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AN ILLIQUID MARKET IN THE DESERT: ESTIMATING THE COST OF WATER TRADE RESTRICTIONS IN NORTHERN CHILE

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An Illiquid Market in the Desert: Estimating the Cost of Water Trade Restrictions in Northern Chile
Eric C. Edwards, Oscar Cristi, Gonzalo Edwards, and Gary D. Libecap
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ABSTRACT

This paper estimates the cost of a policy to restrict water trades to mining firms in northern Chile to protect riparian ecosystems and indigenous agriculture. In response to the policy, mining firms have developed high-cost desalination and pumping facilities to secure adequate water supplies. We develop a methodology and estimate the cost of market transactions that fail to occur due to the policy. Lost trade surplus is estimated at $52 million per year. Without trade restrictions, around 86% of the remaining agricultural water in the region would be transferred to mining.

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I. INTRODUCTION

In developed countries, high demand for environmental protection can lead to high-cost policies, especially when coupled with distortionary policies that occur through trade restrictions, rather than more efficient instruments due to their political exigency (Anderson 1995). In the context of the United States, economists have estimated the costs of several policies including the Clean Air Act (Greenstone et al 2012); the Arctic National Wildlife Refuge (Kotchen and Burger 2007); the protection of the Spotted Owl (Montgomery et al 1994); and EPA pesticide regulation (Cropper et al 1992). Arrow et al. (1996) suggest that benefit-cost analysis has a crucial role to play in the creation and evaluation of environmental regulations, and therefore these cost estimates contribute to our understanding of regulation generally. This same logic can apply to the context of a developing country. Regulation in developing countries can reduce growth or provide significant net benefits to consumers, depending on the relative costs and benefits (Guasch and Hahn 1999)

In this paper we estimate an environmental policy cost in the context of a developing economy—water trading restrictions in northern Chile. We focus our estimate in a partial-equilibrium setting on the "direct compliance cost," as categorized by Pizer and Kopp (2005). In doing so, we are conscious of Davies' (1997) note of caution in evaluating regulatory costs in developing countries: "Many regulatory problems entail an asymmetry, with the impact on a large and diffuse group being evaluated against that on a small, more cohesive one… Economic measures of the value of time, of health and of life itself are likely to be low for the poor, and efficiency assessments are therefore likely to place a low value on regulations designed to save their time or lives or improve their health." This concern is relevant, as the regulation in question is intended in part to provide water for the developmental and cultural needs of indigenous populations, and the regulatory burden falls primarily on a small group of mining firms. While the valuation of policy benefits is beyond the scope of our work, we discuss the nature of the policy benefits in detail in the discussion section.

Chile's water code generally allows for unregulated trading of water rights (Hearne and Easter 1995; Bauer 1998; Hearne and Donoso 2014).[2] However, Chile's growing income has increased demand for environmental amenities, which are not well defined in the private right system (Hearne 1998) and the impacts of the initial water right assignments on indigenous communities remain unresolved (Prieto 2016). In the hyper-arid Antofagasta Region of northern Chile, which produces 17% of world copper supply (Cochilco, 2014), these issues have led to a change in policy by the water regulator, the Dirección General de Aguas (DGA). The DGA has denied mining firms in the region the ability to use purchased agricultural water rights in mining operations in order to protect water access for small, indigenous farming communities and regional wetland ecosystems. Mining firms have responded by shifting water input to the desalination and pumping of seawater, which must be pumped as far as 150 km (93 miles) to altitudes over 3,000 meters (9,800 feet) above sea level. The cost of desalinated water is substantially higher than the observed market price of water in local agriculture, and the generation of energy for both desalination and pumping releases greenhouse gases.[3]

We use a dataset of water right transfers, available in Chile due to a unique reporting requirement equivalent to that required for real estate sales, to estimate the policy cost. Ideally, we would like to compare the willingness to pay of agricultural water users with mining users using actual market transactions. Unfortunately, the policy change induced mining firms to shift

[2] An anonymous reviewer points out that DGA retains the power to restrict changes in water use or location after trades throughout Chile (Bauer 1998; Hearne and Easter 1995).
[3] Currently, electricity generation in northern Chile is dominated by coal. Efforts are underway to increase the share of renewables, especially solar, which currently make up around 3.6% of generated supply (CDEC-SING, 2015).

to desalinated water. To estimate mining willingness-to-pay, we develop cost estimates for the desalinated water projects undertaken after the implementation of the trade restrictions. We do observe the market price in the regulated market, which we use to estimate agricultural willingness to pay. We then simulate the transfer to mining firms of water currently in use in agriculture. Doing so allows us to estimate that the direct cost of this policy is $52 million per year.[4] These costs are primarily borne by mining firms, whose gross revenues from the region in 2015 were around $11.8 billion.[5]

While a great deal of attention has been paid to the costs of environmental policy, this work typically examines regulation that affects production directly. There has been less analysis of the cost of environmental regulation of input markets where final product costs are more difficult for consumers to detect. This paper contributes to the literature by: (i) providing a methodology for estimating the cost of potential market transactions that are lost due to regulation; (ii) estimating the cost of environmental regulation in the context of a developing country; and (iii) estimating the costs associated with water transfer regulation. Estimating the benefits of the policy is beyond the scope of the current work, but cost estimates do provide a baseline, indicating what value benefits must exceed to have a benefit-to-cost ratio greater than one. In Section II we explain the Chilean setting and how water is traded and regulated. Section III explores the regulatory effect on market prices. Section IV develops a methodology and estimates the deadweight cost of the policy. Finally, section V is a discussion of the results, including a discussion of the benefits of the policy.

[4] All monetary values are given in 2014 US dollars unless otherwise noted.
[5] Source: Cuentas Nacionales de Chile, PIB regional 2015, Banco Central de Chile.

II. BACKGROUND

Water allocation in the Antofagasta region of Chile has become a contentious policy issue due to the coincidence of low precipitation, less than 5mm per year, and high demand. The mining sector, accounting for around 50% of $21.5 billion in regional GDP in 2016, requires significant water input for ore production and processing. The local agricultural sector retains rights to a significant portion of the region's water while producing less than $6 million in output annually.[6] Although the agricultural sector holds 18% of water rights, it accounts for 33% of freshwater consumption. The mining industry holds 76% of water rights but consumes 56% of freshwater. The discrepancy is due to the restrictions imposed on the use of water rights by mining firms. Because many water rights owned by mining firms are not used, the proportion of actual water use in agriculture is higher. Table 1 shows the estimates of water consumption and rights held by sector.

Mining freshwater is obtained from surface dams and groundwater pumping in the Andean highlands above the seeps and diversion points that feed wetlands and provide water to indigenous villages. As a result, mining water extraction has reduced water tables and surface flows, leading to declines in arable land and wetlands:

> *"Environmentally, Andean wetlands are also essential components of the regional hydrological cycle, and concentrate biodiversity and environmental services in the border or in the middle of the desert. They have offered permanent native grasses and allowed the development of agricultural crops. These crops have sustained ancestral village settlements made up of indigenous communities, for whom land and water are indivisible goods, with high economic, social, cultural, and spiritual values. Historically, mining has exploited surface water bodies, whose depletion and overexploitation have reduced availability and dramatically affected ecosystems and local communities (Romero et al, 2012)."*

[6] GDP figures from Central Bank of Chile: Cuentas Nacionales de Chile, PIB Regional 2016. Converted to dollars using the observed-dollar average annual price of 676.83 Ch$/USD. Source: Central Bank of Chile.

