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RESEARCH ARTICLE



Water option contracts for climate change adaptation in Santiago, Chile

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ABSTRACT

Climate change-induced extreme events pose an important challenge for urban water managers. In Santiago (Chile), the total cost of such events can be reduced by an option contract that sets ex ante water prices and water volumes to be traded when certain triggering conditions are met. This article discusses two types of option contracts: water leasing to trade water from agriculture to urban uses during droughts; and a savings option contract to reduce urban water consumption during short-term turbidity events. We find that water option contracts are flexible instruments that improve the distribution of hydrological risks.

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Option contracts; climate change; adaptation; water markets; urban water; Chile

Introduction: the impacts of climate change on water supply in urban areas

Water security has always been integral to the resilience of people living in cities. Water security is defined as the ability of hydrological systems to provide water for different human consumption needs and ecosystems while being able to manage the risks associated with water-related extreme events or contamination (for a discussion of the definitions of water security see Cook & Bakker, 2012). Water security is an important aspect of domestic water supply as it influences hygiene and therefore public health. At present, rapid population increase, urbanization, rising incomes, industrial expansion and growing water demands for the environment are increasing pressure on local water supplies. Nearly 80% of the world's population faces high levels of threat to its water security (Vörösmarty et al., 2010). In response, many cities around the world have increased investment in water management infrastructure for improved water production, distribution, recollection and wastewater treatment so as to provide greater water security. Water infrastructure also helps reduce the risks associated with extreme events such as floods and droughts.

Cities that are highly water-secure are characterized by a diversified water management strategy that includes a variety of water supply sources with associated storage

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facilities and distribution infrastructure that are managed publicly or privately. If correct incentives are in place for investment and operation, then the combination of infrastructure and management practices enables a cost-effective response to climate variability. Although developed and developing countries have made considerable progress in enhancing water security, climate change poses new threats to water security in the form of rising temperatures and reduced precipitation, increased water demand, and changes in the frequency of extreme events that impact total water supply (Major, Omojola, Dettinger, Hanson, & Sanchez-Rodriguez, 2011).

Several cities have designed a variety of adaptation strategies to the impacts of climate change on water security such as supply or demand management, improvements to infrastructure, and land-use planning, among others. However, these adaptation strategies face important decision-making difficulties due to the high levels of uncertainty involved (Adger, Huq, Brown, Conway, & Hulme, 2003). Although most scenarios project potentially high risks in future, uncertainty arises due to the differences between predicted impacts simulated using different global climate models (GCMs) under a variety of emission scenarios (Revi et al., 2014).

Policy makers who are principally concerned with avoiding disasters and ensuring water security adopt the safety-first principle in making decisions. Such an approach may lead to over-investment, and may also cause increases in the costs associated with guaranteeing water supply. In turn, it can lead to increases in tariff and affordability issues for vulnerable, low-income households. Even if uncertainty related to the estimates of long-term scenarios were solved (considered impossible by Kiparsky, Milman, & Vicuña, 2012), the present value of future benefits would probably not justify such large investments.

An alternative solution based on the existence of water markets is water options. Options have previously been proposed to mitigate the risks posed by drought (Brown & Carriquiry, 2007; Gómez-Ramos & Garrido, 2004; Michelsen & Young, 1993) but also to reduce transaction costs in water markets (Howitt, 1998; Wheeler, Garrick, Loch, & Bjornlund, 2013). More recently, options have been considered as a tool for tackling water scarcity and climate change within an integrated water management approach (Cubillo, 2010), for improving inter-basin transfers (Rey, Garrido, & Calatrava, 2016a), in combination with other water sources (Rey, Calatrava, & Garrido, 2016b), and used jointly with other financial instruments (Rey, Garrido, & Calatrava, 2016c).

Option contracts have been proposed as flexible mechanisms to deal with hydrologic extreme events such as droughts, but they have been implemented infrequently because of their institutional requirements in certain regulatory contexts. An early example of a proposal of water options between agriculture and urban uses was developed for the state of Colorado, USA, in 1993 (Michelsen & Young, 1993). Another proposal that explores the requirements for implementation was developed for California in a context of existing water markets (Jenkins & Lund, 2000). Other examples include Metro Manila in the Philippines, where option contracts were proposed in combination with insurance schemes (Brown & Carriquiry, 2007), and in Australia, where option contracts between agriculture and urban uses were designed to deal with climate change impacts (Leroux & Crase, 2010). In Spain, Rey et al. (2016a, 2016b) have proposed the use of options in the Segura basin, whereas Gómez-Ramos and Garrido (2004) and Cubillo (2010) have evaluated option contracts for urban water supply.

Using experimental economics, some authors have shed light on the effect of alternative water market designs such as options. In the United States, options were tested in California to manage drought risks, conceptualizing a dry-year option where water is transferred from existing rights holders to buyers with higher-value uses if drought conditions exist (Hansen, Kaplan, & Kroll, 2014a). Murphy, Dinar, Howitt, Rassenti, and Smith (2000) investigated the institutional changes needed for the implementation of options. In Spain, Garrido (2007a) used experiments to verify whether storage capacity helps in the implementation of options and other economic instruments for water management. He also highlighted the inefficiencies due to the implementation of market restrictions to protect urban uses. Some proposals have also discussed how these options should be valued (Cui & Schreider, 2009; Hansen et al., 2014a) looking at case studies in Australia (Leroux, Crase, & Wisener, 2007) and California (Hansen, Howitt, & Williams, 2014b; Tomkins & Weber, 2010).

Taking into consideration the institutional requirements for the adoption of water option contracts and the fact that their optimal design is context-specific, the objective of this article is to develop two economic instruments based on water option contracts as adaptation measures for water supply and sanitation (WSS) operators to ensure water security under extreme events associated with climate change. Such instruments are not new and have been adopted by WSS operators elsewhere, as in the Metropolitan Water District of Southern California for water leases in 2003 (Tomkins & Weber, 2010). We propose these economic instruments for the Maipo basin, which supplies water to the city of Santiago in Chile. In Santiago, WSS operators have achieved high levels of service coverage, providing continuous water supply that is only interrupted in exceptional circumstances such as earthquakes, infrastructure breakdown, and source supply failure. To design and evaluate a set of specific contractual solutions to offset the risk of urban water insecurity, a hydrologic and water resource model of the first section of the Maipo basin was developed. This model was used to assess the potential impacts of future climate scenarios on water supply to the city of Santiago when water option contracts are introduced as adaptation alternatives.

The possible increase in the frequency of extreme events due to climate change may increase the costs of providing water in Chile in future. As proposed in this article, a risk-based approach using water option contracts enables the design of cost-effective adaptation measures; the proposed option contracts for temporary use of water rights in the first section of the Maipo basin are a low-cost alternative that provides insurance against water shortages. Also, water option contracts can be easily developed in Chile because the dynamics of water markets are known, and existing contractual relations in the watersheds help reduce some of the institutional costs. Hence, the implementation of these risk management instruments in Chile does not require large regulatory changes, as has been the case in other contexts. Moreover, as Foster (2013), Hansen (2008) and Wheeler et al. (2013) show, they help reduce the negative impacts of increased investments in water infrastructure on water affordability. The article is structured as follows: following this introduction, the next section describes the basis of the proposed water option contracts. The third section describes the key features of the water supply system in Santiago and the projected impacts of climate change on this system. The fourth section describes the implementation of option contracts as

adaptation measures and presents the main results. A final section concludes the article and presents directions for future research.

