of comparison, water trading in Australia's Murray-Darling Basin has accounted for one-third or more of total water availability (AITHER 2014, 2015; Howitt 2014). Indeed, water seems to be less "liquid" than expected (Hollinshead 2008) and the reality of water markets falls short of their potential.

Inflexibility in water markets is particularly problematic during extreme events such as droughts. In such situations, water markets can lessen the costs of scarcity by enabling the reallocation of water to higher value activities. As an example, at the height of Australia's Millennium Drought, water deliveries to agriculture were slashed by about half, but agricultural output was only cut by about one-quarter, thanks to active trading (AITHER 2014, 2015). During California's 2015 drought, Howitt, Medellin-Azuara, and MacEwan (2014) estimate that water scarcity resulted in agricultural sector losses of roughly \$1.7 billion in 2014 (roughly 3–4% of annual revenues), along with 7,500 lost farm jobs (3%) from land fallowing. Trading cannot eliminate scarcity, but it can help mitigate the impact of such extreme events by reallocating water to higher-value crops.

It is relatively well accepted that costs associated with water transfers deter some trading. Zilberman (2003) reviews several of California's water allocation reforms. In particular, he identifies two institutions that were established and tested to reduce transaction costs and facilitate trading: the state-managed water bank (in which the state sets fixed buying and selling prices) and the electronic water "market" (in which prices could adjust flexibly) in the Westland's Water District—a 600,000 acre agricultural operation district.<sup>1</sup> But few studies explicitly assess the effects of such costs on trading (Archibald and Renwick 1998; Hanak 2005; Lefebvre, Gangadharan, and Thoyer 2012). Hansen, Howitt, and Williams (2015) find that existing state-level procedures for

expedited approval of water leases in western U.S. states increase the likelihood of leasing. Griffin (2006) states that "Too much is omitted to associate results with potential market results. The behaviors of individual agents (true market agents) are not represented, and the frictional transaction costs of market activity are neglected too." Such frictions are indeed an essential component required to evaluate and compare different forms of institutions, as transactions costs are always limiting the Production Possibility Frontier (PPF) and therefore could imply misleading policy implications (Griffin 1991).

Following the seminal work of Tinbergen (1962) and more recently Anderson and Van Wincoop (2003) and Helpman, Melitz, and Rubinstein (2008)—who analyze the frictions in international trade—we estimate the costs associated with water transfers in California through a micro-founded gravity equation. In the international trade literature, the core of such an empirical tool is based on the New Economic Geography framework (NEG) that geography impacts not only the capacity to produce, but also the capacity to export through transportation costs (a function of distance) and geographically-delimited institutional differences. While heterogeneity in production capacity, with differential marginal values of production between regions, is indispensable for exchanges to occur, heterogeneity in export capacity is likely to curb such exchange by increasing matching difficulties. In the context of water markets, these impediments to trade are the costs of water conveyance, which increase with distance, as well as transaction costs that increase nonlinearly with distance due to formal and informal rules limiting water export outside certain geographic areas (district, county, hydrologic basin, etc.). Throughout this article, we define such costs associated with water trade by the broad term "transfer costs"—including both transaction costs and the costs of water conveyance. We complement the existing literature on water markets with a focus on these transfer costs and show that transfer costs (approximated by distance and institutional impediments to trade) are an important factor in water trade. We thereby validate the relevance of the gravity equation to the study of water markets and, more specifically, to the explanation of observed geographical patterns of water transfers and the preference toward proximity in water exchange.

<sup>1</sup> Zilberman, MacDougall, and Shah (1994) argue that adjustment costs (water-quality-related, irrigation-technology-related, and water-conveyance-related) also have to be considered in the analysis of likely water trading.

The article is developed as follows. The first section describes the relevance of using the New Economic Geography framework with transfer costs to explain the observed geographical pattern of trade. We then develop a simple theoretical model of water trade between water districts by applying an international trade framework in which a combination of variable and fixed transfer costs creates a bias toward proximity. This provides an explicit formalization of different friction costs and the foundation for the empirical test. In a third section, we provide empirical evidence of such effects in bilateral water trades between water districts in California for the period 1995 to 2011.

### Transfer Costs and Geography

“Why are there so few transactions among water users?” This question, raised by Young 30 years ago (Young 1986), is still relevant today. One of the major impediments suggested by the literature is the highly complex institutional setting in which transfers occur. Indeed, due to the intrinsic characteristics of water, a set of restrictive laws and regulations have been promulgated to limit the risk of market failure; as a consequence they have curbed the incentive to trade. Thus, prior to any water transfer, both transacting parties have to engage in a costly process to ensure the completeness of the transfer contract: what we call the transaction cost. As indicated by Culp, Glennon, and Libecap (2014), the intrinsic characteristics of water lead any decision regarding the allocation of this resource to be highly politicized, with an important bias toward risk aversion: “[w]ater rights holders are theoretically free to transfer their rights to upstream or downstream water users. But the reality is more nuanced, with transfers complicated by a series of procedural and regulatory requirements that characterize western water rights, making it very difficult to transfer water rights,” (Culp, Glennon, and Libecap 2014). In other words, the transfer of water is costly in terms of time and money. By limiting transfers, such costs induce a post-trade allocation very close to the initial endowment, preventing a move toward more efficient outcomes within the economy.

However, the question of efficiency has to be considered with caution, as any institution

(from decentralized market-based instruments to centralized allocation through administrative procedures) is subject to transaction costs (Griffin 1991); such costs arise because of incomplete contracts, which in practice is always the case. While transfer costs can be synonymous with inefficiency when comparing water markets to the idealized situation expressed in the Coase Theorem, this is not always the case when comparing water markets to other possible institutions (Griffin 1991). As pointed out by Colby (1990), such costs can be viewed as a tax to factor in various forms of externalities induced by a water transfer. For instance, by changing the time and place of use of a water right, a transfer might adversely affect the volume of water available to downstream water rights holders or to the environment. In this respect, water markets are not the sole institution to reallocate water. The legitimacy of each component of transfer costs is beyond the scope of this article. Whether they legitimately adjust for such externalities or not, transfer costs are not neutral in the trading process, and should be considered in water markets analysis.

Over time and across different states in the American West, a wide range of water institutions have been developed to reallocate water. In this respect, water banks (Washington State Department of Ecology and WestWater Research 2004)—with preset purchase and sale prices—appear more common than spot water markets. One reason may be their ease of operation: the costs associated with price negotiation are generally incurred by the bank, which sets the price. However, banks can still incur transfer costs for participants related to environmental and pecuniary externalities of trade (Archibald and Renwick 1998). Further, a major pitfall of water banks is the lack of price flexibility, which can limit the gains from water transfers for potential exporters (see Green and O’Connor 2001, on the Snake River experience) and is not always suitable to cope with drought (as proven by the experience of the California water bank in 2009, see Howitt 2014). Despite these limitations, Green and Hamilton (2000) nevertheless argue that the water bank in the upper Snake River was quite successful, as it addressed critical institutional issues such as how existing rights holders may be affected by the following: changes in water-use patterns due to the transfer; the likelihood of physical and

economic externalities from transfers; and the impact of transfers on water conservation behavior. In an analysis of the performance of California's 1991 water bank, Howitt (1994) argues that existing institutions in the form of differing property rights and rules for operating transport facilities across counties were a major impediment to the performance of the water bank, which was developed in a matter of four weeks due to the emergency drought situation.

### *The Nature of Transfer Cost*

In this article we refer to the cost of water transfers between locations using the broad term of transfer cost in order to capture terminology of both the transaction cost as well as the conveyance cost. The transaction cost includes any cost induced by search and negotiation with all relevant parties in the trade, such as the buyers, the sellers, and any other agents affected by the transfer (Libecap 2005). Previous empirical work on this matter found that an important share of the water price is due to this component of transfer cost. For example, Colby (1990) estimated a mean supplemental cost in New Mexico at 6% of the agreed price.

From the taxonomy of Archibald and Renwick (1998), the transaction cost can be distinguished into two categories. The first is the "Administratively Induced Cost" (AIC) and is generally common to any property transfer. This includes the search for a reliable partner and the negotiation process over price, quantity, and time of deliver, and is borne by the seller as well as the buyer. While such a cost is difficult to suppress, it can be reduced by improving the dissemination of information. For example, Bjornlund (2003) shows how the use of an Internet platform in Australia's water markets made information much more easily accessible and decreased the *ex ante* cost of search for a good match. In California's water markets, water exchanges are often driven by bureaucratic processes and become abstruse (Libecap 2011a), thereby deterring small agents from entry (Carey, Sunding, and Zilberman 2002).