Regional wetlands encompass an area of 6,904 hectares, around 0.05% of total land area, and provide important habitat for many species, as well as being linked to traditional agricultural lifestyles (Centro de Ecología Aplicada, 2011, p. 54). Approximately 2,000 hectares of irrigated land, out of a total of 12.6 million hectares in the Antofagasta Region, allow indigenous communities to engage in traditional agriculture. Mining diversions reduce the water available for ecological production and agriculture. Figure 1 shows a map of the region and includes the locations of major mines. The figure also shows the main local water source for the region, the Loa River, which forms a "U" near the border with the Tarapacá region. The small triangles represent the approximate locations of indigenous agriculture and nearby principle wetland sites, although only a portion of the mapped areas are active wetlands.[7] Mines extract water above these areas and pipe the water to the mines.

The indigenous population is primarily not located in the small, rural communities, but in the urban areas, and preferences across this population for environmental and indigenous policies are heterogeneous. Data from the Chile National Socioeconomic Characterization Survey (2015) show there are 20,820 employed indigenous persons in the region, with 706 (3.4%) working in agriculture and 4,853 (23.3%) working in the mining sector. Both sectors make up a larger portion of the indigenous workforce than in the non-indigenous workforce, 0.53% and 18.6% respectively, and the large difference in agriculture suggests more sensitivity to the indigenous workforce to changes in agricultural employment. To date, there has been little discussion of the effect of DGA policies on mining sector employment, perhaps because regulatory costs affect profitability but not demand for employment or the causal link is less clear.

[7] The locations of these communities are approximate based on water right descriptions and aerial photos of irrigation.

The allocation of water is determined by the country's 1981 water code, which established tradable water rights that were separable from the land. The original water code included few environmental controls (Bauer, 1997; Mentor, 2001); and rights to environmental amenities associated with in situ water use were not defined statutorily (Grafton et al., 2011).[8] In the Antofagasta Region, the period after the adoption of the water code in 1981 was characterized by rapid development of water resources by mining firms with little regard to larger externalities. Water infrastructure projects focused on providing water for mining rather than local or wetland uses (Peña, 2011). Downstream from mining and agricultural diversions, streamflow in the Loa River, the main water source in the region, decreased by two-thirds from 1961 to 1990.[9]

Buyers and sellers in the water market fall broadly into three categories: agricultural, mining, and government. Agricultural buyers and sellers are individual irrigators transacting in the market for water rights to irrigate small fields. Mining buyers and sellers are firms engaged in mining or industrial activities and their direct use of the water is typically in ore extraction and processing and related services. Governmental buyers and sellers are communities as well as the national government.[10] Indigenous communities buy water rights through the national Fund for Indigenous Lands and Waters to preserve their community's access to water, and are therefore

[8] In 2015, the water code was modified (Law 20017). The main changes included the requirement of a fee for a water right that is not being in used and granting to the DGA the authority to establish an ecological flow at the time that new water rights are granted.
[9] Measurement data from 1961 is from Universidad de Chile and Corporación de Fomento de la Producción; data from 1990 is from DGA monthly means.
[10] One of the largest holders of water rights in the area is Codelco, a government-owned mining firm. However, Codelco does not appear as a participant in transactions in the period covered by our dataset because their rights acquisitions took place prior.

classified as governmental buyers even though the water's ultimate purpose is typically agriculture (World Bank, 2011).

After Chile's return to democracy in 1990, a rapid expansion of mining occurred in the region, driven by investment by large multinational mining firms, both Chilean and foreign-owned. Figure 2 shows copper revenue in the region split into income from the nationalized firm, Codelco, and others.[11] Private firms began to acquire additional water rights in the market to increase production, especially as copper prices rose in the mid-2000s. After a water right sale is complete, a mining firm applies to the DGA to transfer the right to a new use and extraction point under the water code and environmental law (Chilean Law 19.300). In the mid-2000s these reviews led to the rejection of several change-of-use or change-of-extraction-point applications. While mining firms still held the water right, they were forbidden from using the water for mining. For example, the mining company Minera Quadra bought underground water rights in 2008 in the Pampa Llalqui, 30 kilometers from Calama, for around US$40 million, but has not received permission to use the rights for mining.

The rejection of change requests by the DGA had a significant effect on the market for water rights. As trade restrictions limited mining purchases from agriculture, firms turned to desalination and the transport of water from sea level to remote mines (Cristi et al. 2014). Mines vary in their distance from the coast and elevation above sea level. The highest cost desalinated water is that delivered to the Escondida mine, 150 km (93 miles) inland at an altitude of around 3,200 meters (9,800 feet) above sea level. Because the cost of desalinated water is substantially

[11] Revenues for the region are estimated by using company production totals, the location of mines held by the company, and yearly copper prices.

higher than the observed market price of water in local agriculture, this policy is potentially costly.

The remainder of the paper estimates the cost of the policy. First, we perform an econometric analysis on recorded water right transactions, from which we arrive at a point estimate for the price of an agricultural water right. Second, we parameterize a simulation model of the deadweight cost of the policy using the water right transfer data as well as data on desalination costs.

III. TRADING RESTRICTIONS

Water Transfer Data

A dataset of surface water transfers was constructed by the authors from records in the Loa River basin of the Antofagasta Region from 1995 to 2014, the full time period for which data are available. Transaction records are compiled by the Superintendencia de Servicios Sanitarios for use in setting water rates to urban customers. Records were obtained for the "Official Database" used for rate setting, which eliminates trades beyond the Loa basin, those with missing water price data, exchanges involving land and buildings where water is bundled in the transaction, groundwater transfers, and trades among family members. The final dataset consists of 534 surface water transfers for which information is available on the date, buyer, seller, quantity transacted, and the price at which the transfer occurred. Buyer and seller types were classified into one of three categories—mining, agriculture, or government—described above. When the transacting party was an individual's name or a series of names, the party was classified as agricultural. Mining classification occurred when the name of the transacting party contained *Ltda.*, *Ltd*, or *S.A.*, indicating a business, or the name directly referenced a known mine, mining firm, or a company associated with mining. Government classification occurred when the transacting party's name references a community, or local or national agency.[12]

To simplify the analysis, we look at trades in three categories encompassing 91% of recorded water transactions: agriculture-to-mining, agriculture-to-agriculture, and agriculture-to-government. As the high-value users, mining firms have been active buyers of water rights but not sellers. Similarly, government entities have been buyers. By limiting the sellers to agriculture we are able to examine the effect of buyer type on sales from a single sector. Overall summary statistics on prices, volume, and number of transfers are provided in column 4 of Table 2. Prices are for a permanent transfer and are given in flow units. Throughout the paper water prices are expressed as a right to a cubic meter of water, every day, in perpetuity: dollars per m^3/day.[13]

We use the available data on DGA reviews of surface water right transfers in the Calama region to understand how these reviews may have affected the market.[14] In figure 3, the shaded grey area shows the cumulative number of requests for water transfers reviewed by the DGA, by the date submitted. The rejection rate is a five-year average of the percentage of reviews that were rejected or withdrawn, by the date a decision was made. Only *one* application for a change in surface water was approved after 2003. From February 2003 to July 2004, five surface transfers representing 46% by volume of water transfer requests submitted up to that date were denied.

[12] The dataset does not contain any transactions by urban utilities directly. Both large cities in the region, Antofagasta and Calama, hold reserved water rights. However, trades have occurred, for instance Antofagasta's water is managed by a subsidiary of Antofagasta Mineral, which desalinated 550 L/s of seawater so that the city's freshwater could be used by its mining arm.

