Incorporating climate change adaptation strategies in urban water supply planning: the case of central Chile

Sebastián Bonelli, Sebastián Vicuña, Francisco J. Meza, Jorge Gironás and Jonathan Barton

ABSTRACT

Water management systems have been typically designed and operated under the assumption of stationarity. This assumption may no longer be valid under climate change scenarios. Water availability may change dramatically at some locations due mainly to possible impacts of changes in temperature and precipitation over streamflow volume and seasonality, adding pressure to water supply systems. It has been shown that snowmelt-dominated basins are particularly sensitive to such changes. Hence, human settlements and economic activities developed in such areas are particularly vulnerable. The Maipo river basin in Central Chile – where more than 6 million people live – is one of these areas. We used a calibrated water resources model of the Maipo river basin, in order to propose a general framework to evaluate adaptation options at the urban level. When comparing a mid-21st century period to a historic control period, results for three selected performance metrics showed a decrease in water system performance. Adaptation measures were evaluated in their capacity to maintain current water security standards. Two alternatives stand as highly effective options to this end: water rights purchases and improvements in water use efficiency. The political and economic costs of implementing these options, which could deem them unviable, are not considered here but are worthy of further research.

Key words | adaptation, climate change, Maipo basin, Santiago, water security

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INTRODUCTION

Over the last century, global population growth, increases in agricultural land under irrigation and rising standards of living have all led to an intensification of water demand (Gleick 2000). Consequently, maintaining high standards of water demand coverage (i.e. level of satisfaction of domestic water demand) has become a major challenge in many places.

Urbanization processes exacerbate this water supply problem, forcing many utility companies to invest in infrastructure or to implement water conservation programs to meet water demands (Michelsen & Mcguckin 1999;

Olmstead & Stavins 2009). It is quite evident that global population will continue to grow for at least several decades, affecting water demand as a result (Oki & Kanae 2006; Vörösmarty et al. 2009). Therefore, it is expected that pressure on water resources should keep on growing in urban areas, as 60% of the global population will be concentrated there by 2030 (United Nations 2012).

Projected climate change is also expected to have major impacts on freshwater resources. In Mediterranean and semi-arid regions it is expected that less winter precipitation will fall as snow, and since warmer temperatures tend to

dominate, snowmelt will occur earlier in spring. In fact, earlier timing on snowmelt processes has already been identified in some regions (Barnett *et al.* 2008; Casola *et al.* 2009; Vicuña *et al.* 2013). Thus, regions where water supply is currently dominated by melting of snow or ice (i.e. where more than a sixth of the world's population lives) are particularly vulnerable (Barnett *et al.* 2005).

These types of changes represent a further threat to water distribution systems (Bates *et al.* 2008) and water security, defined as the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economies (Grey & Sadoff 2007). Hence, adaptation activities to reduce vulnerability to current and future climate impacts become vital (Penney 2007; Heinrichs *et al.* 2011; Pelling 2011).

Incorporation of climate change into urban planning remains as a relatively undefined process (Hoornweg *et al.* 2011; UN Habitat 2011). Systems for water management have been typically designed and operated under the assumption of stationarity. Climate change undermines this assumption and new approaches in water management systems are needed (Milly *et al.* 2008). In fact, climate change in urban water planning has been recently considered only in a few countries. In England and Wales, incorporation of climate change scenarios in utility company planning has been a requirement for several years (Arnell 2011). In the USA many companies have already established (or are in the search for) planning tools to be better prepared for dealing with expected changes (Waage & Kaatz 2011). At a research level, infrastructure and operational adaptation have been addressed to some extent: Brekke *et al.* (2009) considered climate change impacts on the development of a framework to assess reservoir operation risk under climate uncertainties; Vicuña *et al.* (2010) developed an optimization algorithm that can be used for different studies relating to water resources management and climate change; Lempert & Groves (2010) developed a more integrated approach, in which they identified vulnerabilities in the original planning of a water and waste water utility in Southern California, to assess the effect and costs of adaptation alternatives. In Chile, Melo *et al.* (2010) studied the vulnerability of the main water utility company to climate change and estimated the number of extra

water rights necessary to maintain a high water security for Santiago. Although results from that work are valuable, and serve as an approach to the road of adaptation, there is a need for a more integrated assessment which considers a range of adaptation options, with a well-defined performance evaluation of alternatives.

In this study we develop a conceptual framework of an integrated adaptation process to climate change and urban water use for Santiago. The city is the largest urban centre in the country, holding 5.5 million people (35% of the national population) in an extension of 640 km^2, and generating 43.3% of national gross domestic product (INE 2011). Located in a snowmelt-dominated basin, Santiago is a good example of a highly populated city with a high level of pressure on water resources.

The main objective of this work is to assess climate change and population growth impacts on the urban water supply system of Santiago and to apply a conceptual framework to assess adaptation.

Methods and results presented here aim to be a contribution to the process of adaptation for human settlements located at semi-arid regions and snowmelt-dominated basins, as well as a valuable and useful tool for stakeholders. The study is based on the use of a simple conceptual framework that should be taken as a perfectible example to support decision-making in water use and climate change adaptation related issues.

METHODS

Conceptual framework for evaluating adaptation decisions

The main objective of developing an adaptation process to climate change is to quantitatively assess different adaptation strategies. Several different elements must be addressed in the construction of a method to carry out this process. For instance, climate and population projections and their effects on water supply and demand are essential to this assessment, as well as a good representation of available infrastructure and administrative allocation of water.

The conceptual framework proposed to evaluate adaptation decisions (Figure 1) considers climate and population changes to be the main drivers of possible changes in water resources availability and demand. Such drivers are considered to be the most important ones in stressing water availability and demands in the long term (Vörösmarty *et al.* 2009; Buytaert & De Bièvre 2012). Climate change projections may vary according to the global circulation models (GCMs) used, the greenhouse gases (GHG) emission scenario and the downscaling method potentially applied. Consequently, a range of scenarios

should be adopted to account for inherent uncertainties, which are also present in population projections. This diversity of available scenarios is represented within the 'drivers projection uncertainties' box in Figure 1, by using probability distribution functions. Projected values for each driver are represented on the X-axis of these functions. Probability for each value is represented on the Y-axis.

In Figure 1, climate and population change projections are inputs for a water resources model, which is at the core of the evaluation process. Selection of the modeling tool depends on its capacity to represent water supply and
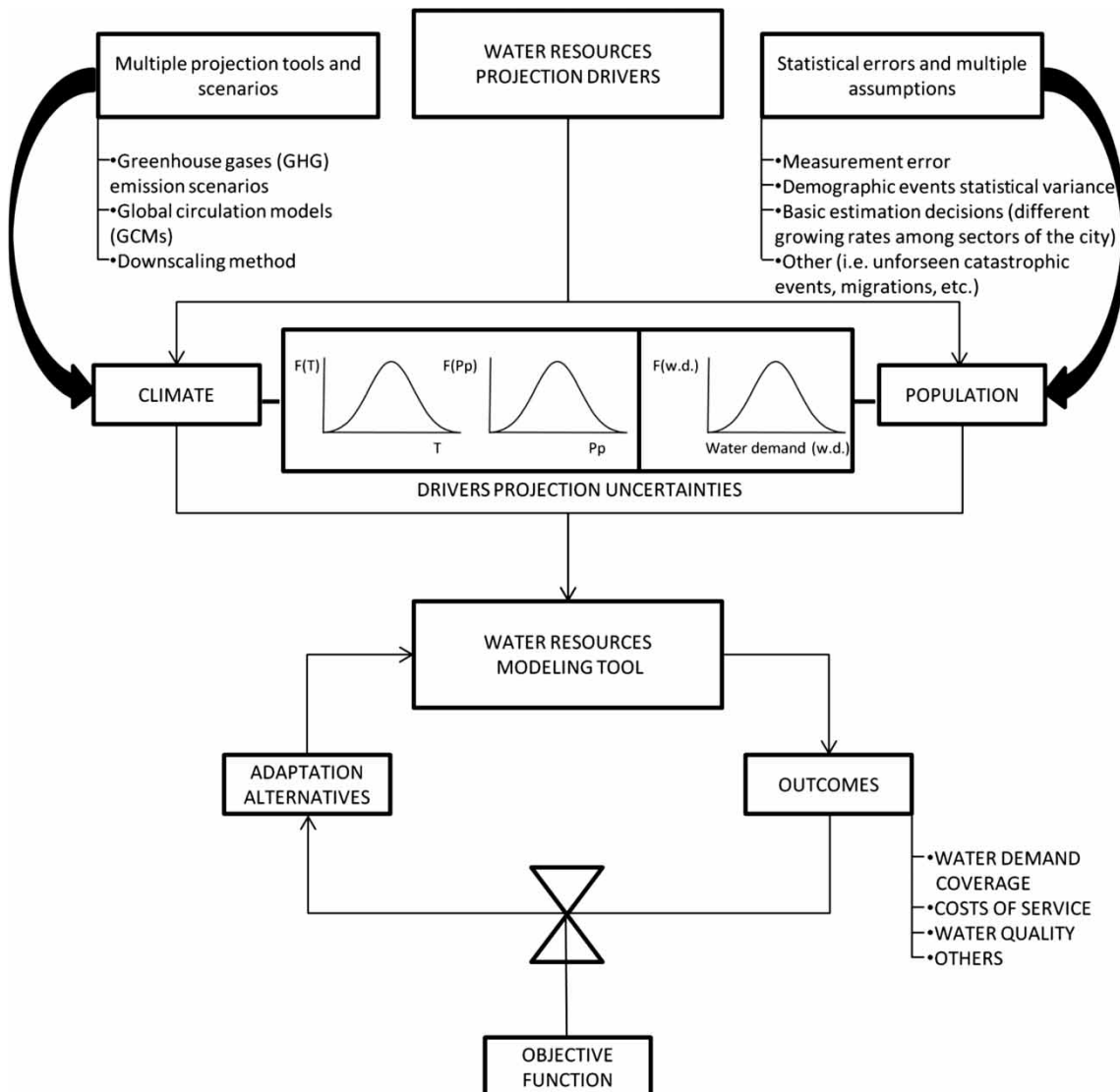