The second type of cost, more specific to water markets, is the "Policy Induced Cost" (PIC). This is designed to adjust for potential incompleteness of water contracts. Indeed, due to the complex and sometimes non-observable features of water, defining a complete set of property rights for this resource may be difficult (if not impossible). Any water

transfer is thus subject to a set of policy rules to prevent agents not directly involved in the contract, but possibly affected by the exchange, to be harmed. Such so-called "no-injury" rules, combined with the "wet water" policy (designed to ensure that water is physically available for a trade at the specified time and place) define more precisely the quantity of water available for trade, the source of water (surface water or groundwater), and the approval process with which a seller has to comply. The seller generally bears the cost of demonstrating that a water export will not affect other users, which requires a closer look at the hydrological and legal aspects of the trade (Easter and McCann 2010). For any transfer of water, a public notice and approval by at least one of the competent authorities is required (depending on the type of water right traded, federal and/or state environmental agencies), implying a non-negligible investment in time and money.

Furthermore, the concern from the area of origin over potential environmental, economic, or pecuniary externalities has led some local authorities to implement groundwater ordinances (Hanak 2003). Such rules are generally designed to restrict groundwater extraction for the purpose of exporting water outside of county boundaries. These ordinances do not prohibit such trades, but they require potential sellers to undertake costly studies to document the potential effects of groundwater exports (Hanak 2003). Using panel data on trading, Hanak (2005) finds that the widespread adoption of ordinances reduced exports from 1996 to 2001 by 20%, increased within-county trades by 65%, and lowered the overall volume traded by 11%. As of 2014, 22 of California's 58 counties had implemented such ordinances (Hanak 2015). Such transaction costs are generally seen as a major impediment to water transfers because the required up-front investment can discourage market entry (McCann and Easter 2004; Carey, Sunding, and Zilberman 2002).

Even in the absence of local ordinances, objections by source-region residents can also exert pressure on potential sellers to limit out-of-county trades. Holland (2012) reported the case of a potential transfer between Modesto Irrigation District (MID) and the San Francisco Public Utility Commission (SFPUC) where the City of Modesto and several local groups tried to block the contract even though the SFPUC offered a price 70

times higher than the local price (MID ultimately chose not to finalize the transfer agreement). As another example, a transfer from the Glenn-Colusa Irrigation District (GCID) to the Metropolitan Water District of Southern California (MWDSC) during the drought in 2009 was challenged several times by local groups, slowing down the approval process and finally preventing the transfer from occurring (Howitt 2014).

Ghimir and Griffin (2014) looked at such issues in Texas, focusing on the impact of differences in water districts' institutional settings to explain the relatively low participation in trade among the irrigation districts (ID). The main idea is that IDs are facing larger problems of coordination due to their decision rules. The authors show that such institutions lead to an internal over-use and external under-use of water. In this case, it is not a formal policy-induced cost (as with California's export ordinances), but rather a more diffuse cost of lobbying activities and negotiating with different conflicting parties within the district or the county (Colby et al. 1989).

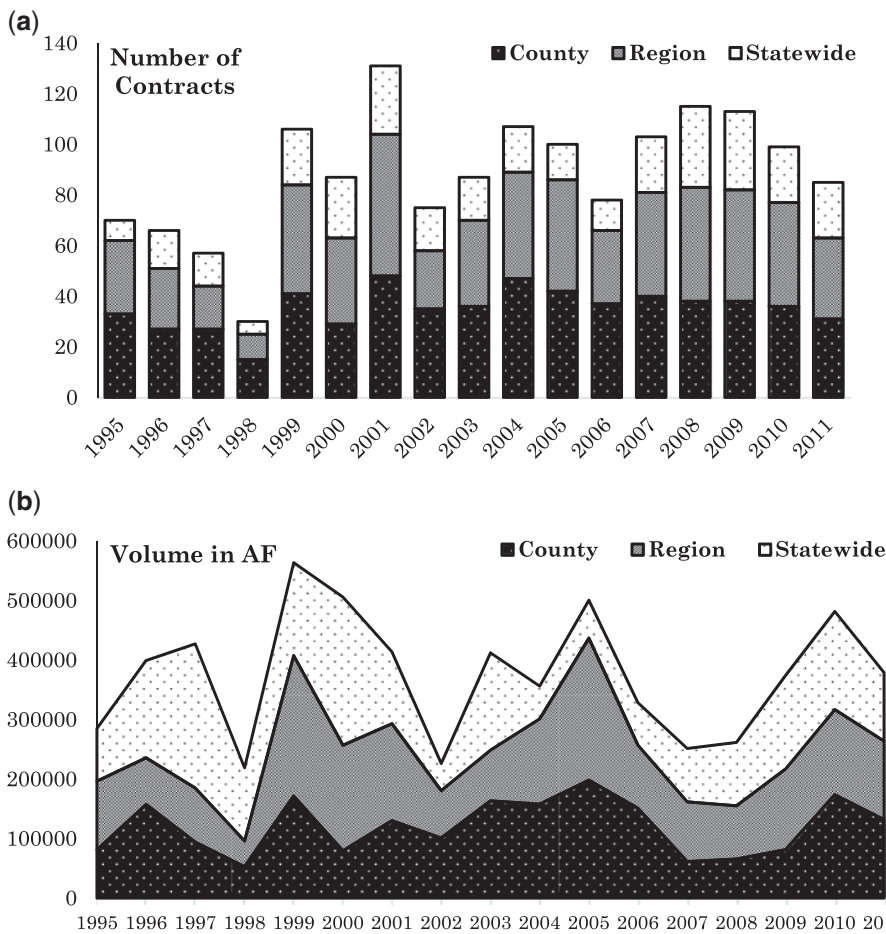
Finally, the conveyance cost encompasses all costs related to physically moving water from the seller to the buyer, and is thus principally related to infrastructure constraints. The cost of conveying water, as well as the difficulties of accessing the network of canals and storage facilities for purposes of trading, can discourage districts from water market entry (Israel and Lund 1995). For California, a century of water supply-enhancing policy and investment endowed the state with a relatively well-developed conveyance infrastructure. But nowadays this network is constrained (Hanak 2015). In particular, the Sacramento-San Joaquin Delta, the crossroad for many north-south and east-west trades, presents obstacles. Due to environmental concerns, pumping from the Delta is restricted, thereby limiting the water available for trading. In addition, a "wheeling charge" is usually required for using conveyance facilities for transfers. Chong and Sunding (2006) report the example of the water transfer between San Diego Water Authority and Imperial Irrigation District, which occurred in 1998. In this case, the facilities owned by the Metropolitan Water District of Southern California (MWDSC) were required to convey the water transferred, but the MWDSC charged a wheeling price of 262 dollars/acre-feet(AF), which doubled the initial price that the San Diego Water Authority had to pay for this water.

### The Impact of Distance on Transfer Costs

Figure 1 depicts the geographic patterns of short-term water transfers (leases) over a 17-year period. We divided the state into three geographic categories: the *county* if the seller and buyer are located in the same county, the *region* if the buyer is located in a contiguous county to the seller, and finally *statewide* if the export of water goes beyond the contiguous county. Such depiction bolsters statements in previous studies that water markets are predominantly local (Hanak 2015). Indeed, altogether county and regional transfers account for the lion's share (roughly four-fifths) of short-term water contracts, and they also dominate the volumes traded. In short, figure 1 shows a strong bias toward proximity.

The geographic pattern of water trade depicted in figure 1 is in agreement with the transfer cost hypothesis described above. Indeed, many such costs depend on the geographic scale of water transfers. For example, groundwater ordinances make water export outside of county boundaries particularly arduous and thus tend to bias trading to occur within-county. Similarly, pumping restrictions in the Sacramento-San Joaquin Delta hinder trades across longer distances (mainly north to south of the Delta), even though northern counties tend to have more abundant water supplies available for trading.

Distance is also an important factor in conveyance costs, as the transferors have to bear the charge of carrying water through the California network plus the loss of water by evaporation or possible percolation into the ground. As assumed in the work of Chakravorty, Hochman, and Zilberman (1995), the longer the distance between the seller and the buyer, the higher is this conveyance cost. Finally, due to the geographic dimension of the Policy-Induced Cost, distance can raise the costs of search for potential partners. Because it is costly to ascertain the possibility to trade water over a long distance (with a higher risk of denial) and to learn about water conditions elsewhere, potential sellers might prefer to minimize search costs by seeking local buyers rather than by conducting a statewide search. Such a propensity for proximity makes the market thinner and mostly regional. For Texas, Ghimir and Griffin (2014) present some evidence that the proximity between an irrigation district and an urban center significantly increases the propensity to trade water.