[13] A m^3 is around 265 gallons, slightly more than the 208 gal./day the average Chilean family of four uses but less than the 400 gal./day used by the average American family. Therefore a right to a m^3/day is enough to supply a Chilean family in perpetuity.

[14] Data is from the Catastro Público de Aguas of the DGA.

Because of the change in the rate of regulatory denial in 2003, Table 2 displays summary statistics through-2003 and post-2003 as well as for the entire period. Throughout the sample period, mining firms appear to pay more for water on average than do agricultural and government buyers. This may be indicative of mining firms selecting rights to purchase that differ based on properties unobservable in the dataset.[15] The summary statistics are consistent with a post-2003 change that constrained the supply of agricultural water rights available for purchase by mining firms. The average volume transferred for all purchasers decreases from the pre- to post-2003 period. Further, despite there being two more years in the post-2003 period, the overall number of transfers to mining drops from 60 to 52. Prices and means for the summary statistics table are calculated using the price per m^3/day. However, the distribution of the log of prices has a more symmetric distribution, as seen in the appendix figure A1. For this reason the transformed prices are preferred for statistical analysis.

Econometric Approach

We estimate a regression equation to find the price paid when both buyer and seller are agricultural users, as well as to examine the effect on water right prices of the 2003 increase in regulatory rejections on different classes of transacting parties. We define an indicator variable such that $I_R=1$ when time t>2003 and $I_R=0$ otherwise. The price of a water right, *j*, per unit (a perpetual right to one cubic meter per day) is P_j. We regress the log of P_j on indicators of buyer type, I_q, where q={M,G}, so that $I_M = 1$ for a mining buyer, and $I_G = 1$ for a government buyer, and both are 0 for an agricultural buyer. Generally, our empirical specification takes the form:

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[15] An anonymous referee notes, correctly, that other explanations such as lower transaction costs for trades between neighboring farmers could also partially explain these price differences.

$$\ln(\mathrm{P_j}) = \alpha + \gamma \mathrm{I}_R + \sum_{q \in \{M,G\}} \lambda_q \mathrm{I}_q + \sum_{q \in \{M,G\}} \delta_q \mathrm{I}_R \cdot \mathrm{I}_q + \mathrm{u_j} \qquad (1)$$

The expected log value of an agricultural water right post-2003 when the seller and buyer are agricultural is $\alpha + \gamma$. This log price is distributed $N(\alpha + \gamma, \sigma^2)$. We observe the coefficient estimates, $\hat{\alpha}$ and $\hat{\gamma}$, and the robust standard error estimate of their linear combination, $\hat{\sigma}_n$. The λ coefficients indicate the extent to which mining and governmental buyers, relative to agricultural buyers, paid higher prices to agricultural sellers, prior to 2003, while the δ coefficients indicate whether this difference changed for rights purchased after 2003. These coefficients provide some indication of whether non-agricultural buyers paid higher prices for water rights. To better isolate the δ coefficients, we use a year dummy to control for year-to-year variation in water right price in one specification.

Econometric Results

We run the regression from equation 1 to estimate the agriculture-to-agriculture transfer price, $\hat{p}$. The results are shown in the first two specifications on Table 3, where we estimate the 2004-2014 average price of agricultural water: (1) regresses the log of the water right price on an indicator for post-2003; and (2) includes controls for differential prices for government and mining purchases both before and after 2003. Both specifications arrive at similar estimates for $\hat{p} = \hat{\alpha} + \hat{\gamma}$, the mean price post-2003. Using the estimate from (2) we find that the joint estimate of $\hat{\alpha} + \hat{\gamma}$ is 6.346 and $\hat{\sigma}_n$ is 0.110. Transforming our estimates to dollars, the mean price is around \$574. We construct a 99% confidence interval for $\hat{p}$ of (\$264, \$1247).[16]

[16] The expected value of the transformed lognormal distribution, from Zhou and Gao (1997), is: $\hat{p} = e^{\hat{\alpha}+\hat{\gamma}+\frac{1}{2}\hat{\sigma}_n^2}$. We construct a confidence interval, from Olsson (2005), of the exponent of:

We now turn to analysis of the mining price premium through time. Figure 4 plots the results of regressions showing the yearly premium paid by mining buyers relative to agricultural buyers. The specification used for this figure and coefficient estimates are shown in Table A1. There is a two-year hiatus of mining water right purchases after 2003 as well as zero recorded purchases in 2010 and 2014. This result is consistent with our understanding that the number and volume of mining rights purchases decrease after 2003. While the price of water rights purchased by mining firms does appear to increase relative to agricultural buyers for a few years post-2003, there is not price divergence post-2010.

Results from the figure are consistent with those from running equation 1, shown in Table 3. Specification (3) looks at the mining and government price premiums for the entire sample period, while (2) looks at premiums before and after 2003, and (4), which includes a year dummy to control for variation in a given year across trade types, only looks at the post-2003 premium. For the entire period, mining firms pay more on average for water rights. It may be the case that firms can select on quality or regulatory attributes of rights that are unobserved in our data set, causing their purchases to occur at higher price levels. However, after controlling for year fixed effects in (4), it is not apparent that post-2003 the price premiums change relative to what they were during the pre-2003 period. When mining firms do purchase water post-2003, they pay a price similar to the going market price for agriculture-to-agricultural water—significantly less than the desalination costs they concurrently undertake. We conclude from this

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$$\left(\hat{\alpha} + \hat{\gamma} + \frac{1}{2}\hat{\sigma}_n^2\right) \pm t\sqrt{\frac{\hat{\sigma}_n^2}{n} + \frac{\hat{\sigma}_n^4}{2(n-1)}}$$

Where t is the Student's t-distribution test statistic with degrees of freedom n. Conservatively, we use n=2 because our regression uses two groups to calculate $\hat{\alpha} + \hat{\gamma}$.

that mining willingness-to-pay cannot be estimated using market transactions. We describe an alternative estimation approach using estimated desalination costs in the next section.

IV. DEADWEIGHT LOSS

Simulation Approach

Similar to Griffin (2006, 40), we examine a simplified setting via a two-sector model, where the supply of water is S, and this water can be put to two purposes, mining or agriculture, as illustrated in Figure 5 with price on the y-axis and the amount of water in mining, Q_M, on the x-axis.[17] We define the initial inverse demand curve for water in mining as $D_0(P) = Q_M$ and for water in agriculture as $D_A(P) = Q_A$. Initially, mining demand is low and the market clears. Because $Q_M + Q_A = S$, the condition for the market clearing is $D_A^{-1}(S - Q_M) = D_0^{-1}(Q_M) = P^0$.[18]

When demand for water in mining increases, represented by demand shifting to $D_M(P)$, regulatory restrictions are put into place, enforced via a rationing rule. We assume the regulatory rule assigns a subset of the water that has been freely transferred to mining firms, $\bar{Q}_M$. This leaves $S - \bar{Q}_M$ water in agriculture. Now, two prices emerge, $P_M^1 = D_M^{-1}(\bar{Q}_M)$ and $P_A^1 = D_A^{-1}(S - \bar{Q}_M)$. The price of rights that can be transferred to mining must be at least as valuable as those that cannot be moved from agriculture, $P_M^1 \geq P_A^1$.[19] Without the transfer restrictions, the

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[17] For simplicity this model does not examine the urban sector as buyer or sellers, which is consistent with empirical observations: over the period 1995-2014 our data set shown no municipal purchases or sales.
[18] In this simplified model, there is no explicit term for water dedicated to ecosystems and environmental uses. However, in the setting at hand, agricultural water is extracted after providing ecosystem flows, and so the agricultural water and ecosystem water is the same.
[19] This model is an abstraction of the reality. Mining firms may purchase rights at a price below P_M^1 knowing that there is some probability of rejection.

market clearing price would satisfy $D_A^{-1}(S - Q_M) = D_M^{-1}(Q_M) = P^1$, with the resulting amount of water in mining $D_0(P^1) = Q_M^1$.