Water option contracts for water supply as adaptation measures

This section presents the origins of water option contracts, and their use and advantages, and defines the water option contracts considered in this study. First, we review financial options and how this concept has been applied to water markets. Thereafter, we discuss the benefits brought by using water option contracts as insurance instruments and their potential complementarity with infrastructure investments. We conclude the section by presenting the water option contracts devised for our case.

A variety of risk-based tools developed in other contexts can be used to adapt to the negative impacts of climate change such as increasing urban water insecurity. Most of these tools are based on the principle that if there is heterogeneity between parties, then there are risk-hedging opportunities. For example, in an insurance contract, where risk is unevenly distributed across different users, each user contributes towards compensating for the impact when the event occurs. In climate change risks, too, studies have shown that the use of insurance to hedge extreme events is likely to increase (Falco, Adinolfi, Bozzola, & Capitanio, 2014).

Similarly, financial markets provide instruments based on an underlying asset to offer contracts that allow parties to manage associated risks. For example, futures contracts specify a purchase and sale agreement at a future time and at an established price. These contracts can be used to hedge risks associated with future price variations. In the same context, financial options specify a future transaction date and price but the contract is exercised at the will of only one of the parties. The price of an option contract depends on the underlying asset and its price, and is determined by the demand and supply of the option contracts. The price of the option contract also reflects potential future payoffs (Trigeorgis, 1996).

Option contracts have also been implemented outside financial markets by offering an alternative risk-management tool to deal with risks associated with other types of assets such as water (Howitt, 1998; Michelsen & Young, 1993). Risk-sharing economic instruments such as option contracts have the ability to deal with hydro-climatological risks (Brown & Carriquiry, 2007). But, more specifically, water option contracts are used to manage downside risks, i.e. risks related to low-water-security periods (Foster, 2013). Option markets are a proven drought-management mechanism (Hansen et al., 2014b), and therefore act as insurance against specific situations where lack of water threatens significant negative economic impacts. In the context of water rights markets, water option contracts can be seen as a midpoint between trading water rights and water volumes (spot market), thus having the potential to reduce conflicts due to permanent transfers of water between sectors such as farming and water utilities (Gómez-Ramos & Garrido, 2004).

It has been found that option contracts distribute transaction costs over a longer period, increase adaptation flexibility, and increase sellers' willingness to participate in water transactions (Wheeler et al., 2013). Options also allow greater gains from water right transactions (Hansen, 2008). Gains from water trade also increase when options can be traded, are more consistently distributed and shared (Hansen et al., 2014a), and may

involve greater welfare gains than permanent water transactions (Tomkins & Weber, 2010). Therefore, the introduction of such option contracts between sectors facilitates risk management of water shortages under exceptional or extreme events (Cubillo, 2010).

Farmers will not invest in new management tools unless the expected present value of innovations is greater than the potential cost (Carey & Zilberman, 2002; Rey et al., 2016c). Thus, the water price and the contract price must be sufficiently attractive to be considered by buyers and sellers, and eventually become a real instrument to manage the risks related to water unavailability. Water market stakeholders react to scarcity signals by using the most efficient tools available, whereas in rigid environments, over-exploitation of non-tradable rights predominates (Garrido, 2007b). Option markets offer an alternative to infrastructure investments to face increased water insecurity. However, they may also complement each other. For example, the existence of reservoirs may facilitate the implementation of options by allowing storage of optioned water. Under markets for permanent water rights as well as temporal leases, agents react to market signals and scarcity levels using storage facilities more efficiently than in the absence of this economic instrument (Garrido, 2007a). Moreover, a combination of water options and traditional drought-management measures may provide the most efficient approach (Gómez-Ramos & Garrido, 2004).

Experiences in countries with no water markets have shown the need for complex institutional arrangements to add new water risk management alternatives such as water options (Wheeler et al., 2013). Despite requirements such as complex institutional arrangements and a greater understanding of the dynamics of water markets (Wheeler et al., 2013), option contracts for temporary use of water rights have been evaluated as a cost-effective alternative to provide insurance against water shortages (Michelsen & Young, 1993). Given the relatively well-known dynamics of water markets, the case of Chile presents an opportunity to evaluate option contracts as adaptation to water insecurity.

To ensure water security in the Maipo basin in the face of the projected impacts of climate change, the proposed option contracts should be able to manage the risk of extreme events, i.e. water deficits or turbidity events, while enhancing resilience to such events so as to avoid failures that would increase associated costs. In this article, we propose water option contracts as adaptation instruments against the risk of urban water supply failures due to long-term reduction in precipitation (drought) and short-term high-turbidity events. In the first case, the proposed option contract is between the WSS (buyer) and agricultural users (sellers) so that the water supply operators can continue urban water supply at a lower cost. For high-turbidity events, the option contract is designed between the operator (buyer) and urban users (sellers) in the city with the objective of reducing water consumption to extend the duration of water supply. This latter water-saving option contract amounts to an interruptible service contract, where the provider has the right to stop providing water for a given time. Details of the implementation of these two instruments are provided after a description of the case and the modelling tool that tests the potential applicability of the instruments in the context of Santiago.

The case: urban water security in the city of Santiago, Chile

Water supply in Santiago: context and model development

The evolution of the water supply system in Chile is relevant to understand the economic instruments proposed here. In the 1980s, the water and sanitation sector in Chile was dominated by state-provided water supply. The inclusion of private operators began towards the end of this decade, in 1988. At present, six regions in Chile have completely privatized water and sanitation services and eight regions operate through concessions. In 2014, 95.5% of consumers were served by private companies, reaching 99.8% supply coverage. These concessions or privatized services have the obligation to maintain proper water supply service within their jurisdictions. To ensure that this service maintains the urban water consumer's well-being, a regulatory agency sets water tariffs, and approves the types of investments that are needed to maintain the quality of service while considering changes in demand or other conditions. Part of these investments consider the provision of enough water rights (surface or groundwater) to supply water under extreme climatic conditions, where an extreme event is defined using historic hydrological data.

To own enough water rights, private water supply companies have to procure them through water markets. Water markets have been one of the most distinguishing features of Chilean water policy since the implementation of the National Water Code of 1981. One of the key features of the Chilean case was the establishment of private water rights which are not sector-specific; the only potential for reallocation is through voluntary market transactions. Water markets have matured in the 36 years since the implementation of the 1981 Water Code. The frequency of market transactions has increased throughout the nation during the last decade, with increased frequency in relatively dry years. Recent analysis shows that the trading of water rights has occurred throughout Chile in 2005–2015. Agriculture accounted for over 60% of all these purchases and sales. Thus, trading of water rights in agriculture has been quite common during this period (Donoso, 2013; Hearne & Donoso, 2014).

It is important to recognize that there are some limitations in the operation of water right markets in Chile. The evidence suggests that water right markets are thin and have a large price dispersion (Cristi, Melo, & Donoso, 2014). This large price dispersion is partially explained by the lack of a price-revealing mechanism and asymmetric information on water right prices and transactions. This implies that each water right transaction is the result of a bilateral negotiation between an interested buyer and seller of water rights, where each agent's information, market experience and negotiating capacity are key (Cristi et al., 2014; Donoso, 2013; Donoso, Melo, & Jordan, 2014).

The city of Santiago is in one of the regions where water and sanitation services are privatized. Santiago is the most populated city in Chile and concentrates most of its wealth. Located beside the Andes, Santiago is home to nearly 7 million people, and produces around 40% of Chile's GDP. The Maipo River, followed by the Mapocho River and groundwater, are the main sources of water for residential and commercial consumers, including industry and agriculture, in the Maipo basin. Both the Maipo and Mapocho Rivers have a hydro-scheme typical of semi-arid mountainous areas – high rainfall variability during winters and a high concentration of water availability on the riverbed during spring and summer due to melting snowpack. Almost 90% of

the population receives water supply from a private WSS company, Aguas Andinas, which manages the concession and the corresponding water infrastructure. The remaining 10% is supplied through a municipal company, Servicio Municipal de Agua Potable y Alcantarillado, which operates mainly in the southern part of the city. Santiago shares water resources with other major users in the Maipo River basin, particularly the agricultural sector, which has nearly 140,000 hectares of irrigated high-value crops (fruits and vegetables) and is the largest water consumer in the area. Other users in the basin are hydroelectricity, copper production, tourism, and recreational activities (Figure 1).