Figure 1 │ General framework of adaptation process.

demand within the study area. This representation basically includes the hydroclimatologic cycle dynamics, incorporation of water demands and existing water infrastructure. Once the calibration of the model has been undertaken, projected climate and population scenarios are used as input.

The outcomes box in Figure 1 represents selected metrics to check the water system performance under current or projected scenarios; the objective function is the goal to be achieved by the system. Achievement of this goal is directly related to metrics values that are obtained (i.e. 100% of coverage for urban demands); this in turn allows for the comparison of adaptation alternatives. Finally, when the objective is not accomplished due to driver impacts, adaptation strategies are incorporated and a new evaluation is performed.

Application of the conceptual framework to a case study of the Maipo basin

The Maipo basin and Santiago's water supply system

The Maipo river basin (Figure 2, upper panel) has an area of 15,000 km^2, and is located between latitudes 33 and 34° S. From a source at an altitude of 5,600 m in the Andes Mountains, the Maipo river runs 250 km to the Pacific Ocean. The river has a snowmelt-dominated regime with a mean flow of approximately 90 m^3/s (DGA 2003), and streamflow peaks occurring in late spring (December) (Figure 2, bottom panel).

Irrigated agriculture is the main water user in the basin, covering an area of 136,000 ha. (INE 2007). However, irrigation efficiency is considered to be low (approximately 50%) due to the predominance of furrow irrigation which leads to high water losses. The city of Santiago is also a major water user in the basin. Average per capita water use reaches 150 l/day and can rise up to 617 l/day in high income neighbourhoods (Superintendencia de Servicios Sanitarios (SISS) 2009a). During the dry season of the year, Santiago's water demand may be up to 20 m^3/s. Most of the water production plants which produce drinking water for Santiago (i.e. more than 70%) are linked to surface runoff from the Maipo river (Figure 2, upper panel). The Mapocho river is the second largest river in the basin, and complements the Maipo river mainly in the northern area of the city. Surface runoff

coming from both rivers is the first priority source within the water supply system, mainly due to economic costs. El Yeso reservoir, located in El Yeso river (tributary of the Maipo) is the only reservoir in the basin used to support Santiago's water supply. El Yeso reservoir can store up to 250 hectometers of water, and is used as a water supply source mainly during the dry season and scarcity periods. According to a monthly average discharges available database for the last 20 years, El Yeso discharge reaches 5 m^3/s during the winter season, and nearly 10 m^3/s during the summer season. This means that during dry periods of the year, El Yeso may supply half of urban water demands within the region. Groundwater pumped by nearly 200 wells, is the last priority source, mainly because of higher operation costs, and covers approximately 5 to 10% of water demands in most sectors of the urban area.

Peak water demands for both agriculture and urban users occur during spring and summer, water availability during this season being highly dependent on snowmelt dynamics since precipitation is unlikely to occur.

Aguas Andinas is the main water utility company of the city. The city's water supply and distribution system has been designed with high reliability standards. Moreover, the regulatory framework establishes that water utility companies must fully meet demands, whenever streamflows are higher than the flow that is exceeded 90% of the time. In fact, continuity of service – considered as the percentage of time that demands are fully covered – has remained above 98% since 2005 (SISS 2009b).

Allocation of water between different users is based on a market mechanism established by the 1981 National Water Code. This code recognizes water as 'national property for public use', but grants water use rights to individuals as a means of operationalizing this concept. The number of rights is established by the national water resources agency (Dirección General de Aguas, DGA), and once assigned they can be traded by the users without restrictions. The National Water Code distinguishes between surface and groundwater sources as well as consumptive and non-consumptive uses. Non-consumptive water-use rights correspond to water that is diverted, and for which there is an obligation to return the flow to its original course. Such uses usually correspond to electricity generation. By contrast, consumptive water-use rights
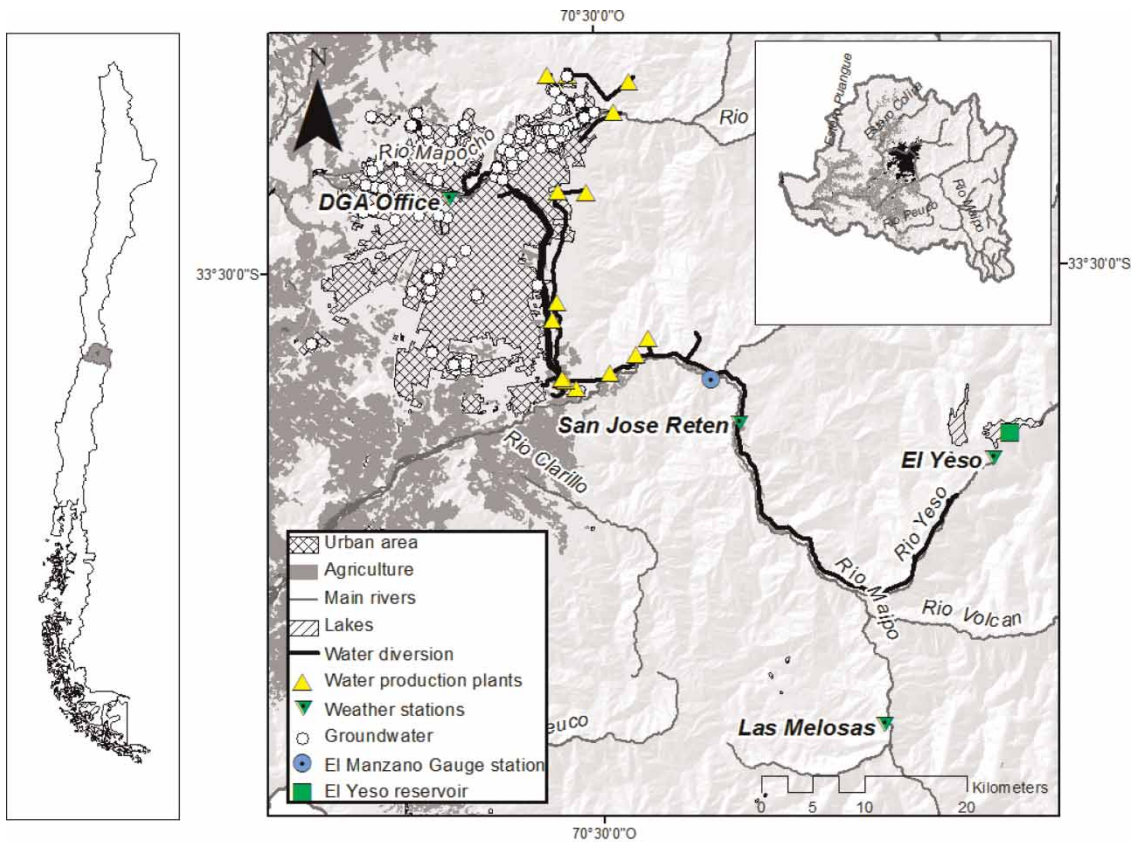
Figure 2 │ The Maipo river basin (upper panel) and main hydro-climatic conditions (bottom panel). Streamflow values are from El Manzano station (see upper panel).

usually belong to farmers and utility companies, to be used for irrigation, industrial and domestic consumption. Due to the natural variability of streamflows, DGA considers the streamflow that is exceeded in 85% of years to define the total number of water rights available within a specific basin. Allocated volume of water to a particular user is proportional to the share of water rights owned from the total amount of water use rights, and based on streamflow availability. Considering this definition and historic records, one water right should be equivalent to a streamflow 5–15 l/s depending on the time of the year. According to current legislation, water rights are not

associated to a particular type of use, and first priority of use is drinking water.