**Figure 1. Short-term lease contract numbers (Figure 1a) and volume (Figure 1b) of water transferred (1995 to 2011)**

Source: See empirical section and Hanak and Stryjewski (2012) for more explanation on the data.

Note: In our analysis, we only consider short-term leases across water districts. This excludes a significant share of total water traded through long-term leases. However, long-term leases have a broadly similar geographic pattern.

The fact that distance and other related costs are potentially important factors in water trade make the well-known gravity equation tool particularly attractive to study water markets in more depth. Indeed, this empirical method enables the analysis to account for any type of friction in an elegant manner. First introduced by Tinbergen (1962) to study the flows in international trade, the gravity equation is now widely used to explain many impediments that can enter in a bilateral interaction. In its naïve form, the trade (where  $i$  is the exporter and  $j$  the importer) is positively correlated with the economic size of both partners and negatively correlated with the frictions variable (such as

distance), with  $\sigma$  being the elasticity parameter and  $G$ , a constant term.<sup>2</sup>

$$(1) \quad Trade_{ij} \propto G \frac{Size_i \, Size_j}{(Frictions_{ij})^\sigma}.$$

The resemblance with the Newtonian equation gave the name to this economic

<sup>2</sup> We do not provide the theory behind the gravity equation and its multiple forms in the international trade context, which is not the purpose of this article. While many improvements (in term of theoretical foundation and empirical strategy) have been added since its first use, the logic continues to be as explained in the text.

tool, and it is particularly useful for analyzing the frictions in many types of trades. Furthermore, the multiplicative form makes it easy to handle for theoretical modeling and empirical estimation. The equation has been introduced in other fields of economics research such as migration (Anderson 2011) and foreign direct investment (Head and Ries 2008), and it can be applied in a wide range of bilateral interactions (Head and Mayer 2014). It is thus an interesting framework to study impediments in water markets, and with needed adaptations it can be applied to the context of this article. The major difference between the gravity equation above and the original model in Tinbergen (1962) is that here transfer costs include both variable and fixed components, whereas Tinbergen's model included only variable costs.

#### *Fixed and Variable Components of the Transfer Cost*

The mean transfer cost of 6% of the transaction price found in Colby (1990) does not reflect important variation in transfer costs. Brown et al. (1992) estimated a transfer cost ranging from \$2 per acre-foot (AF) to \$1,384/AF, and in other studies, transfer costs range from 3% to 70% of the total cost of water acquisition (McCann and Garrick 2014). The authors partly explain such a variation by a large fixed cost with a mean value of \$474/AF if the transfer is below 5 AF, which falls to approximately \$4/AF if the exchange is above 150AF (with a progressive increase from 5 to 150 AF). Carey, Sunding, and Zilberman (2002) define such fixed costs as the cost of searching for a potential trading partner. These authors demonstrate how this transfer cost can bias trade, within the same district, toward intra-network (identical canals) rather than inter-network (between different canals but still connected in the same district). Indeed, as developed in the previous section, the risk of denial increases with

distance and the necessary sunk cost to enter into a water market spurs sellers to favor closer importer districts over more outlying districts. Again, some recent work in the field of international trade introduced a fixed component to the estimation of the gravity equation (Helpman, Melitz, and Rubinstein 2008; Chaney 2008; Arkolakis 2010; Allen 2014). Such specification is particularly attractive to explain the zeros in bilateral trade (the multiplicative form of the gravity equation implies that trade is never zero, which is obviously false in reality). Thus, adding to the variable transfer cost, a fixed component for each participation in water markets allows us explain and predict the decision to enter into the water market and to explain the zeros in trade.

We identify several types of variable and fixed transfer costs (table 1).

Both variable and fixed transfer costs have an impact on the decision to trade (the so-called extensive margin of trade) but only the variable cost affects the quantity of trade (the intensive margin of trade). It is thus particularly important to disentangle these two types of costs in order to properly analyze their effects and understand the potential impacts of reforms that could reduce these costs.

#### **Theoretical Model**

In this section we develop a simple theoretical model to highlight impediments in the water trading process. We identify the variables representing the fixed cost of water trade and provide a foundation for the gravity equation estimated in the empirical section. This model is relatively similar to that developed by Archibald and Renwick (1998), but we relax some of their assumptions to facilitate analysis of different types of transfer costs and to improve the tractability. This enables us to derive an analytical solution to the model.

**Table 1. Decomposition of Transfer Costs between Variable and Fixed Components**

<b>Variable Transfer Cost</b>	<ul style="list-style-type: none"> <li>– Water loss through evaporation and percolation</li> <li>– Wheeling cost for using conveyance facilities (storage, canals, and pumping)</li> </ul>
<b>Fixed Transfer cost</b>	<ul style="list-style-type: none"> <li>– Physical network limitation (Sacramento-San Joaquin Delta)</li> <li>– County groundwater ordinances</li> <li>– Inter-project transfers</li> <li>– Search for potential trading partners</li> <li>– Negotiation over prices, quantity, and quality</li> </ul>



### The Setup

In this sub-section we present the economy of water use inside a district and without any water export (the intra-district water economy). Then we introduce the economy of a potential exporter district (the inter-district water economy).

*Intra-district water trade.* Consider a discrete set of  $n \in N$  water districts distributed over a continuum but finite space  $S$ . Each district is said to share its total entitlement of water  $W_n$  among a set of  $k_n = 1, \dots, K_n$  discrete and heterogeneous members at a non-discriminatory price of  $\alpha_n$  that covers the marginal cost of extraction for the district (assumed to be constant and noted as  $c_n$ ). Thus, net revenues for a district without any trade activity is

$$(2) \quad \bar{Y}_n = W_n(\alpha_n - c_n).$$

Each member  $k_n$  receives a quantity  $\omega_{k_n} \geq 0$  of water and earn an incremental value  $\psi_{k_n}$  from the water used. As the district is generally a non-profit organization, the net income given by equation (2) is redistributed in equal shares among all members such that the private profit function for members without any trade activity is

$$(3) \quad \bar{\pi}_{k_n} = \omega_{k_n}(\psi_{k_n} - \alpha_n) + W_n \frac{\alpha_n - c_n}{K_n}.$$

As the district usually holds the water use right, it has the final decision on water management decisions such as the price  $\alpha_n$  or the decision to enter into the water market. However, such choices can be affected by members' voice if the district's structure is sufficiently decentralized and the district's board can exercise power. In that case, the profit maximization is not based on district income from water deliveries (right term of equation [3]), but on the private profit from water use (left term of equation [3]). Therefore, pressure is generally exercised to lower the water price  $\alpha_n$  toward its minimum  $c_n$ , which means that district's income tends to reach zero while private profit of members increases. Furthermore, we assume throughout the article that the share of water delivered to each member is symmetric such that  $\omega_{k_n} \equiv \omega_n = W_n/K_n, \forall k_n \in K_n$ . While such an assumption is somewhat simplistic, it allows us to encompass a broad range of

district organizational structures (from decentralized to centralized governance and from private to public organizations).

From these assumptions, we can redefine more formally the profit function in equation (3) in order to account for multiple types of water districts. Therefore, equation (3) becomes

$$(4) \quad \bar{\pi}_{k_n} = \omega_n(\psi_{k_n} - c_n).$$

The more the decision of the district is centralized, the less is the number of differentiated agents  $K_n$ ; with a complete centralization of decision making  $K_n = 1$ . In other words, when the organizational structure of districts allows members to have power over decision, the district's board has to accommodate the heterogeneous demands, but when a highly centralized structure is in place, such heterogeneity vanishes and there is only one value of water use: the delivery of water.

*Inter-district water trade.* During a drought, the demand of a district subset  $J \in N$  could exceed the current supply, while districts in a subset  $I \in N$  can be in excess of supply (or at least, not in water shortage). This makes water exchange between districts economically possible, leading to an inter-district water market.

Members of district  $i \in I$  can participate in a water market through the export of a share  $x_{k_i,j} \in [0;1]$  of its water allocation  $\omega_i$  to district  $j \in J$  at a price  $p_{ij} > 0$ , negotiated beforehand between district  $i$  and  $j$ . We assume that this market price  $p_{ij}$  is independent of the water value  $\psi_{k_i}$  for any members of district  $i$ : members in the exporter district are price-takers.<sup>3</sup> But frictions in the form of transfer costs (combination of transaction and conveyance cost) limit the amount of water that can be exported by members of district  $i$ .