As part of a research project called MAPA (Maipo: Plan de Adaptación), a hydrologic and water resource model was developed in consultation with a number of stakeholders in the Maipo basin. The objective behind the development of the model was to create a tool that could be used to assess the potential impacts of future climate scenarios and study the effectiveness of adaptation measures designed to confront these impacts. The model was developed using the Water Evaluation and Planning System (WEAP) platform (Yates, Sieber, Purkey, & Huber Lee, 2005a; Yates, Sieber, Purkey, Huber Lee, & Galbraith, 2005b) and corresponds to a refinement of the model used by Meza, Vicuña, Jelinek, Bustos, and Bonelli (2014). Here, we present some details of the model construction in relation to the features and operation of the Aguas Andinas WSS system.

The system is complex because it has different types of raw water sources, including surface water intakes that supply the treatment plants, and groundwater is also pumped in different areas of the city. The production and demand areas for surface water

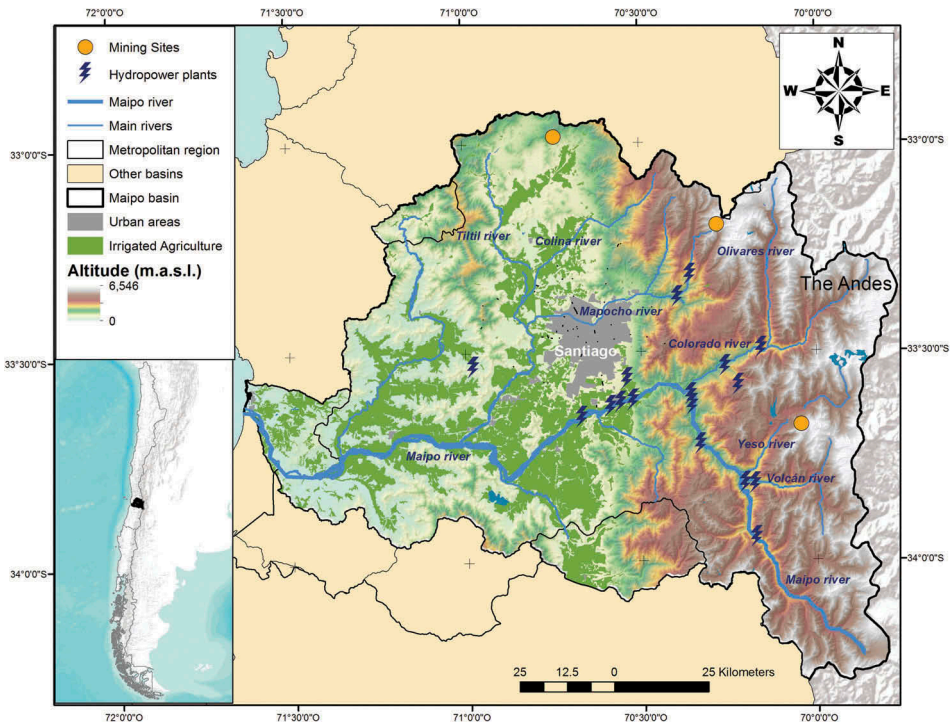


Figure 1. Maipo River basin and water users.

resources belong to three hydrographic systems, the Maipo River, the Mapocho River and the Quebrada Ramon system, which supply more than 150 sectors of water demand through a complex distribution system with different operational rules.

The average amount of water produced by the system using surface water was 574 Mm³/y in 2005–2012. There was also groundwater pumping in certain demand sectors, corresponding to a volume of 56 Mm³/y. The raw water is treated in 12 different treatment plants, three of them in the Maipo system, eight in the Mapocho system, and one in the Quebrada Ramon system.

Water is distributed from these treatment plants to hundreds of small storage tanks in the city and finally to over 1,500,000 consumers, including households, industries, municipalities, and businesses. A simplified diagram of the connections between raw water supplies, water treatment plants and final consumers is presented in Figure 2. This representation was elaborated using the WEAP model and information supplied by Aguas Andinas. The WEAP modelling platform allows us to develop a supply-demand water balance for the city using weekly time steps.

Our focus is on a portion of the system that is fed by the Maipo River (the Maipo system) and that is responsible for more than 85% of the total water production in the city. The main features of the Maipo system are presented in detail in insets in Figure 2. The Maipo system supplies water for 16 of the 23 city-wide distribution sectors via two raw water treatment plants (RWTP1 and RWTP2) from three main sources of water: the Laguna Negra aqueduct, the El Yeso reservoir, and the water rights that Aguas Andinas holds in the Maipo River. There are rules of operation, especially in terms of

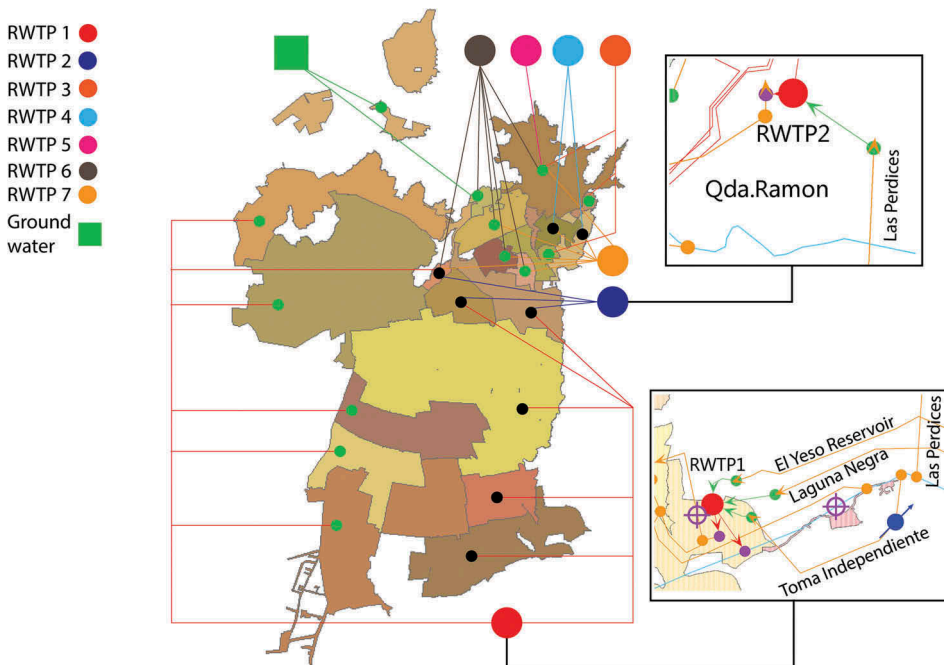


Figure 2. Schematic diagram of the Aguas Andinas water supply/treatment/distribution system in Santiago.

reservoir operation, in this system that define the quantity of water that can be extracted to fulfil the needs of water production from both treatment plants.

The first source of water used in the Maipo system corresponds to water rights/shares owned by Aguas Andinas. The first section of the Maipo River has a total of 8133 water rights. Each water right holder can extract the relative flow passing in the Maipo River corresponding to their proportional amount of water rights, up to a maximum volumetric flow rate. Aguas Andinas owns almost a quarter (1917) of these water rights. Agriculture users own the remaining rights.