Projected impacts of climate change on water resources in Santiago

Climate change plays a major role as a driver of the modifications experienced by the hydrological cycle. Research reveals that precipitation in the area is highly correlated to snowpack accumulation, which in turn determines annual discharge volumes (Masiokas *et al.* 2006), while temperature has been found to be more related to the timing of peak discharge.

Climate change projections coincide with recent observed trends, such as decreasing trends in streamflow (Rubio-Álvarez & McPhee 2010) and precipitation (Quintana & Aceituno 2012), as well as increasing trends in temperatures (Falvey & Garreaud 2009). Figure 3 shows the output for three different GCMs (ECHAM, HadCM3, GFDL) using two GHG emission scenarios (A1b and B1, Nakicenovic & Swart 2000) for the Maipo basin. The 2035–2065 period was compared to the 1980–2010 control period, on an annual average basis. All models and GHG scenarios reveal that climate change impacts on the Maipo basin will lead to reductions in precipitation (10–15%) and an increase in temperature (1–2 °C). These projections agree with previous research (Cortés *et al.* 2011).

To obtain these results, a downscaling method was previously applied to raw data generated by the GCMs. The
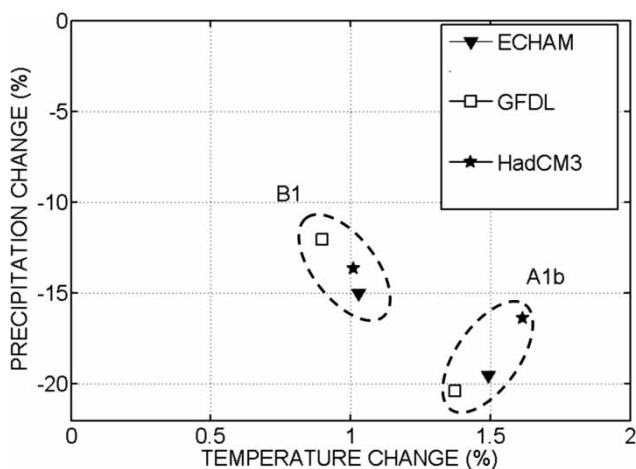
downscaling method used resembles the quantile mapping and bias correction method developed by Wood *et al.* (2004). Instead of developing grid-based results, our method produces point estimates at the location of the stations used to drive the water resources model. From this approach and selection of representative historic months (with a daily resolution), we recreated weekly temperature and precipitation time series for all three GCMs and the two GHG emission scenarios.

To model the hydrology of the Maipo river basin, we used the Water Evaluation and Planning (WEAP) platform (Yates *et al.* 2005a, b) on a weekly basis. WEAP uses climate information as input to generate streamflow in a semi-distributed scale. Within the model, elevation bands are established and serve as the hydrological unit or catchment where climate, soil, topography, surface water hydrology and land use characteristics are specified.

Availability of precipitation and temperature data is very limited in mountainous areas within the study region and no public data are available over 2,500 m.a.s.l. Available precipitation data for three different meteorological stations – DGA, San José and El Yeso stations, at 500, 1,000 and 2,500 m.a.s.l., respectively – were used to find the best total annual precipitation-altitude relation (see Figure 2, upper panel). Considering the quality and length of data, San José and El Yeso stations were selected as index stations within the model, and precipitation data were extrapolated to each catchment according to its altitude by using a logarithmic relation, supported by the analysis previously mentioned. The use of a logarithmic relation is also useful to attenuate the effect of altitude on climate conditions, avoiding large amounts of snow accumulation at high altitudes. Therefore, catchment precipitation weekly values below 2,500 m.a.s.l. were based on San José station available data, and catchments located above that altitude were based on El Yeso available data.

A similar process was carried out to represent weekly temperature values at each catchment. Weekly adiabatic lapse rate values were calculated by using available temperature data from El Yeso station and from Las Melosas station (1,500 m.a.s.l.). El Yeso station was used as the index station, and weekly values from it were adjusted to each elevation band after considering the lapse rate and the difference in altitude between El Yeso and each catchment.

Figure 3 | Climate change model projections for El Yeso meteorological station in the Maipo basin for 2035–2065 period compared to control (1980–2010).

Additionally, we incorporated soil parameters such as runoff resistance factor, soil water capacity, root zone conductivity and deep conductivity. Climate change projected data and the downscaling method previously described were used to force the WEAP model.

We calibrated the model at different sub-watersheds using existing available streamflow records at 5 gauges in the Maipo river and 1 gauge in the Mapocho river. The goodness-of-fit was assessed using the Nash–Sutcliffe index and the bias of estimators. The minimum and maximum values of the Nash–Sutcliffe index obtained for the Maipo sub-watersheds were 0.7 and 0.77. The Nash–Sutcliffe index value for the Mapocho river was 0.6.

A decrease of 10–40% in discharge volumes and peak discharges occurring 1 to 4 weeks earlier were found. Projected streamflows for the mid-21st century period compared to historic control periods are shown in Figure 4. Similar runoff projections have been obtained in other snowmelt-dominated basins in central Chile (Vicuña *et al.* 2011). Available studies for other Mediterranean regions show that these changes will likely impact urban water systems and infrastructure. For instance, reductions in water availability in spring are expected in California due to significant snowmelt decreases in that season (Tanaka *et al.* 2006; Brekke *et al.* 2009).

Santiago's water system adaptation assessment

We applied the general conceptual framework of adaptation assessment to Santiago's water system, using the calibrated WEAP model for the Maipo river basin. One advantage of the WEAP model is that it allows the representation and projection of environmental requirements of water and urban water demands and infrastructure. Thus, WEAP is a powerful tool to assess water management in an integrated manner. We defined three specific metrics to assess the water system performance and four adaptation strategies to cope with the impacts. Each of these steps is represented in Figure 5.

Climate and population projections were considered as the main drivers of change in water supply and demand (see Figure 5). The previously mentioned GCM models, GHG emission scenarios and downscaling method were used to represent climate change at a local scale.