As explained in the previous section on transfer costs, we differentiate between a variable and a fixed transfer cost (similar to Carey, Sunding, and Zilberman 2002) but both are dependent on the distance  $D_{ij}$  between  $i$  and  $j$ . We define more formally the different transfer costs as follows.

<sup>3</sup> Such an assumption is a simplification of the real process, as the market price is more likely the result of a negotiation within the district. However, such an effect is beyond the focus of this article and is left for future research.

Variable transfer costs are an increasing function of the share of water traded  $x_{kij}$ , with a parameter  $\tau_{ij}$  dependent on the distance  $D_{ij}$  and other institutional frictions that occur for trades conveyed through the Sacramento-San Joaquin Delta. The variable transfer costs function is therefore  $\tau_{ij}x_{kij}^2$ ; and, assuming for the moment that water market price is equals to unity ( $p_{ij} = 1$ ), the gain from water export is  $x_{kij}(1 - \tau_{ij}x_{kij})$ .<sup>4</sup> Therefore, we explicitly follow postulate 3 from Griffin (1991), which states: “[Transfer] costs increases (*sic*) with the distance between initial endowment and final (post trade) allocation.” The reason for this functional form can be better understood if we consider the situation where  $x_{kij}$  corresponds to the share of water entitlement planned for export, and  $x_{kij}(1 - \tau_{ij}x_{kij})$  is the actual share of the water entitlement that can be exported. For values of  $x_{kij}$  that are close to zero, the difference between planned and actual export is low, but as long as  $x_{kij}$  increases, the supplemental quantity of water that can be conveyed is diminishing until it reaches the threshold  $1/(2\tau_{ij})$ , which corresponds to the potential amount of water that can be exported.<sup>5</sup> Beyond that value, any intention to export  $x_{kij} > 1/(2\tau_{ij})$  implies an actual export of less than  $1/(4\tau_{ij})$ . It is worth noting that as the variable transfer cost is dependent not only on distance but also on other factors such as institutional frictions, we define two districts as being close to each other in terms of the variable transfer cost and in terms of geographic distance. In other words, for three districts  $i, j$ , and  $l$  (all within  $N$ ), we say that  $i$  is closer to  $j$  than  $l$  if  $\tau_{ij} < \tau_{il}$ .

The fixed transfer cost  $f_{ij}$  is independent of the water share  $x_{kij}$ , and is incurred for each transfer. Different functional forms can depict this fixed cost, depending on how it is shared among the district members. It can be a specific value attached to each member ( $f_{kij}$ ), a reallocation of a total fixed cost  $F_{ij}$  among all members ( $F_{ij}/K_i$ ), or a reallocation only among exporter members ( $F_{ij}/\sum_{k_i} 1\{x_{kij} > 0\}$  with  $1\{x_{kij} > 0\}$  being the indicator variable, which equals one if  $x_{kij} > 0$ , and zero if  $x_{kij} = 0$ ). However, in the

rest of the article we keep the general form of this fixed cost  $f_{ij}$ .

From equation (4), the profit function of a member  $k_i$  when engaging in water markets is thus

$$(5) \quad \pi_{kij} = \omega_i [p_{ij}x_{kij}(1 - \tau_{ij}x_{kij}) + \psi_{k_i}(1 - x_{kij}) - c_i] - f_{ij}.$$

It is straightforward to see that  $x_{kij}(1 - \tau_{ij}x_{kij}) < x_{kij} \forall x_{kij} > 0$ . The limit of unity imposed on the variable transfer cost ensures that the share of water allocated to transfer is less than one (however, this condition could be easily relaxed with some caution). The maximum value of  $x_{kij}$  is thus  $1/\tau_{ij}$  because the revenue from the trading activity is then negative, and thus induces a loss compared with the profit when  $x_{kij} = 0$ .

### Water Markets

So far we have set the different assumptions needed in this model and presented the situation of each district with respect to water markets. In this section we determine analytically the extensive and intensive margins of trade. The former corresponds to the decision to trade or not, while the latter refers to the quantity of water (in acre-feet) that district  $i$  will transfer to district  $j$  when the two parties have already agreed upon a contract. For each district willing to enter into the water market, the extensive margin question has to be determined before the intensive margin. Here, however, we first calculate the intensive margin because it is the determining factor in the decision to finalize a water contract.

#### The Intensive Margin of Water Trade

Solving the derivative of equation (5) with respect to  $x_{kij}$  yields the optimal share of water that can be traded by member  $k_i$  in district  $i$  with district  $j$ :

$$(6) \quad x_{kij} = \frac{p_{ij} - \psi_{k_i}}{2\tau_{ij}p_{ij}} < 1 \quad \forall p_{ij} > \psi_{k_i} \text{ and } \tau_{ij} > 1.$$

In order to ensure a non-negative value of transfer  $x_{kij}$ , we impose the condition that  $x_{kij} = 0$  for all values of  $p_{ij} < \psi_{k_i}$ . The next section, which discusses the extensive margin of trade, will prove that this condition is

<sup>4</sup> Raising the share of water  $x_{kij}$  to the power of 2 is done for ease of exposition, but the model is still solvable with any power value superior to 1.

<sup>5</sup> Inserting the threshold into the actual water export  $1/(2\tau_{ij})$  yields the potential amount of water exported as  $1/(4\tau_{ij})$ .

necessary but not sufficient to have non-zero water transfers.

**PROPOSITION 1.** *Compared to the Pareto optimal situation, the variable transfer cost  $\tau_{ij}$  is the first measure of water market potential inefficiency.*

*Proof:* As a proof for proposition 1, it is straightforward and intuitive to see that the quantity of water traded by  $i$  is decreasing with the variable transfer cost ( $\tau_{ij}$ ) and increasing with the water market price  $p_{ij}$ . This leads to a total quantity of water transfer inferior to the case without variable transfer costs. The total quantity of water traded by district  $i$  is thus the sum of water exported by all members  $k_i$  that accept to engage in water markets. ■

*The Extensive Margin of Water Trade*

Equation (6) is a depiction of the quantity of water exported by each member in district  $i$ . However, this equation alone is not sufficient to explain the low occurrence of water trade observed in reality. Indeed, districts would always export water in that case (as long as the internal price  $\psi_{k_i}$  is less than the water market price  $p_{ij}$ ). But the existence of a fixed cost for entering into the water market introduces another constraint to the agents willing to transfer water.

Plugging equation (6) into the profit function in equation (5) results in the following:

$$(7) \quad \pi_{k_{ij}} = \omega_i \left( \psi_{k_i} + \frac{(p_{ij} - \psi_{k_i})^2}{4\tau_{ij}p_{ij}} - c_i \right) - f_{ij}.$$

Member  $k_i$  will engage in water market if and only if the gains from transferring water outside of the district exceed the status quo of using water inside the district, as defined in equation (4). Therefore,  $\pi_{k_{ij}} > \bar{\pi}_{k_i}$  and with rearrangement we obtain a threshold value of  $\bar{\psi}_{k_i}$  for which a district's member is indifferent between engaging in the water market or using its entire water allocation for its normal use within the district:

$$(8) \quad \bar{\psi}_{k_i} = p_{ij} \left( 1 - 2 \left( \frac{\tau_{ij}f_{ij}}{\omega_i p_{ij}} \right)^{\frac{1}{2}} \right).$$

All agents with a water value below the threshold  $\bar{\psi}_{k_i}$  will enter into the water market,

while agents with values above the threshold will not. As we have assumed that the share of water allocated between members  $\omega_i$  is symmetric, the threshold of water value is no longer dependent on the heterogeneity of members:  $\bar{\psi}_{k_i} = \bar{\psi}_i \forall k_i \in K_i$ . It is also important to note that this threshold value will never exceed the water market price  $p_{ij}$  for any non-negative values of  $\tau_{ij}$ ,  $f_{ij}$ , or  $\omega_i$ . We can thus develop the second proposition:

**PROPOSITION 2.** *Compared with the Pareto-optimal situation, the value of  $2(\tau_{ij}f_{ij}/\omega_i p_{ij})^{1/2}$  is the second measure of water market potential inefficiency.*

*Proof:* Indeed, the maximum value of the threshold is  $p_{ij}$  when fixed cost  $f_{ij}$  is set at zero and in this case, the variable transfer cost is the only source of inefficiency (as stated in proposition 1). However, with any non-zero and positive value of  $f_{ij}$ , participation in the water trade is dependent on both types of costs (fixed and variable). ■

*The District's Water Export*

From equations (6) and (8) we can now include in one simple equation the total quantity of water exported by district  $i$  to district  $j$ . We define an indicator variable  $1_{\{\psi_{k_i} < \bar{\psi}_i\}}$  that takes the value one if the water value for member  $k_i$  is inferior to the threshold value  $\bar{\psi}_i$  calculated by equation (8), and zero otherwise. Using the fact that each member engaged in the water market will export a quantity  $\omega_i x_{k_{ij}}$  of water, and with equation (6), we obtain the total water exported from district  $i$  to district  $j$ :

$$(9) \quad X_{ij} = \frac{\omega_i}{2\tau_{ij}} \sum_{k_i} \frac{p_{ij} - \psi_{k_i}}{p_{ij}} 1_{\{\psi_{k_i} < \bar{\psi}_i\}}.$$

At least one agent in district  $i$  has to satisfy the condition stated in equation (8) for a transfer of water to occur between  $i$  and  $j$  as expressed in equation (9). If it is not the case, then  $X_{ij} = 0$  and no water transfer is taking place.