A second source of water corresponds to an aqueduct coming from a natural lake (Laguna Negra), fed by the lake's overflows and filtrations. Finally, when surface water from the Maipo River and the Laguna Negra reservoir are insufficient, Aguas Andinas uses water stored in El Yeso reservoir. Water can be stored in this reservoir whenever water flows in the Maipo exceed the demand from all users (urban and agriculture). In addition to these water supply needs, discharges from the reservoir can be used to increase the available storage before the snowmelt season.

The following text and figures present some system details from a hydrologic and operational perspective. The calibration of the hydrologic parameters (snow dynamics, soil) was carried out by adjusting some of snow dynamic and soil parameters (hydraulic conductivity, storage capacity) of the hydrological model incorporated in WEAP. The 1985–2009 period was selected as the calibration period due to the availability of good-quality measurements for most of the rainfall and fluvimetric stations in the basin. [Figure 3](#) shows the result of the model calibration for the same period at one measurement point, just above the main water discharge to supply water to the treatment facility: Maipo in Manzano. As can be seen, the model correctly represents both the inter-annual distribution and the seasonality of flow at weekly intervals for the period

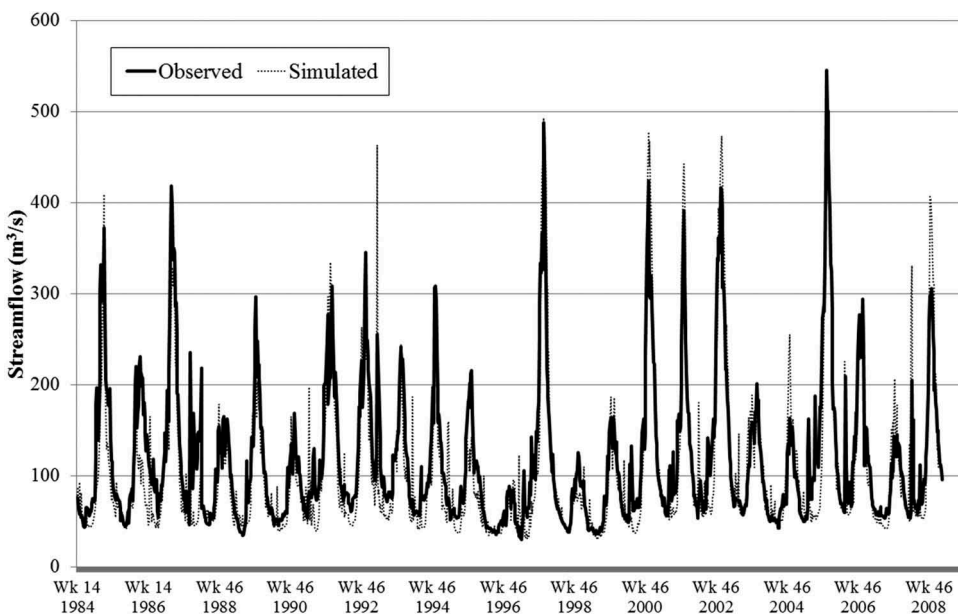


Figure 3. Observed and simulated streamflow at Maipo en el Manzano.

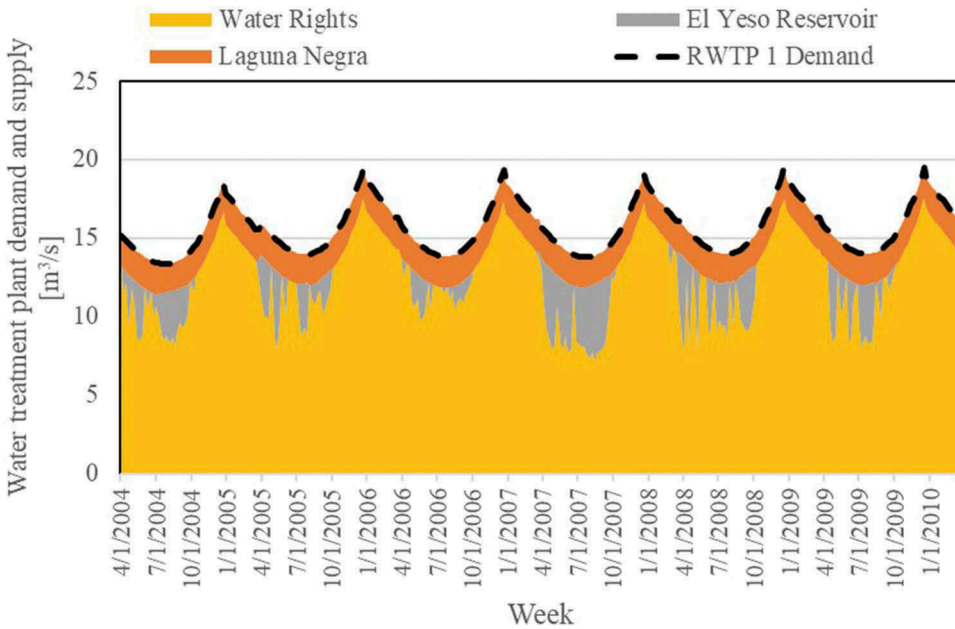


Figure 4. RWTP1 demand and supply delivered by different sources.

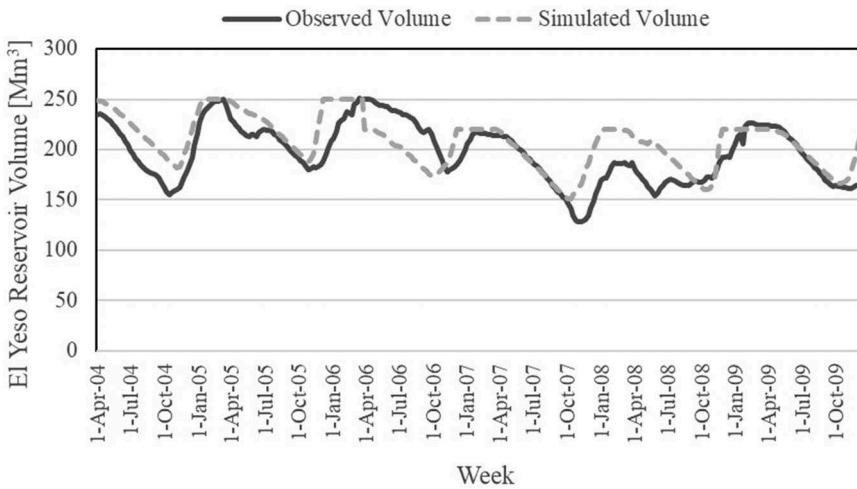


Figure 5. Comparison between observed and simulated stored volume in the El Yeso Reservoir.

considered, with a Nash-Sutcliff coefficient of 0.80. In addition to hydrological calibration, the model can represent the different sources of water that supply the production needs of RWTP1 (Figure 4). Finally, as Figure 5 shows, reservoir behaviour, which compares the observed and simulated operations of the El Yeso reservoir, is also well characterized by the model.