Urban demands were represented in the WEAP platform by using a 5 years' consumption database provided by Aguas Andinas, with Santiago's historic water consumption for approximately 150 different water distribution sectors of the city. On this database, each sector had information for total number of accounts and total water consumption. Seasonality of consumption for each sector was also included. Urban heterogeneity was identified by aggregating sectors into 10 percentile groups according to their average annual consumption. Seasonality of consumption was also represented according to this aggregation level. Each sector's main surface water source was identified to specifically determine the vulnerability of available water associated with the Maipo river. Future water demand was represented using population projections made by the Economic Commission for Latin America and the Caribbean (ECLAC 2009), and these were adjusted to the number of accounts within each
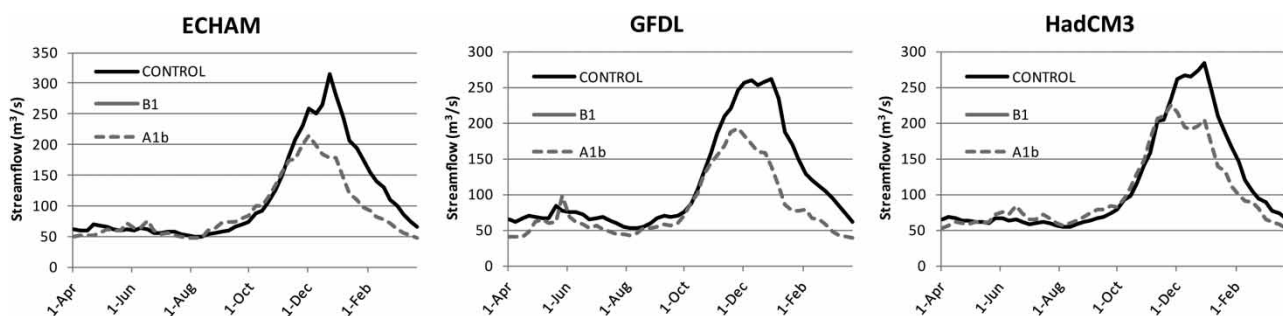
Figure 4 | Projected streamflows for mid-21st century period compared to historic control periods. Results are shown for three GCMs (ECHAM, GFDL, HadCM3) and two GHG emission scenarios (A1b, B1).
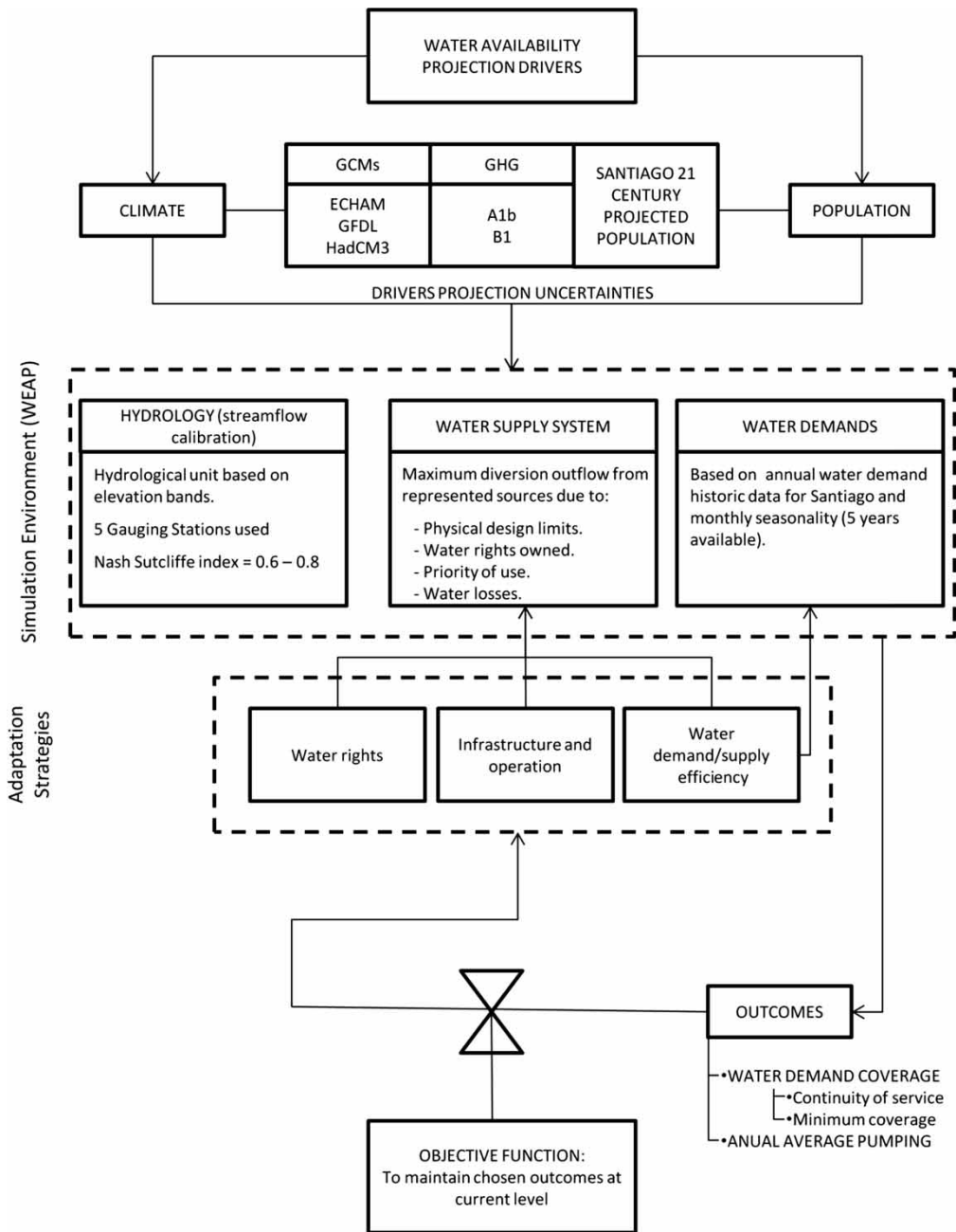
Figure 5 | Conceptual framework applied to Santiago's water system.

water consumption group. The obtained projection considers that the population living in Santiago will keep on growing, reaching nearly 6.5 million people in 2050, and decreasing again to end the century with a population of approximately 5.8 million people. Although according to the general framework (see Figure 1), a range of scenarios should be adopted to account for inherent uncertainties, no other population projections were available for Santiago. Rates of per capita water demand were projected following historical trends from Aguas Andinas records.

Agricultural demands were also represented, considering total agriculture surface under irrigation, and an

annual water use rate was estimated using historic data for water demands. Groundwater resources were assumed to be available in permanent and sufficient quantities. The groundwater table is assumed to be constant and the withdrawal restrictions considered are only due to design limits.

Design parameters for the El Yeso reservoir were integrated into the WEAP model, and a monthly historic database from the reservoir discharges was used to calibrate its operation. In this case we obtained a coefficient correlation of 0.5. For further information on how the WEAP model represents reservoir infrastructure and operation, please refer to Yates *et al.* (2005b).

We assessed and compared the performance of Santiago's water system for two periods: a control period (1980–2010) and a future mid-century period (2035–2065). For the control period, we used available urban demand data for the year 2010 and a 30-year period of historical modeled streamflow. We assumed that the control period represents the baseline water security level for Santiago's water supply system, and thus represents the performance benchmark or level that water managers would like to preserve in the future. Table 1 shows the scenarios considered in the assessment.

Future period results were obtained for two different scenarios (Table 1): a 'Climate change' scenario that uses projected hydrology and the current 2010 urban demand level, and a 'Climate and population change' scenario which uses projected hydrology and the urban demand projected for 2050.

To quantify climate and population change impacts over the urban water system, we used the following metrics or outcomes (see Figure 5), which allow the characterization and comparison of water system performance in future and control scenarios.

(a) Continuity of service (%): defined as the percentage of time that demand coverage is completely met during the assessment period.

(b) Minimum coverage (%): defined as the minimum demand coverage reached during the assessment period, as a percentage of total water demand.

(c) Annual groundwater pumping (hm^3): defined as the annual average volume pumped during the assessment period.

Santiago's water supply system has been designed with high reliability standards, and the city usually receives all the water that is needed. The last time that water shortages had considerable impacts on the urban water system was in 1997, following a long drought period.

The groundwater pumping metric was selected due to its relevance to the system operation and costs. Groundwater is the most expensive source, so surface flow is always selected as the first supply choice when available.

Finally, the selected objective function (see Figure 5) in this study was to maintain the metrics at the current level into the future. In order to identify the accomplishment of the objective function, the metrics were calculated after each run of the model. Adaptation alternatives were incorporated into the model since evaluation by maintaining the current system without any changes did not achieve the objective function in future periods (see Figure 5). By using a simple code, we performed a sensitivity analysis by running WEAP several times to assess adaptation alternatives at increasing levels on each run. Strategies assessed in this work relate to the following three components: (1) water rights; (2) El Yeso reservoir, which is the only reservoir in the basin used to support Santiago's water supply; and (3) urban water use efficiencies. We selected these strategies because: (1) the three assessed components are considered to be key components in determining water availability for the urban water supply system; and (2) all three components can be feasibly assessed in the calibrated WEAP model for the Maipo basin. Specific reasons for selecting each of these strategies and explanation of how they have been applied are presented below.