**Empirical Evidence**

The framework presented in the theoretical model is associated with estimation challenges

due to the highly non-linear nature of the equations. Furthermore, the limited coverage and reliability of data available at the district level is of particular concern for developing a structural estimation. Thus, in this section we provide empirical evidence by estimating a reduced form of [equation \(9\)](#).

We use water trade data from California, which was collected at the water district level, and we construct a table of bilateral relations for 237 water districts distributed among 45 counties and over a period of 17 years. [Table A1](#) describes the variables employed. Please see the [supplementary online appendix](#) for more information.

### Data Sources and Variables

We use several datasets to demonstrate the power of our empirical model.

*Water trade.* Water trade  $X_{ij}$  is our endogenous variable and is collected at the water district level, appropriate to the bilateral estimation. This point can be considered as the main impediment on such empirical studies because it is generally difficult to find sufficient data on water trade. Several previous studies attempted to use water trade data from the Water Strategist dataset. This source provides trading information for the western United States, and it is particularly interesting because it also provides the prices for many transactions. Unfortunately, this database generally presents importers and exporters as a group of districts, which makes it impossible to use in a bilateral study. Such aggregation makes the analysis of transfer costs particularly difficult because it becomes impossible to differentiate between districts engaging in water markets and those who do not. We thus use the data set collected by [Hanak and Stryjewski \(2012\)](#) for water transfers in California from 1977 to 2011. This dataset accounts for most of the trade that occurred between districts, and it identifies each district. For more details on this dataset, see [Hanak \(2003\)](#) and [Hanak and Stryjewski \(2012\)](#).

While this dataset presents transfers ranging from 1977 to 2011, the low occurrence of trade in earlier years and the lack of accurate data on districts' characteristics before the 1990s led us to focus our analysis on the most recent 17-year period (1995–2011). Such a choice removed approximately one-fifth of the observations but allowed us to estimate a more robust model. We also decided

to focus our estimation only on short-term water leases. Indeed, three types of water transfer are reported in the database: short-term (one-year) leases, long-term (multi-year) leases, and sales (sales are permanent transfers of water rights; multi-year leases vary from 2 to 75 years).

As we focus on the extensive margin of trade, the low occurrence of long-term leases makes the estimates particularly difficult and unsuitable in our analytical context. Indeed, transfer costs associated with such long-term leases are generally very high for the first year (when the contract is enacted) and lower for subsequent years. The transfer cost of the water transfer decision in a long-term lease cannot be compared with the transfer cost associated with a short-term lease. Furthermore, the geographic pattern of water transfers stays relatively similar with or without long-term leases. We thus drop this type of trade and analyze only short-term leases.

### District-specific Data

From [equation \(9\)](#) we can see that several district-specific variables are needed to estimate the quantity of water traded. However, these data are particularly difficult to collect at this level because water districts do not always make them available. The first difficulty is to approximate the ratio of prices  $(p_{ij} - \psi_{k_i})/p_{ij}$ . Indeed, we do not know the water market price  $p_{ij}$  or the value of water use within the district  $\psi_{k_i}$ . To be able to test the theoretical model, we need to make the following assumption: the higher the revenue of district  $n$ , the more likely it is that the district will find a member with a high value of water use  $\psi_{k_i}$ . Therefore, we approximate our first bilateral variable, *Revenue ratio* (representing the gradient of water market price net of water value among the trading districts), by

$$(10) \quad \hat{\rho}_{ijt} = \frac{Y_{jt}}{Y_{it} + Y_{jt}}$$

where  $Y_{it}$  and  $Y_{jt}$  are the total income (net of treatment cost) of district  $i$  and  $j$ , respectively, at time  $t$ . We extracted data for  $Y_{it}$  and  $Y_{jt}$  from the California State Controller's Office, which publishes annual financial reports for special districts in California (including water districts). These reports provide district-level

annual revenues and costs. To account for differences in water treatment costs between urban and agricultural districts (since the latter supplies untreated water), we subtracted treatment costs from the total operating and non-operating revenues. Due to some irregularities in this dataset, we needed to apply some transformations. We first corrected and completed this dataset by collecting financial reports provided on several districts' websites and calculated the moving average over a three-year period to reduce the effects of some extreme values; we also replaced missing values with a log-OLS (Ordinary Least Square) estimation (independent variables are the mean income over the 17-year period and the year). Given the low share of missing values and the relatively low year-to-year variation in revenues, this method provides a relatively good approximation of the true value.

The second variable is the water use right of each member ( $\omega_i$ ). Again, we do not possess such information, so we need to find an approximation for this variable. In the theoretical model developed above, the underlying mechanism of water trade is that a member in district  $i$  is able to trade with district  $j$  and conversely, a member in district  $j$  is able to find water in district  $i$ . Therefore, the greater the rate of water use in both districts, the higher is the likelihood that a member in district  $i$  has a sufficient amount of water to sell (at a low value of use) to a member in district  $j$  that has a need for water (with a high value use). We thus use the total quantity of *Water use* in the importer and exporter district (respectively,  $W_j$  and  $W_i$ ). As we need to consider both urban and agricultural water use, we used two types of data sources for this variable. First, we approximated the quantity of water used by the district with the population served within its boundaries. For urban districts, we used water data as reported in Urban Water Management Plans, and included this quantity for each year in the 17-year analysis period. For agricultural districts, we used the service area multiplied by the evapotranspiration of the applied water ( $ET_{nt}^{AW}$ ) net of rainfall ( $R_{nt}$ ) as a function of evapotranspiration values ( $ET_{nt}^o$ ). For two-thirds of these districts, the surface area was taken from the database of Cal-Atlas. Information for the remaining one-third is extracted from official documents from the districts. All surface area values are expressed in acres. The evapotranspiration value ( $ET_{nt}^o$ ) is at county-level land and water

use estimates from DWR (California Department of Water Resources),<sup>6</sup> which estimates the need for applied water depending on the agricultural production in each county. Because the measures begin in 1998, we use the California Irrigation Management Information System (CIMIS) database to fill in the missing values for 1995–1997. This program collects climatic data from around 200 stations distributed throughout California. Because the CIMIS stations do not always correspond to the location of the districts, we calculated the weighted mean of  $ET_{nt}^o$  from CIMIS data to approximate the district location. The methodology is as follows:

In order to have a representative value of the weather condition in district  $n \in N$ , we calculated the distance as a “flying bird” between each station  $s$  in the entire state and the center of district  $n$ . Then we calculate the weighted mean for evapotranspiration and rainfall:

$$(11) \quad ET_{nt}^0 = \frac{\sum_s \left( \frac{d_{sn}^{max} - d_{sn}}{d_{sn}^{max} - d_{sn}^{min}} ET_{st}^0 \right)}{\sum_s \left( \frac{d_{sn}^{max} - d_{sn}}{d_{sn}^{max} - d_{sn}^{min}} \right)} \quad \text{and}$$

$$R_{nt} = \frac{\sum_s \left( \frac{d_{sn}^{max} - d_{sn}}{d_{sn}^{max} - d_{sn}^{min}} R_{st-1} \right)}{\sum_s \left( \frac{d_{sn}^{max} - d_{sn}}{d_{sn}^{max} - d_{sn}^{min}} \right)}$$

where  $d_{sn}$ ,  $d_{sn}^{max}$ , and  $d_{sn}^{min}$  are, respectively, the distance between the center of district  $n$  and station  $s$ , the distance between the center of district  $n$  and the most distant station  $s$ , and the distance between the center of district  $n$  and the closest weather station  $s$ . To estimate the evapotranspiration of the applied water ( $ET_{nt}^{AW}$ ) and to assign values for the years 1995–1997, we regressed the calculated data from CIMIS and the data from DWR (California Department of Water Resources) for the years 1998–2010 using a linear OLS (Ordinary Least Square) procedure.<sup>7</sup>

The variables described in this section are assumed to have a positive impact on bilateral water trade.