The shaded area in Figure 5 represents the lost trade surplus as a result of the regulatory restriction on water markets. To find this area, which represents the cost of the policy, C, we integrate between the demand curves:

$$C = \int_{\bar{Q}_M}^{Q_M^1} [D_M^{-1}(Q) - D_A^{-1}(S - Q)]\, dQ \tag{2}$$

To simulate the gains from allowing additional trades from agriculture to mining requires estimating D_M and D_A, then solving for Q_M^1, and finally solving Equation 2. To estimate D_A we use $\hat{p}$, from the regressions on water rights prices between agricultural water users, to calibrate a demand curve using previous estimates of agricultural price elasticity and an assumption of a constant elasticity of substitution (CES) functional form (Lichtenberg and Zilberman, 1986). The CES demand function has the form:

$$Q = A_0 p^{\eta} \tag{3}$$

Where A_0 is a constant, Q is quantity of agricultural water used, p is price of water, and η elasticity of water demand. The agricultural water transaction price, P_A^1, is used as a point estimate to calibrate the CES demand curve, where Q_0 is the estimated water use in agriculture:

$$A_0 = \frac{Q_0}{(P_A^1)^{\eta}} = Q_0 (P_A^1)^{-\eta} \tag{4}$$

Therefore, the price paid by an agriculturalist for a consumptive water right, P_A^1, is defined as:

$$P_A^1 = \hat{p} \tag{5}$$

Rewriting the agricultural demand curve, equation 3, in terms of price and substituting in (4) as well as (5), we arrive at:

$$p = \hat{p}\left(\frac{Q_0 - Q_M}{Q_0}\right)^{\frac{1}{\eta}} \tag{6}$$

To find the willingness of mining firms to pay for water, D_M, we construct estimates of willingness-to-pay based on the distance from the coast and elevation of mining operations using desalinated water. Mines are located at various distances and elevations, creating a downward sloping curve. We assume that if the policy restricting transfers was relaxed, agricultural water would initially offset the most expensive desalinated water via market transactions.

The literature that considers water as an input in agricultural production often distinguishes between applied water per acre and the effective water per acre (Bogges et al. 1993). The latter depends on irrigation technology, land quality, and soil type. Farmers divert and apply a given quantity of water on their field, and some smaller quantity is used consumptively through evapotranspiration while the remaining water returns to the system, with the reuse possible in some circumstances. Chile's system of tradable water rights does not distinguish between applied water and effective water; an owner can always sell the right to the total amount of applied water (Cristi 2010). For this reason, our analysis supposes the transfer of water from agriculture to mining offsets an equivalent volume of desalinated water. The willingness to pay by mining firms for agricultural water rights, p, is:

$$p = D_M^{-1}(Q_M) \tag{7}$$

By equating (6) and (7) we can find Q_M^1:

$$D_M^{-1}(Q_M^1) = \hat{p}\left(\frac{Q_0 - Q_M^1}{Q_0}\right)^{\frac{1}{\eta}} \tag{8}$$

Then, the integral from equation 2 is evaluated numerically, after simplifying:

$$C = \int_0^{Q_M^1} D_M^{-1}(Q)dQ - \hat{p}\int_0^{Q_M}\left(\frac{Q_0 - Q}{Q_0}\right)^{\frac{1}{\eta}} dQ \qquad (9)$$

Parameterization

Table 5 describes the parameters used to calculate the policy cost. The key parameters are estimated agricultural-to-agricultural water right price, $\hat{p}$; quantity of agricultural water available for transfer, Q_0; the agricultural elasticity of water demand, η; and the cost of energy, E. Each of these parameter has a baseline value, as well as a high and low value used for sensitivity analysis. To estimate the quantity of water currently in agriculture, we use a baseline of the total recorded agricultural surface water rights on the Loa River and tributaries, 185,674 m^3/day (DGA, 2005; Salazar et al., 2003). For the sensitivity analysis a range was chosen based on a low estimate of available water using gauged flow in the Loa River of 129,600 m^3/day and the estimate of water use in agriculture from Table 1 of 285,811 m^3/day.

To calculate agricultural sale price, we use the mean and confidence interval constructed from estimates from specification (2) as described above. The price elasticity of demand for water use is estimated to be -0.79 based on calculations from the literature (Schoengold et al., 2006). A range from -0.25 (from Nieswiadomy, 1988) to -0.9 is used. Finally, we use water cost estimates calculated and presented in Table 4 as our estimate of D_M.[20] The methodology for constructing this curve is provided in the appendix. The demand curve constructed from this table is shown in Figure A2, with demand at quantity equal to zero being the current status quo with no transfers to mining.

[20] Mines may require additional security in water availability, i.e. they will need water even when there is a drought, and therefore might construct desalination and pumping facilities to provide this water. In our analysis we do not include the costs of the infrastructure, only the variable costs of desalination and pumping, to ensure our estimate is conservative.

Two additional parameters, agricultural water return rate, R_0, and the downstream flow reduction coefficient of mining extractions, β, which both range between 0 and 1, are also included in the interest of completeness. While the baseline set of assumptions are consistent with the Chilean interpretation of hydrologic conditions, these additional parameters explore two possibilities. First, that sales from agriculture are modified to reflect return flow; agricultural users purchase a water right that entitles them to an amount of water, but their effective water use is less. For the robustness check it is assumed effective water is only 20% of their applied water. Second, sales might be modified to reflect the water savings of mining firm extractions high in the Andean Plateau: we use calculations from the Ojos de San Pedro sub-basin within the Loa River watershed to estimate that downstream flows are decreased only about 45% of the total amount of upstream mining extraction due to savings from reduced evaporation and seepage losses (Edwards and Kirk-Lawlor, 2013).[21]

Simulation Results

Based on these parameters and estimates, we solve equation 8 to find Q_M^1, the quantity of water transferred such that marginal prices are equalized. We find under the baseline scenario that this occurs when 160,500 m^3/day of water is permanently transferred out of agriculture to mining firms. Full results are shown in Table A2 for the baseline specifications and the results of varying each of the parameters. Because water right prices are expressed in perpetuity, the cost estimate is a total present-value cost, which is $874 million for the baseline parameters. Using a 6% discount rate, the estimate can be converted to the yearly policy cost of $52M.

[21] In this region, estimated water withdrawals of 1,551L/s reduced surface water flow downstream by 700L/s. The additional parameters serve to modify the demand functions. Equation 6 becomes: $p = \left(\frac{\hat{p}}{1-R_0}\right)\left(\frac{Q_0-Q_M}{Q_0}\right)^{\frac{1}{\eta}}$. Equation 7 becomes: $p = D_M^{-1}\left(\frac{Q_M}{\beta}\right)$.