1. **Water rights purchase:** The Maipo water allocation system is based on the definition of tradable water

Table 1 | Water system performance scenarios used to identify vulnerabilities and assess adaptation strategies

Scenario	Hydrology	Level of demand (year)
Control	1980–2010	2010
Climate change	2035–2065	2010
Climate and population change	2035–2065	2050

rights. As mentioned above, due to the natural variability of streamflows, DGA considers the streamflow that is exceeded in 85% of years to define this number, being hence designed under the assumption of stationarity. This assumption may no longer be valid under climate change scenarios. Research on climate change and the local water market framework within the Maipo basin shows that the reliability of the water allocation systems based on water rights may be strongly negatively affected, and will likely become less effective in meeting demands (Meza *et al.* 2012). Water withdrawals made by Santiago's main water utility company are legally limited by the number of water rights that are owned, which currently corresponds to 25% out of 8,133 existing water rights. All of the rights once defined for the Maipo basin have already been assigned. During the last decade, Aguas Andinas has increased its water rights owned on an average rate of 5% per year, proving rights purchase as an important alternative for the utility to increase its water production. It is very interesting to assess the effect of a higher amount of water rights owned by Aguas Andinas under climate and population change scenarios, and what would be the necessary amount to cope with these scenarios. We studied the impacts of purchasing an additional 100 to 800 water rights as an adaptation strategy.

2. **Reservoir storage capacity and operation:** The El Yeso reservoir was designed to be mostly used during the dry season of the year but its use is also effective during short periods of more than expected urban water demand and during droughts. Under current historic conditions, El Yeso reservoir may add up to 10 m³/s to the Maipo river – nearly half of the total demand for Santiago during the dry season – to be withdrawn downstream and used to supply the urban water system (see Figure 2, upper panel). Considering projected changes in natural discharges, available discharge for storage (volume and timing) should also change. Furthermore, the infrastructure and operation rules of the reservoir are the main water management factors determining the amount of water that the reservoir can provide to the water supply system. Considering this, an assessment of adaptation strategies related to the reservoir were focused on the following factors:

(a) *Increasing El Yeso's current storage capacity.* We assessed the effect of increasing the storage capacity of the reservoir by 5 to 40%.

(b) *Changing reservoir operation.* In our model, the seasonal operation of El Yeso reservoir is based on a weekly buffer coefficient, which determines the amount of water that can be released each week, as a percentage of total stored volume. This buffer coefficient is used to calibrate the reservoir discharges. Buffer coefficient values were obtained by minimizing the sum of squared errors between the modeled and observed data of the stored volume. According to this analysis, buffer coefficient values present an annual seasonality going from a minimum value of 0 in the wet season to a maximum value of 0.01 during the dry season, and are equivalent to 2.25 hm³/week. In addition, the reservoir's operation also considers agricultural water rights, so that the El Yeso's natural flow is not modified when the streamflow in the Maipo river cannot meet their demands. An adaptation option is to adjust the operation to increase water supply, allowing the reservoir to reach lower storage levels without affecting other users' water rights. This strategy is represented by multiplying the reservoir buffer coefficient by four increasing factors arbitrarily at every time step during the year (i.e. 4, 8, 12 and 16), allowing the release of larger water volumes at each time step.

3. **Improvements in water demand efficiency:** Water demand efficiency improvements are represented by scenarios that reduce the demand by 5 to 40%. Note that we are assessing different efficiency management goals rather than management actions to achieve these goals. For instance, an efficiency increase may be achieved by avoiding urban system losses (30% approximately), incorporating efficient household water consumption devices and appliances, or by achieving a change in population consumption behaviour.

Assessment based on individual sensitivity analysis was chosen considering the non-linear responses of water coverage to the implementation of adaptation options. The performance assessment of alternatives was always done by using the three evaluation metrics previously defined. On a second analysis, assessment was done by combining the most promising strategies.

RESULTS AND DISCUSSION

Assessment of the GCM representations of historical climate conditions in the basin

To verify the realism of representing the water distribution system, we compared results for the historical period (1984–2009) using observed and GCM-derived climatological data, setting 2010 urban demand levels for the whole period. Figure 6 shows the results for the three metrics under evaluation.

Figure 6(a) shows the percentage of time that water demands are completely met (i.e. the water security level of Santiago's water system). The baseline value – obtained using historical climatic data – is around 98%. The GCM historical simulations produced similar results, with values ranging from 97 to 99%. All GCM-based runs overestimated the minimum coverage (Figure 6(b)). This feature of overestimation is due to the difficulty of reproducing extreme events with GCM outputs. As Santiago's water system design has high security levels, coverage failures at any level occur only when streamflow is considerably low (below the flow that is exceeded 98% of the time in the observed record). These types of failure have historically coincided with long periods of drought, which are not well simulated by the GCMs (Johnson & Sharma 2012).

The ECHAM and GFDL models represent these extremes better, so that the corresponding overestimations are 8 and 5%, respectively, during the specific week where minimum coverage is recorded. In percentage terms these figures are not far from historical values. Nevertheless, they correspond to an overestimation in supply availability of 0.6

to 1 hm^3. HadCM3 overestimates the minimum historical coverage by 21%, which corresponds to 2.6 hm^3. Such a volume is an undesirable mismatch when considering this minimum coverage metric for water resources planning.

The inability to represent contiguous dry periods also has consequences in our third metric (Figure 6(c)). Both the current water supply system and our model consider groundwater as the last source to be used, because of pumping costs. When extreme dry periods occur, pumping needs are higher because streamflow availability is limited. Thus, if dry periods are not well simulated, pumping volumes are poorly represented. For instance, HadCM3 underestimates pumping volume by more than 50%. On the other hand, pumping results are similar to historical values when using ECHAM. Finally, GFDL overestimates pumping volume despite the fact that it simulates a minimum coverage similar to that of ECHAM. This difference is explained by the consistent underestimation of average streamflows by the model (of around 20%), which gives rise to a permanent higher pumping demand.

Interesting discussion elements arise from these results. First, the representation performance of the GCMs is critically important to the results of particular water system metrics. Although some characteristics of the GCM simulated streamflows can be similar to that of observed data (i.e. mean and inter-annual variability), the inability to capture extreme events becomes crucial when using metrics highly dependent on very particular drought conditions, such as minimum coverage and pumping volumes. Hence, this climate model scenarios approach can be more useful when metrics don't depend heavily on these specific events, as happens with the 'continuity of service' metric.
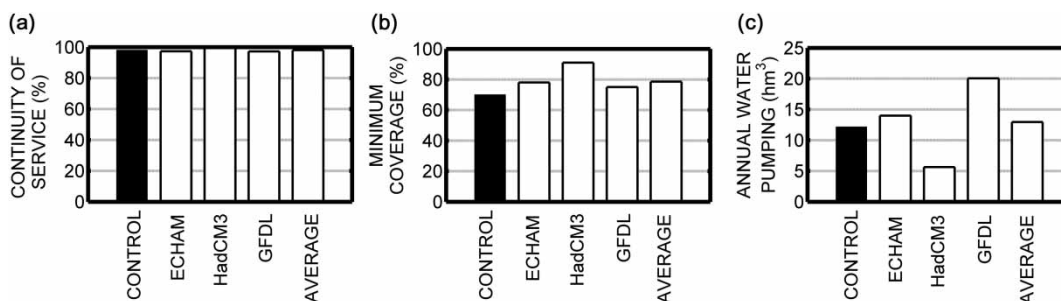
Figure 6 | Comparison of water supply system performance using observed climatic records (baseline) and simulated climatic records from different GCMs for the same period (1984–2009). (a) Continuity of service (%), (b) minimum coverage (%), (c) annual groundwater pumping (hm^3).

Impacts on the water supply system

Figure 7 shows the three selected metrics for the control (1984–2009) and future (2035–2065) periods, when considering 'Climate change' and 'Climate and population change' scenarios (under two GHG emission scenarios), and no adaptation at all. Whiskers indicate the average value of the metric from the three GCMs and corresponding minimum and maximum values yielded by a particular GCM.

As seen previously, all GCMs simulate a historical value of the continuity of service similar to that historically observed. Consequently, minimum and maximum values in Figure 7 tend to be close together, under and above the control average value. The opposite situation is observed for control values in 'minimum coverage' and 'annual water pumping' metrics. These results make us consider 'continuity of service' as a more reliable metric, while the other two

metrics have higher uncertainty resulting from differences between GCMs in representing their historical values.