### Trade Frictions

We need to estimate the impact of frictions that could exist between districts, but this information is not directly available. A classical

<sup>6</sup> Data accessible at: <http://www.water.ca.gov/landwateruse/anaglwu.cfm#>.

<sup>7</sup> See [supplementary online appendix](#) on the Oxford University Press website.

assumption from the bilateral trade studies is to approximate such variables by the distance between the exporter and the importer, which also holds in the context of a water market. Indeed, as discussed in the section on transfer costs, the physical limitation on water conveyance and wheeling costs, which can be quite high, curb the incentive to transfer or even to search for potential trade partners outside of the region. We thus construct our variable of conveyance cost (expressed by the variable  $\tau_{ij}$  in the theoretical model) by using the distance between the two districts and a binary variable that captures whether or not the districts are separated by the Sacramento-San Joaquin Delta.<sup>8</sup>

In order to calculate the *Distance* variable between districts, we use the GPS coordinates of each district's centroid of their area provided by Cal-Atlas database, and approximated the distance using a "flying bird" approach represented by Vincenty's (1975) equation. The database does not report all districts; for those lacking a GPS coordinate we approximated with the coordinates of the district's office.

While it is expected that Distance has a negative and significant coefficient, it is not the sole impediment to water transfers. The Sacramento-San Joaquin Delta is also a matter of concern for any northern transferor willing to trade water with a district located south of the delta. To account for this limitation, we use a binary—*Cross Delta*—variable  $T_{ij}^{\text{delta}}$ , taking the value 1 if the potential transfer requires crossing the Delta, and 0 otherwise. We consider that districts located in San Joaquin County or further south must incur the supplemental cost of moving water through the Delta to receive water from any district located north of San Joaquin County.

We assume that distance also plays a role in the fixed costs of transfers, since geographic proximity is generally known to induce more exchanges. It is hypothesized that districts close to each other have more contact and hence greater ease of trading. We also account for other types of fixed costs with several other binary variables. County

groundwater *Ordinances* are included as  $T_{ijt}^{\text{ord}}$ , which takes the value 1 if the county is subject to a groundwater ordinance and 0 otherwise. This variable takes the value of 0 when two districts are located in the same county because such regulation typically applies for transfers outside of a county's boundaries. The variable is time-dependent, as some counties have passed such restrictions after 1995. As the cost of a county's ordinance (to the water district) is assumed fixed (see table 1), it affects variable  $f_{ij}$  in equation (8). We therefore introduce a variable *Ability to cope ordinance*,  $\hat{F}T_{ijt}$ , which accounts for the capability of the exporter district to overcome the fixed cost that is implied by ordinances:

$$(12) \quad \hat{F}T_{ijt} = T_{ijt}^{\text{ord}} \log \left( \frac{D_{ij}}{\hat{\rho}_{ijt} W_{it}} \right).$$

The logarithm transformation in equation (9) takes place because all continuous variables are transformed as such (see the section on empirical strategy for more details); it equals zero if a dyad is not subject to groundwater ordinances from the exporter's county and decreasing (increasing) with the total water demand  $W_{it}$  and revenue ratio  $\hat{\rho}_{ijt}$  (Distance  $D_{ij}$ ). Following the threshold value  $\hat{\psi}_{k_i}$  calculated in equation (8), we interpret this interaction term as the second measure of inefficiency of water markets (stated in proposition 2), and it is expected to have a negative impact on trade. We also expect that the Ordinances variable will have a more important role in affecting the extensive margin decision rather than the intensive margin decision, mainly because ordinances are set to prevent the migration of water outside of the county, no matter how much water is shipped.

We also include a binary variable that accounts for institutional networks within which trading is more likely because the approval process is easier, specifically when districts are served by the same water supply project: *Different project* (technically, this often means the districts have contracts for deliveries of shares within the same overall water rights, which are held by the project operator). We consider the State Water Project (SWP), the Central Valley Project (CVP) and within the latter project, we differentiate between various regional sub-projects (e.g.,

<sup>8</sup> We are aware that an important cost component is the landscape through which water has to be conveyed and the electricity cost associated with that process. Such detailed information was not available. Therefore, our estimate of conveyance cost can be viewed as a lower bound value.

**Table 2. Summary Statistics**

Variables	Mean	Standard Deviation	Min.	Max.
<i>The whole sample (950,844 observations)</i>				
Revenue ratio	0.50	0.35	0.00	1.00
Water use (all districts)	93,902.7	282,892.5	150.2	4,032,000
Distance	352.89	232.64	0.01	1,170.97
Ordinances	0.41	0.49	0	1.00
Different project	0.96	0.20	0	1.00
Cross Delta	0.39	0.49	0	1.00
Ability to cope ordinance (exporter)	-1.291117	2.04769	-12.669280	12.99992
Trade inexperience	0.63	0.48	0.00	1.00
<i>Sample restricted to positive trades (1374 observations)</i>				
Revenue ratio	0.59	0.32	0.00	1.00
Water use (exporter)	135,614.6	228,578.8	470.57	3,935,000
Water use (importer)	347,386.9	525,774	470.57	4,032,000
Distance	69.52	77.31	0.04	833.68
Ordinances	0.23	0.42	0.00	1.00
Different project	0.33	0.47	0.00	1.00
Cross Delta	0.02	0.13	0.00	1.00
Ability to cope ordinance (exporter)	-1.393148	2.665989	-12.59202	0
Trade inexperience (exporter)	0.04	0.19	0.00	1.00
Trade inexperience (importer)	0.10	0.30	0.00	1.00

the Friant-Kern, the Madera, the Delta Mendota, the Tehama-Colusa, the San-Luis and Cross Valley Canal, and deliveries from the Sacramento and San-Joaquin rivers).<sup>9</sup> Here we define the transfer cost  $T_{ijt}^{pro} = 1$  if the districts are not located in the same project, and 0 otherwise.

Finally we include a binary variable, *Trade inexperience*, which captures the “learning” effect of participating in an inter-district water market. We expect that when a district enters into the water market for the first time, frictions and thus fixed costs are higher, but repeated market participation confers experience and decreases transfer costs. Thus, we define the variables  $T_{it,trade}$  and  $T_{jt,trade}$  equal to 0 if the district  $i$  or the district  $j$  has participated in the water market before year  $t$ .

The equations for the variable and the fixed transfer costs are

$$(13) \quad \hat{\tau}_{ijt} = D_{ij}^{\delta_c} \prod_c \exp(\beta_{\tau c} T_{ijt}^c)$$

$$\hat{f}_{ijt} = D_{ij}^{\delta_f} \hat{F} T_{ijt}^{\lambda_f T_{ijt}^{ord}} \prod_c \exp(\beta_{fc} T_{ijt}^c)$$

where  $\delta_\tau$ ,  $\delta_f$ ,  $\beta_{\tau,c}$  and  $\beta_{f,c}$  are the estimated coefficients for distance, and the set of binary variables, and  $\lambda_f T_{ijt}^{ord}$  is the coefficient for the *Ability to cope ordinance*.

We expect that all variables defined in this section will have a negative association with the bilateral trade.

#### *Summary Statistics for Variables Participating in the Regressions*

Table 2 provides the summary statistics of the continuous and binary variables included in our empirical model.

The summary statistics suggest a large difference in the average distance between the whole dataset (upper panel) and the dyads with trade (lower panel). This shows a large bias toward proximity in the decision to engage in short-term trades.