Climate change impacts on potable water supply in Santiago

Although the potable water system of Santiago has been designed to maintain high levels of service (considering both continuity and quality), it is subject to significant threats from climate variability, climate change and population growth. Studies indicate that climate change could reduce the annual flows in the Maipo River by 10–40% (Meza et al., 2014). They anticipate periods of minimum water flow of between one and four weeks, depending on the scenario under consideration. These projected impacts are related to the predicted increases in temperature and reductions in rainfall that are already observed in the region (Vicuna, Alvarez, Melo, Dale, & Meza, 2014). For the Maipo basin, the study by Meza et al. (2014) shows that future changes in climatic conditions range between –20% to 0 and –40% to –10% change in precipitation for an early (2010–2040) and late (2070–2100) time period, respectively, and between 0.5–1 °C and 1.5–3.5 °C increase in temperature for the two time periods, considering uncertainty in models and emission scenarios. The hydrologic signature of these climatic scenarios show a change in water availability similar in magnitude to the change in precipitation, but also the increase in temperature translates into an earlier hydrograph timing on the order of 5 to 30 days, depending on the time period and emission scenario.

Using the WEAP model described earlier, we studied the potential impacts of climate change on the ability of the Maipo system to sustain its current operation performance. The approach to develop future climate scenarios is explained in Chadwick, Gironás, Vicuña, Meza and McPhee (in review), details of which are beyond the scope of this article. The key elements of that approach include consideration of a number of emission scenarios (scenarios RCP 4.5, 6.0 and 8.5) and GCMs considered in the CMIP5 inter-comparison exercise. The latter degree of uncertainty is represented by percentiles of potential changes in key climate variables (temperature and precipitation). Each scenario is then represented by the corresponding emission scenario and the percentile change in precipitation and temperature among the distribution of GCM outputs.

Figure 6 presents the synthesis of the impacts associated with these scenarios. An impact in this case is defined as any week when the sum of all the potential water supplies, explained earlier, is unable to meet the current operational expectations of the water treatment plants that are fed by the Maipo River. The variable presented in Figure 6 corresponds to the sum of weekly unsupplied flows for each climate change scenario for the period 2010–2050. One of these scenarios is RCP45 Pp50_T50, which corresponds to radiative forcing (GHG emission) of 4.5 W/m² and selection of the median (50th percentile) of future projections of precipitation and temperature. This is one of the scenarios that do not alter the current operations of the Maipo system and hence shows no failures in 2010–2050. However, if we consider a scenario with higher emissions (radiative forcing of 6 W/m²) but with similar likelihood among climate model projections, i.e. RCP 60 Pp50_T50, then there are failures in the system, as there is at least one week when supplies from the Maipo system are unable to meet the needs of production of the treatment plants that serve a large portion of the population in the city. In summary, 11 of the 15 scenarios (73%) have these failure conditions. The worst of these scenarios has an accumulated weekly unsatisfied supply of over 30 m³/s.

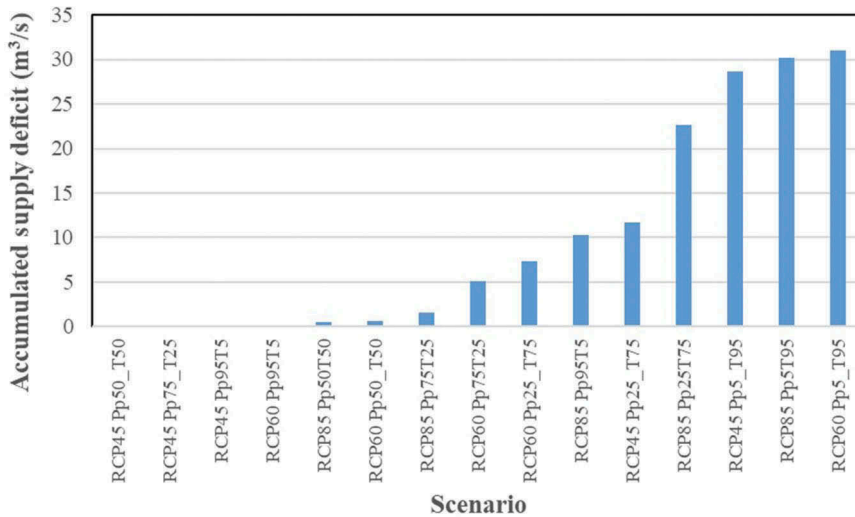


Figure 6. Water supply deficit by climatic scenario.

Note. Climate scenarios are given acronyms of the form RCP Scenario Precipitation Exceedence Percentile_Temperature Exceedence Percentile. For example, scenario RCP60 Pp25_T75 corresponds to the 25th percentile of precipitation projections and the 75th percentile of temperature projections among all GCM outputs run with the Representative Concentration Pathway with a radiative forcing of 6.0 W/m².

Changes in the frequency of extreme weather events could also affect water supply conditions, not because of lack of precipitation but because of increased turbidity associated with sediments eroded from the mountains. Under these conditions and depending on the concentration (and duration) of sediments, water supply intakes fail to extract water from the river. In these cases, the city is supplied from internal resources (groundwater) and water stored in multiple small accumulation reservoirs in the company service area. Higher turbidity associated with extreme weather has been a critical issue in the last five years, triggering investments in infrastructural measures to augment the amount of treated water that is stored.

The next section studies the application of two proposed water option contracts that can be used to reduce the economic costs of both types of risks to water supply: long-term droughts and short-term high-turbidity events. During long-term droughts and turbidity events special measures taken by water utilities or water authorities, like additional pumping, emergency infrastructure, and water distribution by trucks, imply higher costs of water provision. Also, when drinking water provision is interrupted, residential water users incur additional costs to secure water from other sources, and to find alternative solutions to water sanitation services.

Implementation of water option contracts for future water supply reliability for the city of Santiago

The option contracts discussed in this study are intended to be an adaptation measure for two city-specific impacts of climate change: the risk of water supply failures due to long-term reduction in precipitation (drought) and due to short-term high-turbidity events. In

the first case, an option contract is proposed between Aguas Andinas and the agricultural users of the Maipo River basin so that they can comply with urban supply at the lower cost. In the second case, the contract is between Aguas Andinas and urban users, with the objective of reducing water consumption to extend the duration of water supply.

Water lease option contract

In the case of drought-related shortages for the city of Santiago, an option contract of water leasing is proposed between agricultural and urban uses. The option contract for water between agriculture in the Maipo River basin and the city of Santiago is designed to work as temporary leases of water during one season. To test the option contract within the studied climate change scenarios, we propose two different conditions that trigger the execution of the contract by the WSS. The two cases correspond to two levels of water storage in the Yeso reservoir: 55 and 110 million m³ (corresponding to around 25% and 50% of the total reservoir capacity). These two triggers are tested with five different pre-established amounts of water to be purchased by the water company once the trigger is met. These correspond to 100, 400, 700, 1000 and 2000 shares that are transferred from farmers to Aguas Andinas. As Aguas Andinas currently holds around 2000 shares, the final amount after the transfer of shares will result in the doubling of the shares held by the company. The combination of all these different contract designs is tested for the 15 climate change scenarios, giving us a complete picture of the relative convenience of option contracts as an adaptation measure. Once the trigger is met, water is transferred from agriculture to the water company, with the right to use the water if needed, until the end of the season.

If the triggering volume is increased from 55 to 110 Mm³, then maximum and average unmet supplies are reduced compared to the original triggering volume. Unlike the previous case, it is also possible to avoid failures for all potential climate change scenarios. Interestingly, the design that allows this performance needs to consider that 1000 shares are transferred every time the contract is triggered. The total number of shares transferred is slightly above 870,000, but it occurs over 870 weeks (42% of the total number of weeks). So, having a higher trigger volume means the option is used more often but potentially results in lower costs and higher benefits.