Figure 6 shows the sensitivity analysis graphically: the solid vertical line is the baseline estimate; the dashed vertical lines show the 99% confidence interval constructed around the mean agriculture-to-agriculture exchange price while holding all of the parameters at their baseline values.[22] The horizontal lines represent the high and low cost estimates of changes in each parameter value, holding all other parameters at their baselines. The sensitivity analysis shows the cost estimate is particularly sensitive to electricity price. The cost estimate is also sensitive to R_0 and β independently. However, these variables would likely both change simultaneously under a policy that accounted for effective water. A joint sensitivity analysis with $R_0 = 0.2$ and $\beta = 0.45$ results in a policy cost estimate of $76.86M/year.

The policy cost estimate is not a measure of welfare change because it does not incorporate the non-market costs and benefits of the policy. Without the trade restrictions, we estimate around 86% of the remaining surface water in the highlands would be removed from agriculture, desiccating natural water sources and negatively affecting riparian ecosystems and forcing indigenous communities out of their ancestral homeland. The policy also produces non-market costs, shifting mining production from highland water to seawater powered by fossil fuels, and creating additional greenhouse gas emissions. We discuss these issues in the next section.

VI. DISCUSSION

The primary result of this paper is the estimate of an annual $52.46M policy cost associated with the DGA water use regulations. This result may be large or small, depending on what benefits, and to whom, these costs are compared. Many of the benefits of the policy are

[22] Note the upper confidence bound corresponds to the low welfare estimate, because high agricultural prices indicate lower benefits from water transfers.

nebulous, making a full accounting difficult. Comparing the policy cost to total agricultural output in the region of only $6 million annually suggests the cost is large. Indigenous groups represent around 5% of total regional population, although the estimates of those directly engaged in agriculture is only around 706. This implies a policy cost of over $74,000/year for each active indigenous agriculturalist in the region.

However, the direct value of agricultural production is likely to underestimate the importance of water to indigenous communities. The direct agricultural and cultural benefits of the policy include cultural values associated with indigenous water use, avoided relocation costs, and agricultural production. In the Aymara and Atacama cultures, the native people of the Antofagasta region, water is viewed as a community asset (Peña 2004). Further, the costs of relocating entire villages that are desiccated would likely be much higher than lost agricultural production. For example, the Ojos de San Pedro (OdSP) area of the highlands in the Antofagasta Region was once the location of a lake and wetland system that supported a unique ecology and a small village. Even early water extraction by mining firms through 1970, however, led to severe impacts, including a complete desiccation of the area and the abandonment of the village (Edwards and Kirk-Lawlor, 2013). While compensation was not paid in this case, it is difficult to imagine in modern Chile that relocation would not entail significant economic and sociological costs.

The environmental benefits of the policy include tourism and the intrinsic value Chileans attribute to protecting their ecosystems. The policy serves to partially protect highly valued tourist destinations, including the Los Flamencos National Reserve near the city of San Pedro de Atacama. Further, many Chileans place intrinsic value on the preservation of their unique ecosystems, and the policy cost per Chilean is less than $3 per year. When compared to gross mining revenues from the region in 2015 of around $11.8 billion, and coupled with the environmental and cultural benefits, the policy costs may appear small.

There are also additional policy costs that arise from the carbon emissions as a result of desalinating and pumping water. Because freshwater delivery is gravity fed, it is possible to make a back-of-the-envelope calculation on the total carbon emissions. Our baseline projection is that 160,500 m^3/day of freshwater could be provided, offsetting $52.46 million in electricity costs or 1.10B kWh of electricity per year. The northern Chilean grid is 75.6% coal, 13.5% natural gas, and 6.7% fuel oil and diesel (CDEC-SING, 2015). CO_2 releases are 0.972 kg/kWh for coal, 0.434 kg/kWh for natural gas, and 0.865 kg/kWh for fuel oil no. 6 (authors' calculations from 2010 data from EIA (2017)). This leads to an estimate of the policy causing an additional 721,451 metric tons of CO_2 emissions. The social cost of carbon is estimated at $43.00 per metric ton, the mean of the peer-reviewed studies surveyed by Tol (2005). This leads to a cost estimate of $31.02 million per year.

The high policy costs relative to agricultural production and employment and the potential environmental costs of increased carbon emissions, coupled with the high cultural and intrinsic values placed on *in situ* water challenge policy makers and regulators to find alternative solutions. Markets may offer a partial solution. The Chilean government purchases water rights through the Fund for Indigenous Lands and Waters that are then granted to the communities in perpetuity. In this way the rights are purchased at a market price from current right holders, moving water to protect environmental and indigenous benefits without reducing the value of property held by agricultural producers. These trades make marginal water values and the cost to the government of the policy explicit, illustrating the tradeoffs between conservation and development. However, once these assets are transferred to villages, sale requires agreement of the entire community. Thus, these rights, although extremely scarce, have limited direct financial value due to low agricultural productivity in the region.

Beyond making tradeoffs explicit, it is worth considering alternative transfer and compensation mechanisms that might facilitate mutually beneficial exchange. Currently, the guidelines issued by the Chilean Undersecretary on Mining for the best-practices for indigenous relations suggest mining firms work to protect the natural heritage and water flows, utilizing formal commitments with indigenous villages. It goes on to suggest that to meet this objective, firms should preferentially use seawater. We suggest two potential alternatives. First, firms could use this commitment process to determine to what extent village and mining water needs could be met mutually, for instance if mining firms worked with communities on the location and amount of water diversions. Second, indigenous villages could be compensated, for instance investment in infrastructure and education, in addition to the payment firms make to water right holders. While formal property rights offer advantages in the exchange of water by lowering transaction costs, the problem of social cost emerges because the private costs facing decision makers are less than social costs. Although the formal water right system may fail to account for externalities, the argument made by Coase (1960) would suggest that stakeholders and mining companies could potentially engage in beneficial bargaining provided they can define the resource they are bargaining over.

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TABLES

TABLE 1

Freshwater Consumption by Sector in the Antofagasta Region

	Freshwater Consumption		Water Right Allocations	
Economic Sector	m3/day	percentage	m3/day	percentage
Agriculture	285,811	33%	285,811	18%
Urban	87,221	10%	87,221	6%
Mining	484,394	56%	1,182,161	76%
Other	25,603	3%	25,603	2%
Total	857,426		1,555,193	

Notes: Authors' calculations from DGA, 2007, DGA, 2008.

TABLE 2

Surface water sale summary statistics

Buyer Type	Pre (1995-2003)	Post (2004-2014)	All (1995-2014)
	Mean Price (2014$ per m3/day)		
Government	$411	$841	$630
Mining	$657	$1291	$951
Agriculture	$446	$910	$708
	Number of Transactions		
Government	81	84	165
Mining	60	52	112
Agriculture	91	118	209
	Mean Flow per Sale (m3/day)		
Government	115	58	85
Mining	294	206	253
Agriculture	91	36	60

Notes: Authors' calculations from transfer data.