All models and scenarios coincide in projecting impacts on 'continuity of service', 'minimum coverage' and 'annual water pumping'. These impacts are higher when both population and climate changes are considered. Impacts over the water system are higher for the A1b GHG emission scenario. This is more noticeable for the 'annual water pumping' metric.

Worse scenarios project a 20% reduction in 'continuity of service' during the mid-century period, from 97 to 77%. A similar situation occurs with the 'minimum coverage' which may decrease by 28% in the future, from 75 to 54%. 'Annual water pumping' increases disproportionally, exceeding a 300% increase in one particular case, from 20 to 65.5 hm^3 (GFDL + A1b + climate and population change scenario).

Although considerable uncertainty remains behind these results, the need for adaptation in Santiago's water
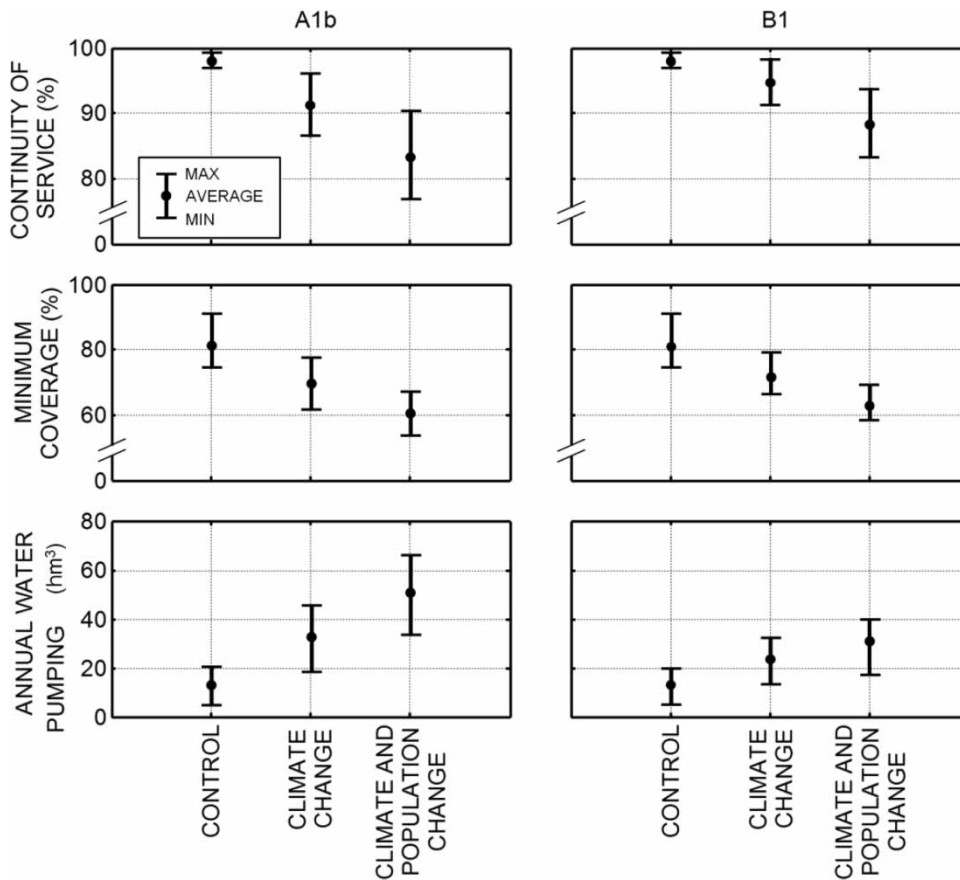
Figure 7 │ Average climate change and population growth impacts for three metrics: continuity of service (%), minimum coverage (%) and annual water pumping (hm^3). For each metric, the graphic shows average, maximum and minimum values for the three GCMs used.

system to ensure water security at current levels in the future, is becoming undeniable. The results of applying single and combined adaptation strategies are shown in the following sections.

Adaptation results

The evaluation of the adaptation alternatives considered: (1) an independent assessment of each strategy (single strategy assessment); (2) a joint assessment of the two best single strategies in reducing water system vulnerability (i.e. portfolio of strategies); and (3) an assessment of the timing adopted to implement a particular strategy. For this last task we evaluated and compared the number of water rights to be purchased when using and not using information of future climates based on projected scenarios.

Adaptation using single strategies

As seen in the previous section, adaptation strategies were assessed by undertaking a sensitivity analysis. Mid-century percentage changes – with respect to control period values – were obtained for each performance metric.

Figure 8 shows the results for scenarios where water rights owned by the utility company increase. Evaluation was made for four purchasing scenarios (200, 400, 600 and 800 water rights acquisition over current company ownership). Results are shown for each GCM and GHG scenario combination, which were ordered on the X axis from lowest to highest projected reduction in precipitation levels.

Results for climate change scenarios show that at least 400 water rights should be bought by the water utility company to maintain current security levels, representing an increase of 20% with respect to the water rights currently
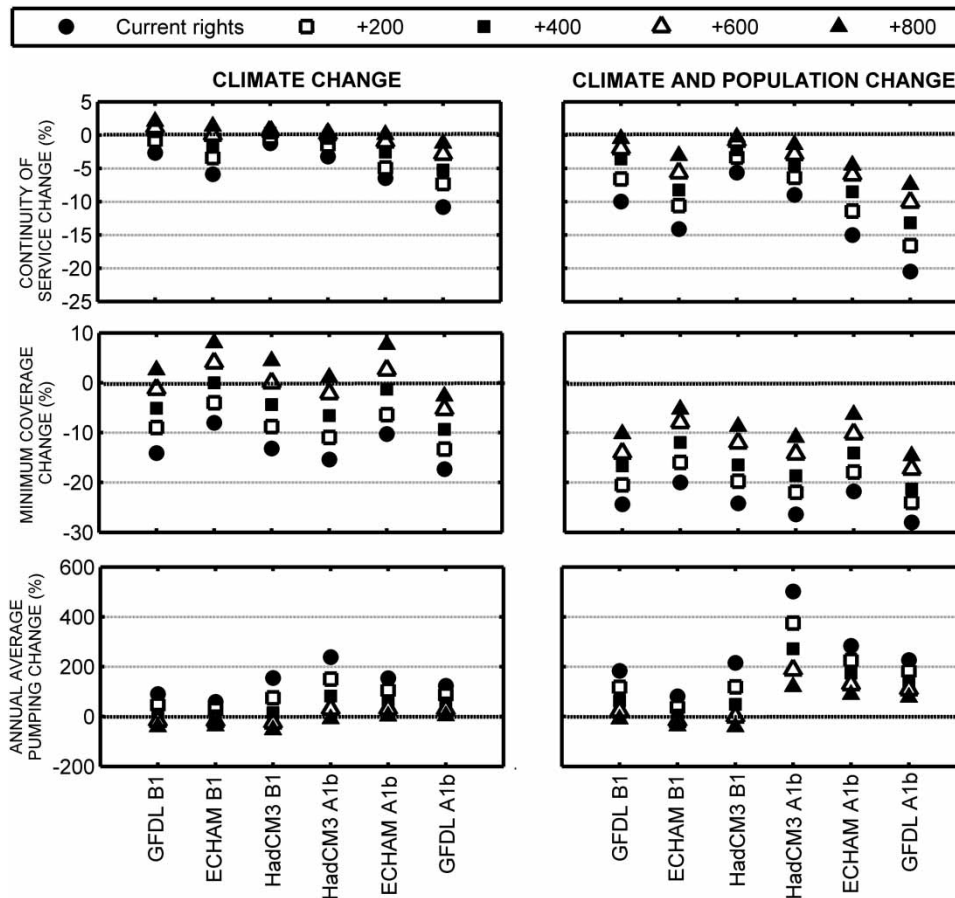
Figure 8 │ Impacts of an adaptation strategy based on water rights acquisition by year 2050. Effects on the water system are presented as relative changes compared to the control scenario.

owned. High purchase levels may yield even better coverage levels and less water pumping volumes when compared to the current situation (positive percentage change values for coverage metrics and negative values for water pumping). The situation worsens when considering population growth, where an additional 800 water rights are, in most scenarios, insufficient for maintaining current system performance.