#### *Strategy and Estimation Issues*

The gravity equation tool has been applied in numerous previous studies within the international trade literature, and many improvements in empirical methods have been introduced since Tinbergen (1962). More specifically, the recent contribution of Santos and Tenreyro (2006) addressed the problem of choosing the right econometric model. The classical way of estimating the gravity

<sup>9</sup> Data on water deliveries from each canal can be found at: <http://www.usbr.gov/mp/cvo/deliv.html>.

equation is to perform a log-linear OLS, with  $k$  explanatory variables  $Z_{ijk}$

$$(14) \quad \ln(X_{ij}) = a_0 + \beta_k \ln(Z_{ijk}) + \epsilon_{ij}.$$

However, Flowerdew and Aitken (1982) showed that with this method the estimated coefficients are severely biased when the errors  $\epsilon_{ij}$  are heteroskedastic (which is generally the case in bilateral trade models). The main reason is that trade data exhibit more variation for smaller volumes of trade, which implies an increase in the variance of  $\epsilon_{ij}$ . Another, more technical problem arises when the dependent variable has some zero values because the logarithm of zero is not defined. Several solutions have been proposed to deal with this issue. The simplest is to throw away the zeros from the database and perform the regression only on the non-zero observations (as in Brada and Mendez 1985 and Bikker 1987). This method is certainly not suitable in our case as we intend to also estimate the factors associated with no water trading (the extensive margin of trade). Simply suppressing the zeros would thus lead to an important selection bias and would allow us to only estimate half of the model (the intensive margin of trade expressed by equation [9]). Other methods imply using a Tobit model (Eaton and Tamura 1994) or keeping the log-linear OLS and adding for each dyad the term  $\ln(X_{ij} + 1)$  as a dependent variable instead of  $\ln(X_{ij})$  (as in Eichengreen and Irwin 1995). As pointed out by Santos and Tenreiro (2006), these two approaches will generally produce inconsistent estimators of coefficients, particularly when the proportion of zeros is high. In our estimation the non-zero trade data only represent approximately 0.14% of the total number of dyads of water districts. It is thus particularly important to have a model that can handle the estimation with such a large share of zeros.

The problem with the traditional method of estimating the gravity equations led some researchers to prefer other types of econometric models such as the Poisson family (Santos and Tenreiro 2006). In this case the assumption is that the volume of trade is represented by a Poisson distribution with a conditional mean as a function of the explanatory variables. Such a model is originally designed to estimate (non-negative) count data, but by imposing the assumption of integer value on trade volumes, we can use

this distribution to estimate water trade. Thus, the equation to be estimated becomes

$$(15) \quad X_{ij} = \exp(a_0 + \beta_k \ln(Z_{ijk})) \epsilon_{ij}.$$

The first striking point is that, due to the multiplicative form implied by the Poisson distribution, the dependent variable is not log-transformed, which eliminates the issue of logs of zeros previously mentioned. Secondly, King (1988) showed that coefficients estimated by Poisson are consistent and generally efficient even in the presence of heteroskedastic errors. The reduced form that we will intend to estimate is as follows:

$$(16) \quad \hat{X}_{ij} = a_0 \frac{\hat{\rho}_{ijt}^\eta W_{it}^{\theta_i} W_{jt}^{\theta_j}}{D_{ij}^\delta \left( \prod_c \exp(\beta_c T_{ijt}^c) \right)} \left( \frac{D_{ij}}{\hat{\rho}_{ijt} W_{it}} \right)^{-\lambda_f T_{ijt}^{ord}}$$

where  $\gamma$ ,  $\delta$ ,  $\eta$ ,  $\beta_c$ ,  $\lambda_f$ ,  $\theta_i$  and  $\theta_j$  are the coefficients to be estimated. One problem with using Poisson is that it is no longer possible to disentangle the extensive margin from the intensive margin. We thus run a Probit regression with the similar right-hand-side variables using the probability of trade as the dependent variable:

$$(17) \quad P(\hat{X}_{ij} > 0) = \Phi \left\{ \frac{\hat{\rho}_{ijt}^\eta W_{it}^{\theta_i} W_{jt}^{\theta_j}}{D_{ij}^{(\delta_f + \delta_c)} (\beta_{fc} \exp(\beta_{fc} T_{ijt}^c))} \left( \frac{D_{ij}}{\hat{\rho}_{ijt} W_{it}} \right)^{-\lambda_f T_{ijt}^{ord}} \right\} + \eta_{ijt}$$

where  $\Phi$  is the standard normal cumulative distribution function. To control for year heterogeneity, we introduce year fixed effects in both the Poisson and the Probit regressions (not shown in results). We used Stata 13.0 for all regressions and data preparation.

### Results

We first present the results for the Probit model (to determine the extensive margin of water trade), and then the results for the Poisson estimation (which include the intensive margin of water trade). As the model is in multiplicative form, we transform all non-binary independent variables into logs. The estimated coefficients are thus elasticities.



### The Extensive Margin of Trade

We start by estimating whether a given district decides to engage in trading. We test different forms for equation (17) to show the importance of the different transfer cost variables. For all models, we provide the pseudo R-square, the AIC and BIC (Bayesian Information Criterion) criterion, and the measure of the Receiver Operating Characteristic (ROC). This last indicator can be viewed as the goodness of fit of the model. Columns (I), (II), and (III) depict trade for districts-districts dyads, while columns (IV) and (V) are for districts-counties dyads. Columns (I) and (IV) test the simplest model with no transfer cost variables. Column (II) includes the same variables as in column (I) but with the binary transaction cost variables. Finally, columns (III) and (V) show the results with all transfer cost variables included. Results are shown in table 3.

In each model we have introduced year fixed effects to control for climatic variability and unobserved heterogeneity over time (not reported). As can be seen in table 3, most of

the coefficients are significant at the 1% level and show the expected sign for Revenue ratio for exporter, and Water use for both exporter and importer. Adding distance improves the robustness as all criteria show a better fit. Furthermore, the distance variable exhibits a negative coefficient, which is consistent with the theoretical model and indicates that districts prefer to trade water with partners at closer distances. Similarly, Trade inexperience (for both districts) is negative and significant in all models, which implies that districts without prior experience may be reluctant to enter the market.

County groundwater ordinances also have a strong negative impact on the decision to trade, and our results are in line with findings in Hanak (2005). The *Ability to cope ordinance* is negative, implying that the lower the relative size of the district, the more difficult it is to overcome the ordinances and the lower is the likelihood of trade. The coefficients of the Different project and the Cross Delta variables are negative and significant, in accordance with our expectations and indicating a lower likelihood to engage in trading

**Table 3. Probit Estimation (Extensive margin)**

Variables	(I)	(II)	(III)	(IV)	(V)
<i>Log(Revenue ratio)</i>	<b>0.06</b> 0.007***	<b>0.07</b> 0.013***	<b>0.05</b> .014***	<b>.036</b> .009***	<b>.002</b> .024
<i>Log(Water use-exporter)</i>	<b>0.12</b> 0.005***	<b>0.09</b> 0.007***	<b>.064</b> .009***	<b>.140</b> .007***	<b>.06</b> .014***
<i>Log(Water use-importer)</i>	<b>0.15</b> 0.005***	<b>0.15</b> 0.009***	<b>0.14</b> .009***	<b>.416</b> .014***	<b>.431</b> .020***
<i>Log(Distance)</i>		<b>−0.38</b> 0.007***	<b>−.285</b> .009***		<b>−.592</b> .023***
<i>Ordinances</i>			<b>−.29</b> .080***		<b>−.286</b> .125**
<i>Different project</i>			<b>−.45</b> .027***		<b>−.589</b> 0.055***
<i>Cross Delta</i>			<b>−.42</b> .063***		<b>−.183</b> 0.07***
<i>Ability to cope ordinance (exporter)</i>			<b>−.033</b> .014**		<b>−.017</b> .023
<i>Trade inexperience-exporter</i>		<b>−1.1</b> 0.050***	<b>−1.02</b> .050***		<b>−1.29</b> .067***
<i>Trade inexperience-importer</i>		<b>−1.06</b> 0.045***	<b>−.93</b> .045***		<b>−.862</b> .061***
<i>Constant</i>	<b>−5.92</b> 0.09***	<b>−2.84</b> 0.126***	<b>−2.52</b> 0.13***	<b>−9.43</b> .224***	<b>−4.16</b> .287***
McFadden adjusted R <sup>2</sup>	0.082	0.385	0.408	0.196	0.509
AIC	18994.611	12720.971	12650.05	10499.988	6413.681
BIC	−1476.596	−7714.940	−8140.052	−2365.892	−6381.45
ROC	0.79	0.9781	0.9803	0.8965	0.98

Note: Standard errors appear below the coefficient value. Asterisks \*, \*\*, and \*\*\* indicate 10%, 5%, and 1% significance levels, respectively.

if the districts are either in different water projects or on the opposite side of the Delta.

When we aggregate the trades to the county level (models IV and V), we observe that the coefficients of the Revenue ratio and the *Ability to cope ordinance* variables become not significant. This can be explained by the aggregation of the trade contracts at the county level, which eliminates the inter-district differences.