TABLE 3

Regressions of price of water sold by agricultural users on buyer type

VARIABLES	(1) ln(price)	(2) ln(price)	(3) ln(price)	(4) ln(price)
Constant (α)	5.303***	4.605***	5.588***	5.485***
	(0.103)	(0.209)	(0.125)	(0.117)
Post-2003 (γ)	1.235***	1.741***		
	(0.118)	(0.236)		
Mining		0.981***	0.581***	1.253***
		(0.271)	(0.172)	(0.288)
Government		1.273***	0.668***	0.551**
		(0.221)	(0.135)	(0.277)
Mining x Post-2003		-0.486		-0.454
		(0.307)		(0.341)
Government x Post-2003		-0.999***		0.210
		(0.251)		(0.333)
Observations	486	486	486	486
R-squared	0.190	0.278	0.050	0.417
Year Control	None	None	None	FE
Linear Combination ($\alpha + \gamma$)	6.538***	6.346***		
	(0.058)	(0.110)		

Notes: Regressions of log of per unit water transfer price from agriculture sellers on indicators of buyer type and post-2003 dummy for years 1995-2014. The sum $\alpha + \gamma$ represents the average log of the post-2003 agriculture-to-agriculture transfer price. Robust standard errors in parentheses *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

TABLE 4
Desalination projects

Mine Name / Project	Pumping Distance (km)	Elevation (m)	Water cost estimate (per m3/day)	Status	Capacity (m3/day)
Urban / La Chimba	0	0	1,904	Operational	52,013
Urban / Taltal	0	0	1,904	Operational	432
Michilla / Michilla	15	835	3,250	Operational	8,800
Algorta Norte / Algorta	65	1300	4,079	Operational	12,960
Sierra Gorda / Sierra Gorda	141	1700	4,854	Operational	128,736
Esperanza / Michilla II	145	2200	5,651	Operational	62,208
Escondida / El Coloso	170	3150	7,197	Operational	45,360
Escondida / Mega Plant	170	3150	7,197	Operational	216,000

Notes: The water cost estimates use a 6% discount rate. Two desalination projects to provide urban water to coastal cities are also included because the urban utility (Aquas Antofagasta) has switched urban users to desalinated water freeing surface water for mining use, without incurring pumping costs. Some of the projects listed (Algorta Norte, Sierra Gorda, and Michilla II) have utilized direct seawater, but we have chosen to estimate the desalinated water cost because the direct seawater has proven problematic due to its corrosive properties. Source: authors' calculations; procedures and sources fully described in the appendix.

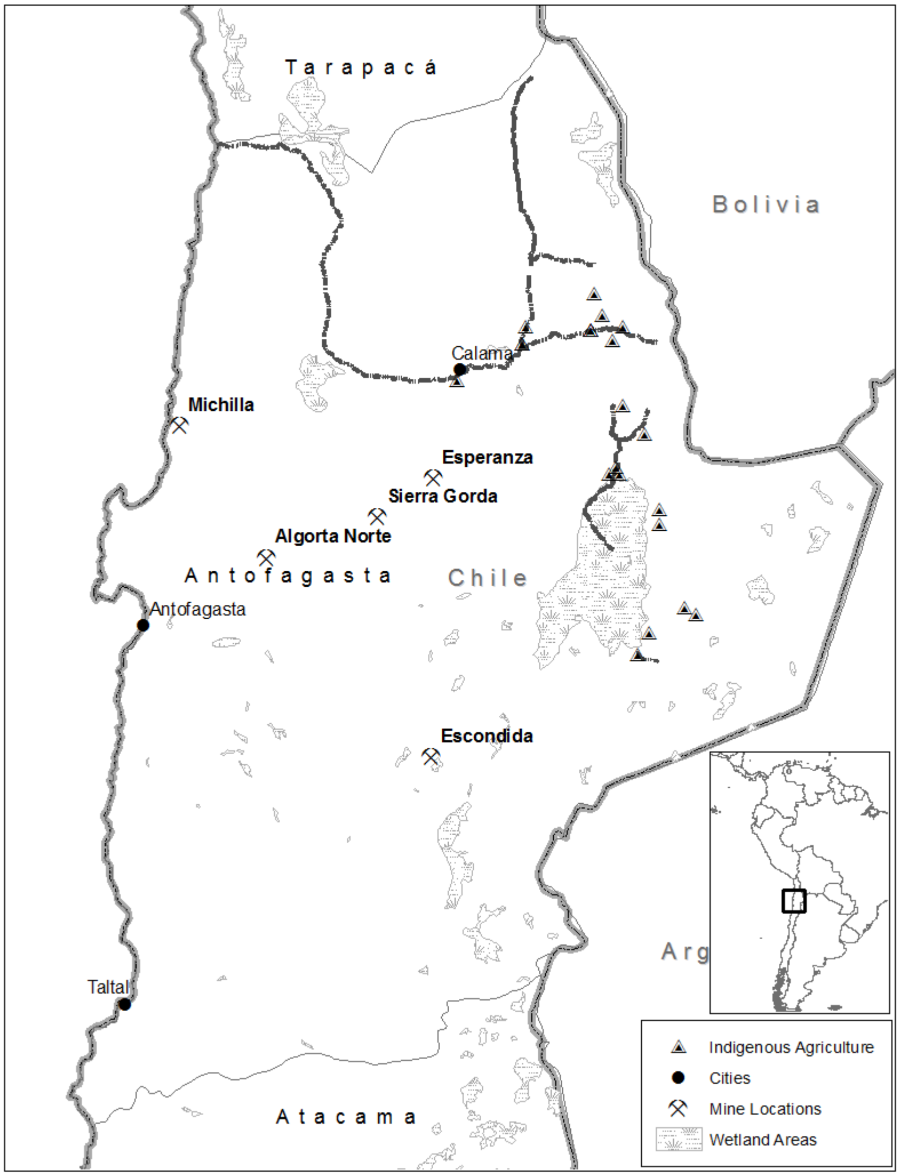
TABLE 5
Parameter descriptions and values

Description	Parameter	Baseline	Low	High
Ag price ($/m^3/day)	$\hat{p}$	$574	$264	$1247
Current ag water	Q_0	185,674	129,600	285,811
Ag elasticity	η	-0.79	-0.25	-0.9
Energy cost	E	47.6	23.8	95.2
Downstream damage	β	1	0.45	NA
Consumptive use	R_0	0	NA	0.8