Table 2 synthesizes water system performance results under different adaptation alternatives. Here we show the minimum (maximum) achievement – referred to as MIN (MAX) – of all GCM and GHG combinations, under a maximum level of adoption of the adaptation strategy (e.g. maximum level of water rights bought). Average achievement obtained from all GCM + GHG combinations under maximum adoption of adaptation levels are also shown (AVERAGE). Results are presented as percentage changes in continuity of service, minimum coverage and annual pumping, for the mid-century period with respect to the control period. In the case of continuity of service and minimum coverage, a successful strategy is one that yields a result of zero or a positive number (suggesting an improvement over the control period). The opposite is expected in the case of annual pumping where we expect a result of zero or a negative number. It must be highlighted that results among strategies are not strictly comparable since strategies are not based on an economic evaluation of their implementation, but on arbitrary levels of improvements integrated during the sensitivity analysis process.

The results shown in Table 2 aim to answer one particular question: can historical conditions be achieved with the application of one single measure? The answer is yes, but marked differences exist among strategies and some important findings can be extracted from our results.

First, a water demand efficiency strategy yields excellent results. All metrics and scenarios show improvements over current levels when this strategy is adopted at its maximum value. Second, results show that a water rights purchase strategy is an effective strategy to cope with climate change impacts; however, this is less effective when population change is also included. On the other hand, infrastructure and operation strategies do not show promising results and all metrics remain below current security values in most cases.

The viability of adopting any of these strategies is highly dependent on the current water governance structure. El Yeso reservoir operation can be managed within a branch of the governance system that involves few actors and in which consensus is easily reached (e.g. a collaborative effort between the public sector organization in charge of water planning and management (the DGA), and Aguas Andinas). The water utility may avoid releasing

Table 2 | Achievements for all three metrics under maximum levels of adaptation

		Climate change			Climate change + population change		
		Min	Average	Max	Min	Average	Max
CONTINUITY OF SERVICE	RIGHTS	−1.2	0.5	2.1	−7.4	−2.9	−0.3
	EFFICIENCY	0.7	2.1	2.9	0.7	−2.0	2.9
	STORAGE	−8.2	−3.5	0.4	−14.5	−7.6	−0.5
	OPERATION	−7.3	−3.0	0.4	−15.2	−7.3	−0.7
MINIMUM COVERAGE	RIGHTS	−2.7	3.5	8.0	−14.7	−9.4	−5.3
	EFFICIENCY	9.9	23.8	33.3	9.9	21.6	33.3
	STORAGE	17.3	−10.1	4.4	−28.0	−21.4	−8.8
	OPERATION	−17.3	−11.2	−4.4	−28.0	−22.5	−16.5
ANNUAL PUMPING	RIGHTS	3.4	−22.6	−53.3	119.8	32.9	−41.3
	EFFICIENCY	−82.3	−91.4	−99.0	−52.6	−70.2	−89.0
	STORAGE	99.0	37.4	−56.3	189.7	116.1	18.7
	OPERATION	97.8	39.9	−44.2	208.5	139.2	61.3

Results are presented as percentage changes in continuity of service, minimum coverage and annual pumping, for mid-century period with respect to control period security levels, by using highest levels of improvement assessment (RIGHTS = 800 water rights purchase, EFFICIENCY = 40% reduction on water consumption, STORAGE = 40% increase on reservoir volume capacity, OPERATION = amplified flexibility by a factor of 16 on buffer coefficient). Minimum, average and maximum achievements among all GCM and GHG combinations are shown.

water whenever the Maipo streamflow is sufficient to satisfy agricultural users' demands. Hence, aside from respecting other users' water rights, reservoir operation is a responsibility of the water utility company, and thus is a potentially easier alternative. Unfortunately, this strategy does not generate strong returns in water system performance levels. Beneficial impacts were only obtained in a very particular scenario (using HadCM3 + B1 GHG, considering no changes in population and maximum level of adaptation). Even in this case, 'minimum coverage' levels remained below the control value.

New storage infrastructure options may be more difficult to manage and would involve more actors. This kind of option should be the result of a political agreement that involves – among others – local communities, environmental groups, and water user associations. In addition, water roundtables would have to deliberate since increased storage capacity affects streamflow regulation and thus rights security. The evaluated expansion of the El Yeso reservoir may require a long process but it should be easier to implement than the building of new reservoirs, as it is an already existing reservoir. When assessing a storage extension in the El Yeso reservoir, positive impacts were obtained for all three metrics. However, this only occurred under the same combination of GCM-GHG emission scenario, population assumptions (no change), and adaptation level (max) noted above.

In contrast, rights purchase and efficiency improvements show high possibilities for maintaining or improving control period water system performance levels. Nonetheless, there are some limitations and considerations with regard to applicability, especially when multiple actors' behaviour (including the population living in the city of Santiago) have to be considered.

A water rights purchase strategy is complex since it involves multiple actors who might not be willing to participate as potential sellers. This is a significant issue since, with projected reductions in precipitation, the value of existing rights should increase significantly over time; this also has to be coupled with the fact that no more surface water rights are being issued (the basin is effectively 'closed' for new surface water rights).

The efficiency strategy might be easier to manage and we see it as a good option in terms of political viability.

Potential gains in avoiding system losses are high, since today 20–30% of extracted water is lost through leakage (based on unpublished information provided by Aguas Andinas). An increase in efficiency of more than 20% could be achieved with short-term implementation of efficient devices and appliances in households and offices (Observatorio de ciudades 2009). Behavioural changes may establish similar gains and are most likely to result from pricing mechanisms (disincentives). However, to move in this direction, incentives for water providers should be in line with targets for reducing water demand.

A portfolio of strategies

An integrated approach of adaptation alternatives, should consider a set of possible options operating together. Here we show one example of assessment of combined strategies.

Water rights purchases and improvements in water demand efficiency proved to be the best individual alternatives. Bearing this in mind, we assessed the effect of combining both. Results were obtained for our first performance metric, 'continuity of service'. Figure 9 shows the 'continuity of service' level for the mid-century period, obtained by combining several levels of each strategy under the ECHAM A1b climate change scenario (not considering population growth). Each line represents the
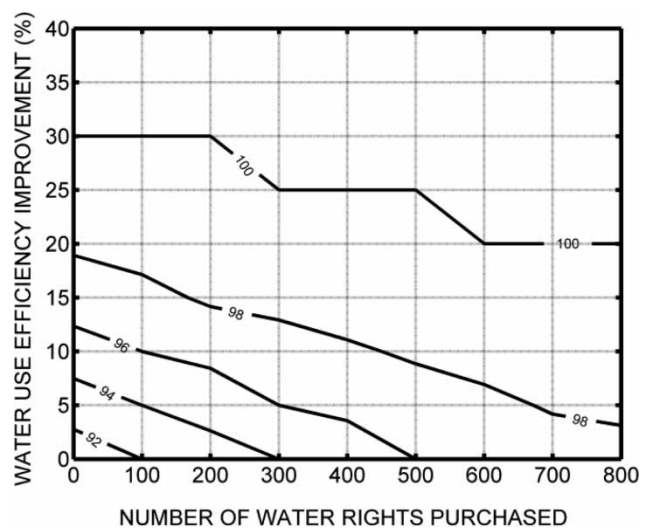
Figure 9 │ Continuity of service (%) for the mid-century period (climate change scenario), under several combined levels of water rights purchases and water use efficiency levels, using ECHAM A1b.

percentage of time when demand is fully met. Baseline simulation performance for this metric is around 98%.

In an effort to assess the uncertainty related to this combined effect, in Figure 10 we plotted the number of rights and efficiency levels needed to reach a 'continuity of service' of 98%, from all the climate change scenarios used in our model.

We have seen that HadCM3 projects the lowest impact on this metric, so projected adaptation needs are also low. For instance, when using this GCM, no needs are projected at all for the B1 GHG emission scenario in the climate change scenario. All other scenarios project adaptation needs at some level.

One remarkable finding is the high potential of both strategies when operating together. Over recent decades, buying rights has usually been the predominant alternative for coping with urban water supply growth (personal communication from water company managers). Here, we demonstrate that when efficiency strategies are implemented, large positive impacts can be generated. On average – considering all GCMs and scenarios – buying 100 water rights is equivalent to a reduction of 1.2% of water demand through efficiency improvement.