Option contracts must set water prices and a premium. To assess the options presented here, a comparison of the expected benefits to farmers with and without the option contract is necessary. Similarly, the cost of procuring the contract should not be greater than the opportunity cost of water. From the perspective of the water company, the costs of the option contract must be lower than the costs of a possible climate change extreme event. Thus, the real viability of this instrument will depend on the existence of an ex ante water price and premium that improve welfare for both parties. Gómez-Ramos and Garrido (2004) developed a methodology based on a dynamic stochastic discrete time model to find the premium required to compensate the farmer. This assessment falls beyond the scope of the work presented here. To evaluate the viability of the option, Gómez-Ramos and Garrido simulate the option contract showing that for the city of Seville this instrument is more cost-effective. In our case, future work should model sellers' willingness to supply such contracts. At present, the only evidence of the viability of such option contracts is their existence between

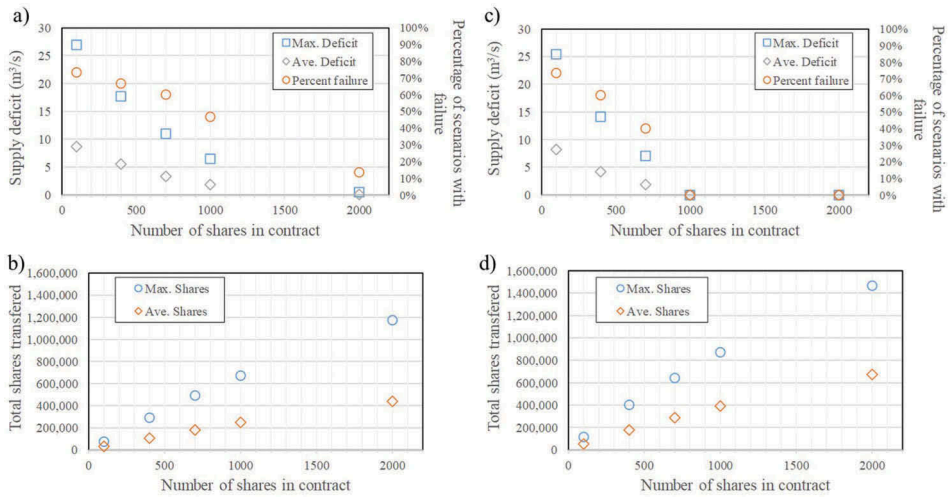


Figure 7. Results of the application of different option lease contracts for water supply reliability. Panel (a) presents the maximum and average supply shortfall taking into consideration all climate scenarios, and percentage of scenarios with shortfall associated with different numbers of shares included in the option contract, with a trigger of 110 Mm³ of water stored in the Yeso reservoir. Panel (b) presents the maximum and average number of shares that are transferred from agriculture to Aguas Andinas over the whole period of simulation. Panels (c) and (d) present the same results as in the above cases but considering contracts with a trigger of 55 Mm³.

farmers and a water utility in the Maipo River, although the exact terms of these contracts are not public.

Figure 7 shows the results of the application of the different design configurations (trigger and number of shares). As seen in panel (a), the implementation of a contract with 100 shares and a trigger of 55 Mm³ does not reduce the number of scenarios with failure (73%), and has little impact on the amount of failures (maximum failure of 27 vs 31 m³/s). As the number of shares is increased, the scenarios with failures and the amount of failures are reduced. However, even under the most extreme contract conditions, where 2000 shares are transferred each time, the trigger is met, and two scenarios still fail before the end of the season, but with much smaller maximum unmet flows (0.5 vs 31 m³/s). However, there is a cost associated with the execution of the contract, as shown in panel (b), which presents the maximum and average total number of shares that are transferred in all events when the contract is triggered in 2010–2050. In the case where the contract is designed to transfer 2000 shares each week under the worst climate change scenario, the number of shares that are transferred is nearly 1,200,000, and the contract is in execution for 600 weeks (30% of the total number of weeks in the simulation period).

Water savings option contract

Option contracts of the water savings type are proposed for short-term climate change events. The main rationale of the contract is based on the possibility of reducing water

consumption of large water users to provide extended potable water service, and avoid water restrictions that impose prohibitive costs.

In the case of a high-turbidity event, the water saving option contract has the same objective of reducing the costs associated with the occurrence of the event while avoiding expensive infrastructural investments. In this case, the contract would be between the water company and large water consumers in the city such as municipalities or industries. Although the analysis in this case is similar to the aforementioned case, there are key differences. The *force majeure* event is comparatively short-term and therefore must be solved with an option contract that triggers a decrease in consumption by certain users, so these users must be within the distribution network of the city. The restriction would also be shorter in duration.

The instrument involves the participation of large consumers that can contribute sufficient water to the system, thereby allowing municipalities, city parks, and industries to participate in these option contracts. For this study, city parks are considered as an example to demonstrate how the option contract could be a useful adaptation measure. As landscape irrigation can vary from 40% to 70% of household water use in many cities (Hilaire et al., 2008), they present an opportunity for the case of Santiago. Similar cases have been tested in California using dry-year option contracts to reduce lawn irrigation (Lund, 1999), but they were designed for long-term events such as droughts.

The specific option contract proposed here provides an example of the potential benefits of such an instrument. The contract may be triggered at the time of the extreme event when potable water systems still have available supplies (e.g., storage within the city) before restrictions are imposed that request zero consumption of water. In the example studied here, on payment of compensation, city parks and green areas stop irrigation during the established period, increasing autonomy for Aguas Andinas. The reduction in total costs is transferred from urban water users to city parks, which are likely to have a lower willingness to pay for security of water supply for shorter durations. This contract can lower the social costs of the turbidity event instead of imposing restrictions. If the reduction in water consumption is sufficiently large, then the water company can provide continuous potable water supply for an extended duration when extreme events occur, avoiding water restrictions such as the ones imposed during the summer of 2013.

To illustrate how water savings from large consumers may help in providing extended service for the city of Santiago in an extreme event, we used data on irrigation water consumption by the city's parks and green areas. This was supplemented by data provided by Aguas Andinas and satellite imagery analysis to determine the presence of parks and green spaces. Figure 8 shows the amount of water needed to irrigate the various parks and green spaces under the different municipalities in Santiago. If a municipality decides to participate in the option contract and the trigger is met, then the amount of water saved could extend the length of time the city could maintain service without extracting additional water from the river. As shown in Figure 9, stopping irrigation of these green areas provides enough water to extend water service for Santiago City for short periods (20 minutes per event maximum). However, the inclusion of other relevant consumers can help achieve longer periods of water supply autonomy.

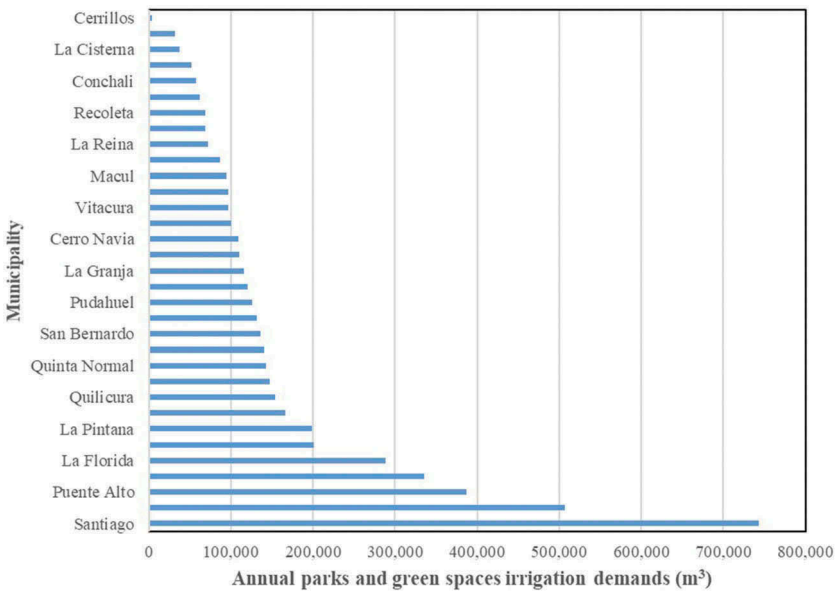


Figure 8. Average annual irrigation water consumption in city parks and green spaces by municipality between 2010 and 2014.