FIGURES

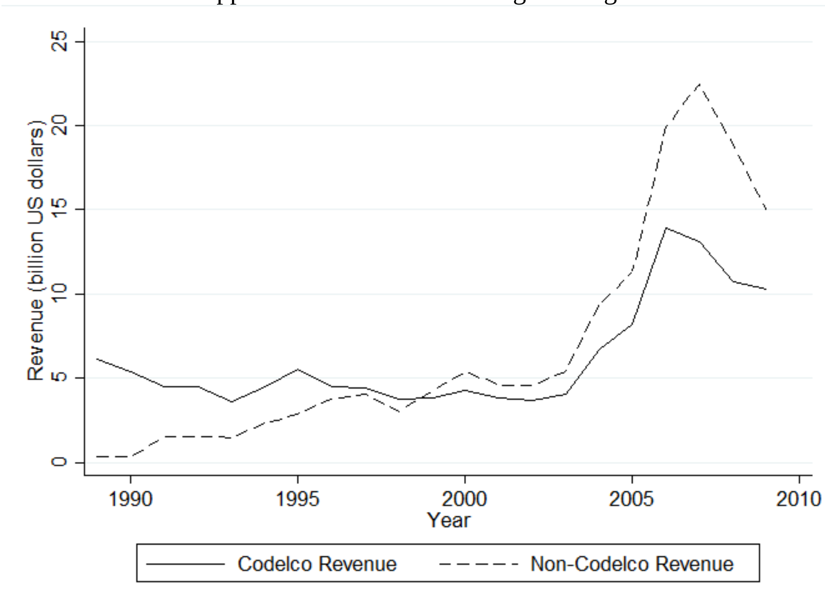
FIGURE 1

Map of northern Chile's Antofagasta Region



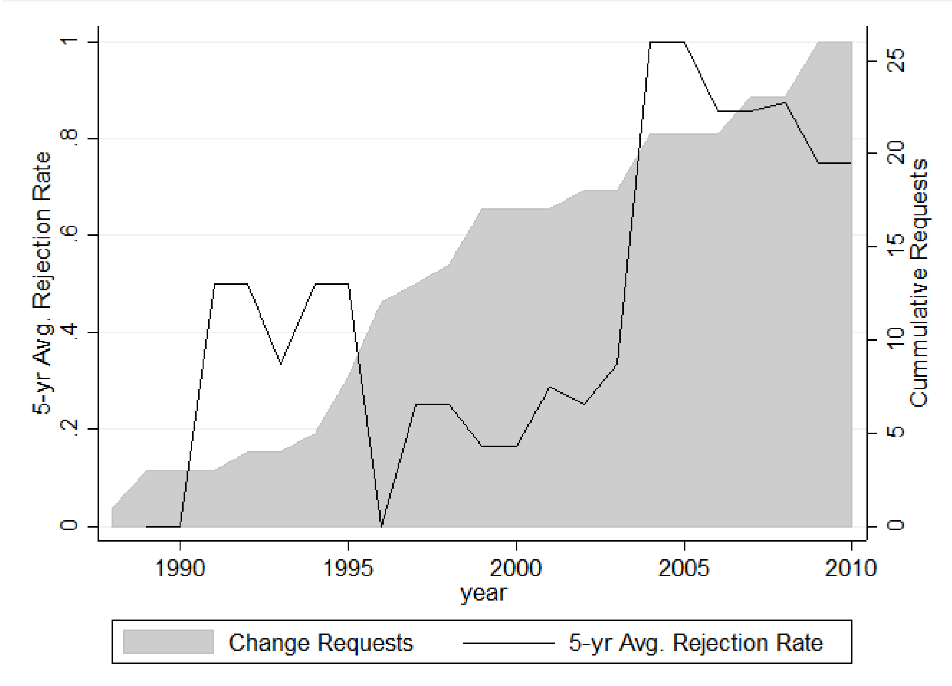
Caption: Authors' drawing with data from ESRI and Red Hidrográfica; City and mine location information coded by the authors.

FIGURE 2
Copper revenues in the Antofagasta Region



Caption: Authors' calculation from Cochilco mine production data. Mines in Region II were designated as Codelco or other, and then production was summed.

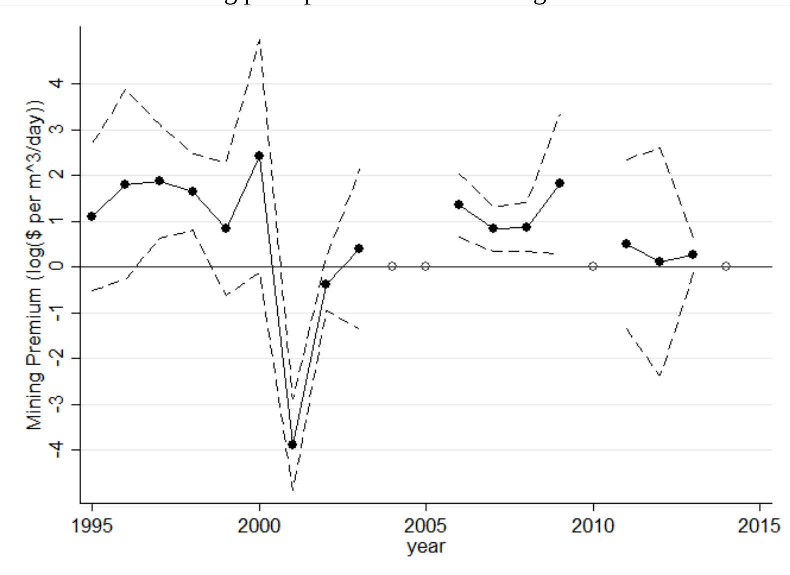
FIGURE 3
Water right change requests and change rejection rate



Caption: Authors' calculations from data on rejections collected from the Catastro Público de Aguas of the DGA.

FIGURE 4

Mining price premium relative to agriculture



Caption: This figure shows the coefficient and 95% confidence intervals for the price premium paid for purchases by mining buyers relative to agricultural buyers in each year. The open points indicate years where agricultural purchases occur but mining purchases do not. Results used to generate this figure are reported in table A1

FIGURE 5
Surface water demand and gains from trade

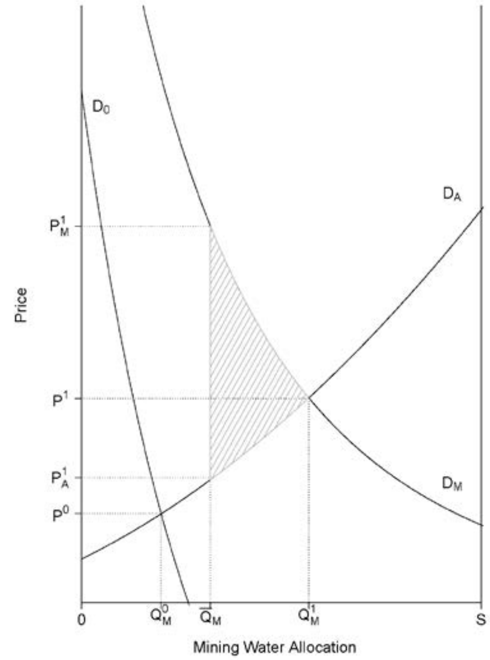
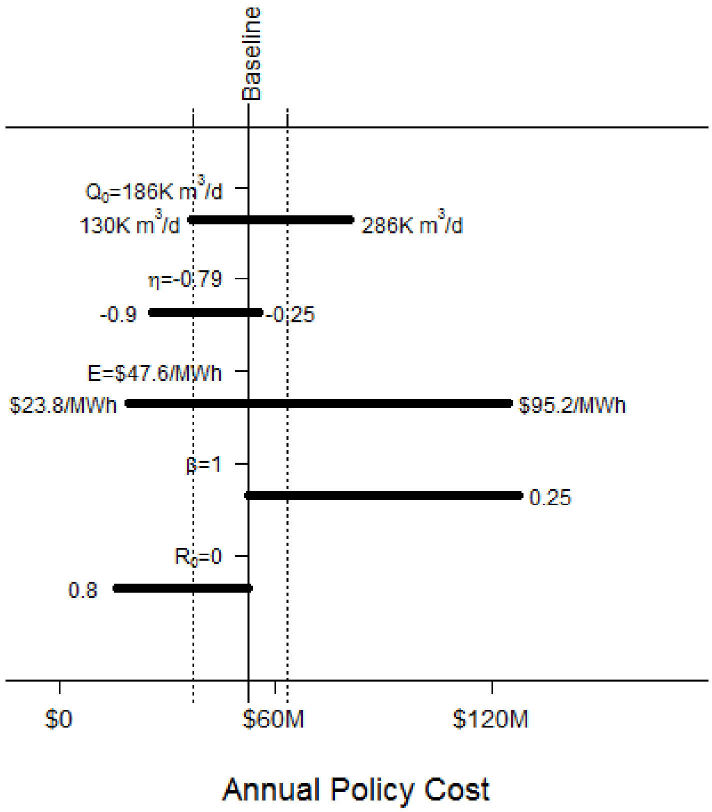


FIGURE 6
Title: Present value policy cost sensitivity analysis



APPENDIX

Energy-Cost Calculations

To calculate energy costs in Table 4, we followed the following steps:

1. In a perfect world with no energy losses in pumps and motors, and no other energy losses due to friction, pipe bends, valves, and fittings, you would use 9.81 Joules of energy to lift one litre of water up a height of one meter.[23]

2. This means that to lift 1 m3 of water up a height of one meter, you would need 9.81 kiloJoules (kJ) of energy.

3. 1 kiloWatt-hour (kWh) of electricity contains 3,600 kiloJoules (kJ) of energy.[24]

4. Statements 1 and 3 imply that to lift a m3 of water up a height of one meter, you would need 9.81/3,600 = 0.002725 kwh. This is so in a perfect, no-loss, world.