### The Intensive Margin of Water Trade

We now turn to the results, including the intensive margin of water trade (the quantity of water that was actually traded, once the district engaged itself in trade) using a Poisson regression (table 4). The different columns represent the same data procedure as in the Probit estimate in table 3. Similar to the Probit estimation, we use year fixed effects to control for heterogeneity across years (not reported).

As depicted in table 4, a qualitatively similar result as in the Probit estimates (table 3) emerges for models I, II, and III: all coefficients exhibit the expected signs and the

same significance level as in the extensive margin, except for model III, where Ordinances, *Ability to cope ordinance*, and Trade inexperience (exporter) that moved to a lower significance level. Including distance and trade inexperience allows significant increases of all GOF (Goodness of Fit) criteria; at the aggregate level (models IV and V), the predicted values with inclusion of the transfer costs variables increased the explained variance. This suggests a particularly important and significant impact of the distance on participation in the water market. However, for models IV and V we can see that Revenue ratio is not significant, and for model V the variables Ordinances, Cross Delta, and *Ability to cope ordinances* are not significant. We expected that in the intensive margin estimations ordinances may be less important and indeed the variables that measure the transaction costs turned out to be not significant.

Table 5 presents OLS regression results for correlation between aggregate observations and aggregate predictions. We sum the observed volume of water transfer for each exporter district (row 1) and for each exporter county (row 2) and regress it with the

**Table 4. Poisson Regression (intensive margin)**

Variables	(I)	(II)	(III)	(IV)	(V)
<i>Log(Revenue ratio)</i>	<b>.426</b> .041***	<b>.441</b> .067***	<b>.435</b> .072***	<b>-.0082</b> .034	<b>.02</b> .067
<i>Log(Water use-exporter)</i>	<b>.704</b> 0.04***	<b>.552</b> .049***	<b>.484</b> 0.05***	<b>.594</b> .032***	<b>.442</b> .049***
<i>Log(Water use-importer)</i>	<b>.844</b> .027***	<b>.799</b> .036***	<b>.770</b> .041***	<b>1.43</b> .044***	<b>1.313</b> .077***
<i>Log(Distance)</i>		<b>-.643</b> .020***	<b>-.507</b> .028***		<b>-.991</b> .071***
<i>Ordinances</i>			<b>-1.31</b> .439**		<b>.312</b> .448
<i>Different project</i>			<b>-.91</b> .148***		<b>-.676</b> .160***
<i>Cross Delta</i>			<b>-.686</b> .397*		<b>-.473</b> .400
<i>Ability to cope ordinance (exporter)</i>			<b>-.183</b> .073**		<b>.104</b> .075
<i>Trade inexperience-exporter</i>		<b>-3.16</b> 0.300***	<b>-2.99</b> .298***		<b>-3.09</b> .304***
<i>Trade inexperience-importer</i>		<b>-2.62</b> .250***	<b>-2.32</b> .265***		<b>-.951</b> .196***
<i>Constant</i>	<b>-15.20</b> .702***	<b>-7.63</b> .836***	<b>-6.53</b> .844***	<b>-22.22</b> .809***	<b>-11.50</b> 1.38***
McFadden adjusted R <sup>2</sup>	0.242	0.465	0.482	0.319	0.557
AIC	6.229e+07	4.402e+07	4.259e+07	4.467e+07	2.906e+07
BIC	-1.994e+07	-3.821e+07	-3.965e+07	-2.094e+07	-3.655e+07
GOF	0.0080	0.0236	0.0248	0.0155	0.0919

Note: Standard errors appear below the coefficient value. Asterisks \*, \*\*, and \*\*\* indicate 10%, 5%, and 1% significance levels, respectively

**Table 5. Goodness of Fit**

	(I)	(II)	(III)
District-County	0.0185	0.0646	0.0803
County-County	0.1240	0.4573	0.4424

predicted coefficient of the three first models of the Poisson regression (from table 4). We find a significant improvement of the adjusted R-square between the simple model of column (I) and the complete model of column (III). It appears that the binary variable of transaction costs are important in the disaggregated model (district-county). However, at the aggregate level (county-county), the dummy variables appear to be less important as the R-square between model (II) and model (III) is slightly decreasing.

### Policy Implications

The empirical evidence suggests that short-term water markets in California lack flexibility. Short-term (one-year) leasing of water is a crucial type of trading because it allows a rapid and potentially easy adaptation to weather shocks and provides a learning process for participants on how water markets work (Culp, Glennon, and Libecap 2014). Given its non-definitive character (in contrast to permanent sales and even long-term leases), exporters and importers can adjust and experience water trade without experiencing a high risk from potential “mistakes.” Although long-term leases are not definitive, as Hansen, Howitt, and Williams (2015) show, a substantial number of long-term leases are for more than 20 years, which are far less flexible than short-term leases. Thus, short-term leases appear to be more suitable for coping with unpredictable and extreme events such the drought that California is currently experiencing, especially for smaller districts, which are less likely to have the capacity to pay the sunk costs for long-term leases.

The major impediment to short-term trades seems to be the search for a trading partner (extensive margin of water trade) due to the uncertainty and fixed transfer costs. Several improvements can be made to promote water markets.

A first and necessary measure is to develop a more comprehensive management system for groundwater instead of imposing export

ordinances. While some regions need to protect their water resources (and more particularly groundwater) from the risk of depletion, the ordinances discriminate against exports instead of regulating groundwater use more generally within the basin, thereby preventing transfers that might be welfare-enhancing (Hanak 2005). The State of California recently chose this path by adopting legislation that will require local agencies to manage groundwater basins sustainably. This may help districts determine whether they can export groundwater (or use it in substitution of surface water exports) under some circumstances. Other types of legal restrictions could also be clarified and implemented in a more comprehensive and flexible institutional setting, such as facilitating inter-project trade. Facilitating the search for trading partners is also important for enhancing market participation. As pointed out by Culp, Glennon, and Libecap (2014), an online platform such as those operated in Australia’s Murray-Darling Basin could lower the fixed transfer cost of search.

Finally, encouraging better collection and management of information at the state level could facilitate water market entry. The example provided by the State of Colorado is interesting in this regard, where most water trade is under the supervision of one water district—Northern Water—which oversees the operations of the Colorado Big-Thompson Project in conjunction with the federal government (Libecap 2011b). Such a system could provide a healthy balance between the necessary protection for third parties and lowering transfer costs to improve market flexibility.

### Conclusion

In this article we developed a simple theoretical model and tested it to highlight the impacts of transfer costs on California water markets. While some of these costs reflect legitimate means of protecting a natural resource, rationalizing the trading process might allow traders to lower transfer costs without increasing risks of unintended externalities. The main result of this article is that transfer costs impede transfers, likely limiting water users from benefitting from the advantages of water markets. Streamlining the institutional framework and developing more

transparent administrative mechanisms seem to be necessary for increased trade.

This article also contributes to the literature by presenting water trading within a micro-based trade theoretical framework, including the gravity equation, which allows us to study the frictions in bilateral interactions. We show empirically that this approach provides insights into analyzing water trading. We believe that the theoretical model and the empirical inference developed in this article could be applied and enhanced in future research to improve our understanding of water markets.

However, further research should focus on improving the accuracy of the data collected and finding a good approximation of prices of water traded, which would make it possible to improve estimates of the impact of transfer costs. Limited information in our dataset on the seniority of water rights, which affects availability during droughts, may have affected our results. Such information is becoming available with the advent of new reporting requirements in the state.

### Supplementary Material

Supplementary material is available online at [http://oxfordjournals.org/our\\_journals/ajae/](http://oxfordjournals.org/our_journals/ajae/).

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## Appendix

**Table A1. Variables Definitions**

Variables		Definition	Unit
<i>District's income</i>	$Y_{nt}$	Adjusted income (net of water treatment cost) of the district	Dollars
<i>District's water use</i>	$W_{nt}$	Water use in the district	Acre-feet
<i>Distance</i>	$D_{ij}$	Distance between the exporter and importer districts	Kilometers
<i>Ordinances</i>	$T_{ijt}^{ord}$	If the exporter county is subject to groundwater ordinance	Dummy
<i>Different project</i>	$T_{ijt}^{pro}$	If exporter and importer district are not located in the same project	Dummy
<i>Cross Delta</i>	$T_{ijt}^{pro}$	If exporter and importer district are on either side of the Sacramento-San Joaquin Delta	Dummy
<i>Trade inexperience</i>	$T_{ijt}^{trade}$	If the district had never experienced the water market at year t	Dummy