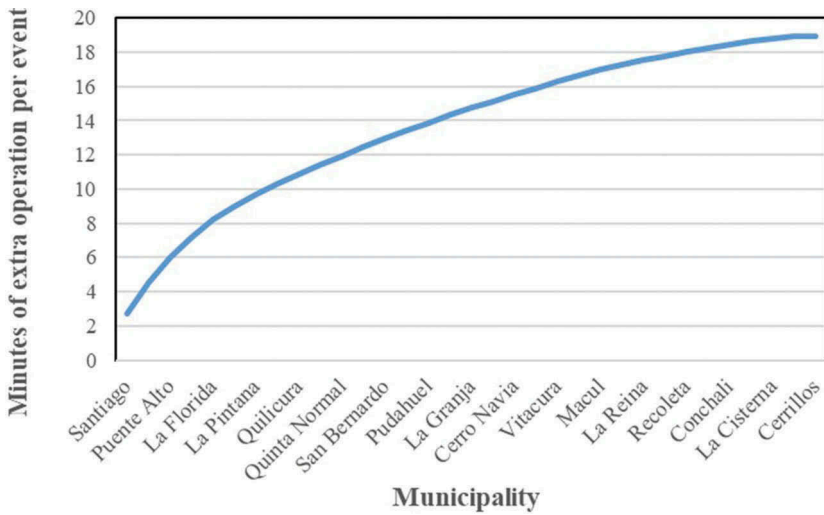


Figure 9. Length of time of extended operation autonomy when municipalities participate in option contracts to reduce water consumption.

Conclusions and policy recommendations

Climate change is likely to affect urban water supply around the world, including in Santiago, Chile. Quantification of the impacts of climate change in Santiago is difficult due to high uncertainty about short-term climate variability and the valuation of its

economic impacts. However, such uncertainty should not prevent the development of adaptation measures to reduce potential impacts and make the city less vulnerable.

In such uncertain contexts, expensive measures may prove inefficient if the worst climate scenarios do not occur; on the other hand, cheaper measures will be adopted only if they are cost-effective. Thus, the adaptive approach in this study is the first attempt to avoid new large reservoir infrastructure in Santiago by proposing new management alternatives based on the characteristics of the existing WSS. In so doing, we have responded to the need to find an acceptable solution between the costs of building more complex systems and the costs involved with policies aimed at market equilibrium and water management (Starkey, Dye, Read, & Read, 2012).

The use of water management alternatives such as option contracts may require complex institutional arrangements as well as a greater understanding of the dynamics of water markets (Wheeler et al., 2013). Nonetheless, option contracts for temporary use of water rights appear to be a low-cost alternative that provides insurance against water shortages (Michelsen & Young, 1993). Option contracts can be easily developed and tested as an adaptation measure in Chile since the dynamics of water markets are known, and existing contractual relations in the watersheds can reduce some of the institutional costs.

The cost of adaptation measures should reflect the scarcity value of water. The success of option contracts as an adaptation measure lies in the exchange of water rights from less vulnerable water consumers to more vulnerable ones during extreme events. This measure utilizes the mechanism of risk sharing and distributes the costs among various consumers, which results in a lower total cost for society.

This study has evaluated how option contracts have the potential to reduce the impacts associated with extreme events without involving complex *ex ante* decision-making processes regarding the occurrence of these climate change impacts. Option contracts have been presented as inexpensive, *ex ante* economic instruments that enable optimal distribution of hydrological risks. The implementation of these instruments does not require large regulatory changes. Moreover, the implementation of option contracts involves the analysis of management processes that might enable participants to be interested in future contracts at convenient prices.

The ability to deal with reduced water security in the face of climate change risks can be viewed as an opportunity to improve water management practices. Considering that the main water users in any system have distinct and differentiated levels of water security, more efficient solutions can be found by reallocating water rights among them with smaller cost increases. If each water user has a different level of willingness to pay for safe supply, allocation mechanisms can be designed as tools to reallocate water from those who have a lower willingness to pay to those that require higher levels of water security.

Based on the available data, this study shows how option contracts of both the water leases type and the water savings type may provide enough water to prevent major damages due to climate change-related events. The proposal described for the city of Santiago, which mainly depends on the Maipo River basin and the services of a private concessionaire, leads us to conclude that option contracts combine the elements of both proactive and reactive adaptation measures, and can be a viable tool for public-private adaptation.

Future research should deal with some of the limitations of the present work. Specifically, assessment of the economic benefits and costs for both agents participating

in the option contract needs to be undertaken. The ability of the water right market structure and water utility regulatory institutions to accommodate a water option contract strategy to reduce future climate change uncertainty also remains to be studied.

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References

- Adger, W. N., Huq, S., Brown, K., Conway, D., & Hulme, M. (2003). Adaptation to climate change in the developing world. *Progress in Development Studies*, 3(3), 179–195.
- Brown, C., & Carriquiry, M. (2007). Managing hydroclimatological risk to water supply with option contracts and reservoir index insurance. *Water Resources Research*, 43W11423. doi:10.1029/2007WR006093
- Carey, J. M., & Zilberman, D. (2002). A model of investment under uncertainty: Modern irrigation technology and emerging markets in water. *American Journal of Agricultural Economics*, 84(1), 171–183.
- Chadwick, C., Gironás, J., Vicuña, S., Meza, F., & McPhee, J. (in review). Statistical pre-analysis as an alternative to GCM ensembles to account for uncertainty and simplify hydrological studies. *Journal of Hydrometeorology*.
- Cook, C., & Bakker, K. (2012). Water security: Debating an emerging paradigm. *Global Environmental Change*, 22(1), 94–102.
- Cristi, O., Melo, O., & Donoso, G. (2014). Análisis Estimación Del Precio Privado De Los Derechos De Aprovechamiento De Aguas (Final Report). Santiago, Chile: Comisión Nacional de Riego (CNR). Retrieved from https://www.researchgate.net/publication/320068177_Analisis_Estimacion_Del_Precio_Privado_De_Los_Derechos_De_Aprovechamiento_De_Aguas_de_Chile
- Cubillo, F. (2010). Looking for efficiency through integrated water management between agriculture and urban uses. *Water Science & Technology: Water Supply*, 10(4), 584–590.
- Cui, J., & Schreider, S. (2009). Modelling of pricing and market impacts for water options. *Journal of Hydrology*, 371(1), 31–41.