5. This means that to lift one m3/day up a height of "x" meters, the annual energy requirement would be:

$$Annual\ Energy\ Requirement = \frac{0.002725\ x*365}{1{,}000} =$$
$$= 0.000994625\ x \qquad (in\ MWH/(\text{m3/day}))$$

6. The above refers only to lifting energy requirements. Additionally, we have considered a "distance cost". We have assumed that the energy required to lift 1 m3 of water up a height of 1.2 meters is equivalent to the energy required to pump the same m3 of water to a distance of 1 kilometer.

7. Statements 5 and 6 imply that the annual energy requirement to pump a m3/day of water up to a height of "x" meters, at a distance of "y" kilometers, is equal to:

$$Annual\ Energy\ Requirement =$$
$$= 0{,}000994625\ \text{x} + 0{,}00119355\ \text{y} \qquad (in\ MWH/(\text{m3/day}))$$

8. Assuming an efficiency factor of 50%, the annual energy requirement can be written as:

$$Annual\ Energy\ Requirement = 0{,}00198925\text{x} + 0{,}0023871\ \text{y}\ (in\ MWH/(\text{m3/day}))$$

9. To this number, we add the desalination-plant annual energy cost, assumed to be equal to 2.4 MWH per m3/day.

10. We assumed an energy cost of 47.6 dollars per MWH, equal to the average clearing price in 2016 auction to supply regulated-clients energy needs for 20 years starting 2021.

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[23] See CottonInfo (2015): Fundamentals of energy use in water pumping. https://www.cottoninfo.com.au/sites/default/files/documents/Fundamentals%20EnergyFS_A_3a.pdf (Retrieved December 12, 2017).

[24] See CottonInfo (2015), op. cit.

11. We assumed a discount rate, to get a perpetuity value of water rights, of 6%, equal to the social rate of discount used by the Chilean Ministry of Social Development to evaluate public projects.

12. The above numbers imply an energy cost, in dollars, per m3/day of water rights (perpetual) equal to:

    $1{,}904 + 1.5781\ x + 1.8938\ y$

13. Table 4 uses the above formula in all cases, even though some projects involve seawater pumping. This is the case of Algorta Norte, Sierra Gorda, Esperanza and Michilla (partially). Today, common practice pumps desalinated water only.

Desalination Plant Data

Data in table 4 was initially collected from GWI (2012). Data was confirmed/updated using the following sources:

- Escondida/ El Coloso II was renamed "Escondida mega plant" and was **operational** in 2017: 216,000 m3/day capacity source: https://www.desalination.biz/news/0/Escondida-mega-plant-poised-to-produce-water-in-March/8648/; http://www.bechtel.com/projects/escondida-water-supply/
- Algorta Norte is an iodine producer and uses direct seawater; project was updated to **operational** (http://algortanorte.com/en/community/medio-ambiente/)
- Sierra Gorda utilizes seawater and was updated to **operational** (http://kghm.com/en/completion-seawater-pipeline-sierra-gorda-mine)
- Desaladora Sur is on hold but still intended to be built so was removed (http://www3.aguasantofagasta.cl/desalacion.html)

TABLE A1

Regression coefficient estimates for Figure 5

	Mining			
Year	Coeff.	Const.	SE Coeff.	SE Const.
1995	1.093	3.723	0.822	0.671
1996	1.804	3.799	1.055	0.780
1997	1.874	3.657	0.634	0.560
1998	1.645	4.105	0.428	0.413
1999	0.836	4.735	0.741	0.622
2000	2.437	5.075	1.300	0.871
2001	-3.899	5.343	0.510	0.510
2002	-0.370	6.026	0.295	0.295
2003	0.392	6.496	0.887	0.553
2004	-	5.003	-	0.482
2005	-	6.381	-	1.119
2006	1.350	5.735	0.356	0.356
2007	0.839	6.021	0.251	0.229
2008	0.876	5.880	0.269	0.253
2009	1.816	5.296	0.778	0.754
2010	-	6.668	-	0.310
2011	0.510	6.442	0.943	0.382
2012	0.113	6.643	1.276	0.139
2013	0.261	6.911	0.196	0.141
2014	-	7.055	-	0.075

Caption: This table is created by examining only trades from agriculture to mining and agriculture to agriculture. The log of the price of a per-unit water right is regressed on a dummy indicating a mining buyer, with coefficients allowed to vary for each year: $\ln(P_j) = \alpha_t + \gamma_t I_{mining} + u_j$. Reported standard errors are robust.

TABLE A2

Results of baseline and sensitivity analyses

Scenario	Pumped Water Offset (m3/day)	Water Transferred from Agriculture (m3/day)	Annual Cost (million US$)
Baseline	160,500	160,500	52.46
$Q_{ag} = 130K$	112,029	112,029	36.61
$Q_{ag} = 286K$	247,061	247,061	80.75
$\eta = -0.25$	87,017	87,017	25.51
$\eta = -0.90$	166,614	166,614	55.39
E=23.8	171,115	171,115	124.52
E=95.2	142,147	142,147	19.38
$\beta = .45$	371,973	167,388	127.57
$R_0 = 0.8$	95,904	95,904	15.80
$\hat{p}$ CI Low	172,044	172,044	63.21
$\hat{p}$ CI High	139,180	139,180	36.84

FIGURE A1

Distribution of prices (left) and log prices (right) of Agriculture-to-Agriculture sales 2004-2014

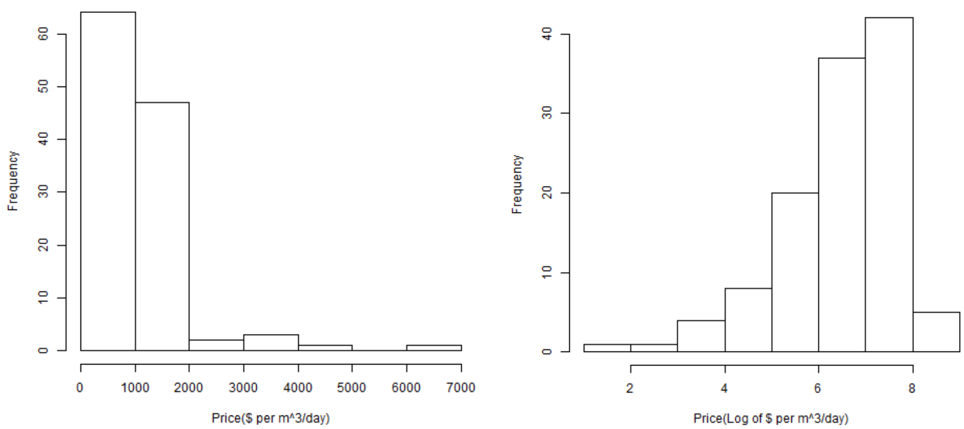

FIGURE A2

Desalinated water price function