- Donoso, G. (2013). The evolution of water markets in Chile. In J. Maetsu (Ed.), *Water trading and global water scarcity: International perspectives* (pp. 110–128). New York, NY: RFF Press.
- Donoso, G., Melo, O., & Jordan, C. (2014). Estimating water rights demand and supply: Are non-market factors important? *Water Resources Management*, 28, 4201–4218.
- Falco, S. D., Adinolfi, F., Bozzola, M., & Capitanio, F. (2014). Crop insurance as a strategy for adapting to climate change. *Journal of Agricultural Economics*, 65(2), 485–504.
- Foster, B. T. (2013). *Managing water supply related financial risk in hydropower production with index-based financial instruments* (Master's thesis). Department of Environmental Sciences and Engineering in the Gillings School of Global Public Health, University of North Carolina at Chapel Hill. Retrieved from http://www.hydrofoundation.org/uploads/3/7/6/1/37618667/foster_thesis.pdf
- Garrido, A. (2007a). Designing water markets for unstable climatic conditions: Learning from experimental economics. *Review of Agricultural Economics*, 29(3), 520–530.
- Garrido, A. (2007b). Water markets design and evidence from experimental economics. *Environmental and Resource Economics*, 38(3), 311–330.
- Gómez-Ramos, A., & Garrido, A. (2004). Formal risk-transfer mechanisms for allocating uncertain water resources: The case of option contracts. *Water Resources Research*, 40(1–11), W12302.
- Hansen, K., Howitt, R., & Williams, J. (2014b). An econometric test of water market structure in the Western United States. *Natural Resources Journal*, 55(1), 127–152. <http://www.jstor.org/stable/24889752>
- Hansen, K., Kaplan, J., & Kroll, S. (2014a). Valuing options in water markets: A laboratory investigation. *Environmental and Resource Economics*, 57(1), 59–80.
- Hansen, K. M. (2008). *Contractual mechanisms to manage water supply risk in the western United States* (Doctoral dissertation). University of California, Davis. ProQuest Dissertations Publishing. Retrieved from <https://search.proquest.com/openview/447348a20289ea29f44ab011db2e7908/1?pq-origsite=gscholar&cbl=18750&diss=y>
- Hearne, R., & Donoso, G. (2014). Water markets in Chile: Are they meeting needs? In W. Easter & Q. Huang (Eds.), *Water markets for the 21st century: What have we learnt?* (pp. 103–126). Dordrecht, Netherland: Springer-Verlag.
- Hilaire, R. S., Arnold, M. A., Wilkerson, D. C., Devitt, D. A., Hurd, B. H., Lesikar, B. J., & Morris, R. L. (2008). Efficient water use in residential urban landscapes. *Hort Science*, 43(7), 2081–2092.
- Howitt, R. E. (1998). Spot prices, option prices, and water markets: An analysis of emerging markets in California. In K. W. Easter, M. W. Rosegrant, & A. Dinar (Eds.), *Markets for water. Natural resource management and policy* (Vol. 15, pp. 119–140). Boston, MA: Springer-Verlag.
- Jenkins, M. W., & Lund, J. R. (2000). Integrating yield and shortage management under multiple uncertainties. *Journal of Water Resources Planning and Management*, 126(5), 288–297.
- Kiparsky, M., Milman, A., & Vicuña, S. (2012). Climate and water: Knowledge of impacts to action on adaptation. *Annual Review of Environment and Resources*, 37(1), 163.
- Leroux, A., & Crase, L. (2010). Advancing water trade: A preliminary investigation of Urban-Irrigation options contracts in the Ovens basin, Victoria, Australia. *Economic Papers: A Journal of Applied Economics and Policy*, 29(3), 251–266.
- Leroux, A., Crase, L., & Wisener, T. (2007). *Options contracts for managing inter-sectoral water trade: A preliminary investigation of the feasibility of urban-irrigation options contracts in the Ovens Basin, Victoria, Australia*. Paper presented at the Australian Agricultural and Resource Economics Society Annual Conference. Retrieved from <http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=78882EA700157C30E24E139EA6497205?doi=10.1.1.581.1921&rep=rep1&type=pdf>
- Lund, J. R. (1999). Drought management and water transfer programs: Recent developments and research in California. In E. Cabrera & J. García-Serra (Eds.), *Drought management planning in water supply systems. Water science and technology library* (Vol. 32, pp. 242–260). Dordrecht: Springer.

- Major, D. C., Omojola, A., Dettinger, M., Hanson, R. T., & Sanchez-Rodriguez, R. (2011). Climate change, water, and wastewater in cities. In C. Rosenzweig, W. D. Soleck, S. A. Hammer, & S. Mehrotra (Eds.), *Climate change and cities: First assessment report of the urban climate change research network* (pp. 113–143). Cambridge, UK: Cambridge University Press. Retrieved from https://www.researchgate.net/profile/Roberto_Sanchez-Rodriguez/publication/285117257_Climate_change_water_and_wastewater_in_cities/links/585caf3408ae8fce48fad58d/Climate-change-water-and-wastewater-in-cities.pdf
- Meza, F. J., Vicuña, S., Jelinek, M., Bustos, E., & Bonelli, S. (2014). Assessing water demands and coverage sensitivity to climate change in the urban and rural sectors in central Chile. *Journal of Water and Climate Change*, 5(2), 192–203.
- Michelsen, A. M., & Young, R. A. (1993). Optioning agricultural water rights for urban water supplies during drought. *American Journal of Agricultural Economics*, 75(4), 1010–1020.
- Murphy, J. J., Dinar, A., Howitt, R. E., Rassenti, S. J., & Smith, V. L. (2000). The design of “Smart” water market institutions using laboratory experiments. *Environmental and Resource Economics*, 17(4), 375–394.
- Revi, A., Satterthwaite, D., Aragon-Durand, F., Corfee-Morlot, J., Kiunsi, R. B. R., Pelling, M., ... Solecki, W. (2014). Urban areas. In C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, ... L. L. White (Eds.), *Climate change 2013, impacts, adaptation, and vulnerability—Working Group II Contribution to the fifth assessment report of the intergovernmental panel on climate change*. New York, NY: Cambridge University Press.
- Rey, D., Calatrava, J., & Garrido, A. (2016b). Optimisation of water procurement decisions in an irrigation district: The role of option contracts. *Australian Journal of Agricultural and Resource Economics*, 60(1), 130–154.
- Rey, D., Garrido, A., & Calatrava, J. (2016a). An innovative option contract for allocating water in inter-basin transfers: The case of the Tagus-Segura transfer in Spain. *Water Resources Management*, 30(3), 1165–1182.
- Rey, D., Garrido, A., & Calatrava, J. (2016c). Comparison of different water supply risk management tools for irrigators: Option contracts and insurance. *Environmental and Resource Economics*, 65(2), 415–439.
- Starkey, S. R., Dye, S., Read, E. G., & Read, R. A. (2012). *Stochastic vs. deterministic water market design: Some experimental results*. Paper presented at the 4th IEEE and Cigré International Workshop on Hydro Scheduling in Competitive Markets, Bergen, Norway. Retrieved from http://www.mang.canterbury.ac.nz/research/emrg/docs/conf_papers/7%20Starkey%20et%20al%202012%20Stochastic%20vs%20Deterministic%20Water%20Market%20Design%20Paper.pdf
- Tomkins, C. D., & Weber, T. A. (2010). Option contracting in the California water market. *Journal of Regulatory Economics*, 37(2), 107–141.
- Trigeorgis, L. (1996). *Real options: Managerial flexibility and strategy in resource allocation*. Cambridge, MA: The MIT press.
- Vicuña, S., Alvarez, P., Melo, O., Dale, L., & Meza, F. (2014). Irrigation infrastructure development in the Limarí basin in central Chile: Implications for adaptation to climate variability and climate change. *Water International*, 39(5), 1–15.
- Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., ... Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature*, 467(7315), 555–561.
- Wheeler, S., Garrick, D., Loch, A., & Bjornlund, H. (2013). Evaluating water market products to acquire water for the environment in Australia. *Land Use Policy*, 30(1), 427–436.
- Yates, D., Sieber, J., Purkey, D., & Huber Lee, A. (2005a). WEAP21: A demand, priority, and preference driven water planning model: part 1, model characteristics. *Water International*, 30(4), 501–512.
- Yates, D., Sieber, J., Purkey, D., Huber Lee, A., & Galbraith, H. (2005b). WEAP21: A demand, priority, and preference driven water planning model: Part 2, aiding freshwater ecosystem service evaluation. *Water International*, 30(4), 487–500.