The performance of El Yeso infrastructure and operation individual strategies were not satisfactory and were not considered in a combined analysis. However, that and all other possible combinations are feasible. The results shown in this section should be taken as an example of the type of product that could support decision-making on

climate change adaptation processes when using this conceptual framework.

Timing of the adoption of adaptation strategies

Water planning has usually been based on historical information, assuming that historical streamflow will remain unchanged in the future (Vogel et al. 2011). Under climate change conditions, this assumption may no longer be reasonable. In this section, we use the water rights purchase strategy as an example to assess the value of using information of future climates based on projected scenarios, under the concept of 'long-term forecast' information in decision-making.

We estimated the number of rights that should be bought by the water utility to preserve the percentage of time at full coverage based on the current level (98%). This number was obtained every 15 years and for the entire century, under the 'climate change' scenario, by applying two different methods. The first method uses the hydrological data from a period of 30 years before the rights purchase decision is made. We called this method 'Without climate projection'. The second method also uses a 30-year period of hydrological data, but in this case data considers the past 15 years prior to the decision, and 15 years of projected hydrology. This method is called 'With climate projection'. Both methods include water demands by considering a constant water demand during the assessed
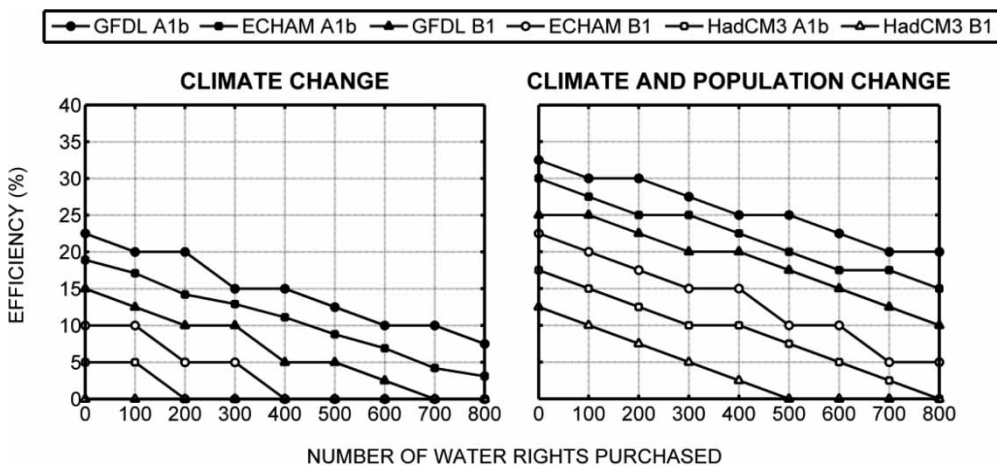
Figure 10 | Rights and efficiency needed for the mid-century period, to achieve a continuity of service at 98% level, under all climate change scenarios used (left panel) and climate and population change scenarios (right panel).

window of time, equal to the water demand projected 15 years ahead. Results for this assessment using ECHAM A1b climate change scenario are shown in Figure 11.

Figure 11 reveals four remarkable outcomes. First, there is very little difference in the amount of rights needed before 2025. Second, as the decision time gets closer to the mid-century, greater needs for water rights are projected when forecast information is used. Third, as we move forward through the century, water rights purchase demands projected by both methods tend to join back together. Fourth, selling water rights was never an option.

The first and second findings reveal that during the early stage of the century, the most important driver on water demands is the increase in population rather than climate change impacts over streamflows. Regardless of whether near future climate and streamflows are assessed or not, the amount of water rights needed remains almost the same. However, differences are much higher at the half century (400 to 500 rights), when using forecast information, where decreases in surface water availability are projected as a consequence of climate change (see Figures 3 and 4). This increases the need to buy water rights during the mid-century period. According to demographic projections used here, the population tends to decrease during the last period of the century. This consequently buffers the impact of lower streamflows at that same period, which explains the third finding. Regardless of the type of reaction (with or without forecast) the number of rights needed reaches a ceiling to cope with the impacts. The main difference between the two methods is that the 'no forecast' method yields a final number of extra water rights later in time. As

similar purchase levels are projected to the end of the century by both methods, a major question arises: should the strategy be applied before or after the impacts? This purchase decision is not only related to water security issues but also to economics. On a market basis, water rights prices change according to water resources availability. It should be presumed that prices rise when water becomes scarce, so an earlier purchase decision is more convenient than taking the same decision later on; the Stern Review (2007) suggests that this is similar for most mitigation and adaptation strategies. Alternatively, failures in demand coverage may be avoided by using forecast information to take the right decisions on time, anticipating the impacts. When assessing water demand coverage for the 2040–2055 period we found that when using past information (2010–2040 hydrological data) urban demand is fully met only 90% of the time. This situation changes when using forecast information, where in the same decision year, projected purchases increase by 400 rights. By using forecast information, 'continuity of service' remains at the 97% level, which is the same as the ECHAM's control period level. This is a rough approximation that demonstrates how valuable forecast information will be in water decision-making. Further research should be undertaken to determine the economic impacts of using such information.

CONCLUSIONS AND FUTURE RESEARCH

We have presented a promising approach for assessing adaptation in urban water systems in order to achieve vulnerability reductions under climate change scenarios. By choosing Santiago as a case study, we have shown the applicability of using a water resources simulation environment to develop a process of adaptation. Significant advantages can be obtained from using this framework, supported by the flexibility of a water resources model such as WEAP. First, a wide range of metrics and adaptation alternatives can be chosen according to the local context where the framework is applied. Second, assessment can be made under a wide range of climate change scenarios. Third, best alternatives can be assessed as an adaptation portfolio, also considering the existing tradeoff among such alternatives and the best timing for implementing
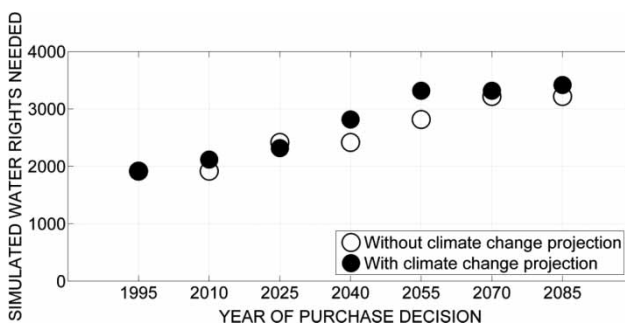
Figure 11 │ Comparison between sources of climatic information over the number of rights that have to be bought by the water utility company to preserve continuity of service at a 98% level (Results based on ECHAM A1b climate change projections).

them when climate projections are available. Finally, the adaptation framework shown in this work may be used elsewhere.

In terms of projected impacts of climate and population change on urban water use in Santiago, the results shown suggest that current water security levels will be hard to achieve in the future. The evaluation of the adaptation strategies included demonstrates the existence of available options for coping with climate change. The results of this work indicate that a water rights purchasing strategy to manage the problem from the supply side, combined with efficiency improvements on the supply or the demand side, could be a highly effective choice for maintaining the current water system performance. The results shown in this paper should be considered as examples of how this conceptual framework could support decision-making on climate change adaptation processes, rather than the actual solution to cope with water scarcity under climate change scenarios.

Although this study has employed a comprehensive framework to evaluate impacts and select adaptation strategies, there are important caveats that have to be considered. First, that climate change impacts on groundwater resources have not been addressed in this study, and for further analysis this variable has to be included explicitly. Second, that a more realistic representation should distinguish between uses of water that are climate-sensitive and uses of water that are not. In this way, water demand sensitivity to climate variations will be captured and simulated when climate change scenarios are run. Daily consumption data – which is not yet available – is needed to correlate water consumption and climate. Additionally, water availability for the city is highly dependent on agricultural land surface evolution; hence land use change needs also to be modeled. Urban land use development must also be understood to relate its transformations with resource availability, e.g. public space and private garden irrigation. In sum, the assessment metrics results shown above are, at best, an approximation of the potential impacts of climate change, due to both the difficulty of extreme dry period representation and also the inherent simplification – needed here as in any model – of a complex water system. Interpretation of the results should be undertaken with restraint and precaution.

Finally, it is essential to involve multiple water users and other stakeholders in this adaptation framework. For instance, the city's supply performance metrics must be discussed further with Santiago's principal utility company, as well as other providers and decentralized 'Rural Drinking Water Systems' organizations, so that adaptation alternatives can incorporate the priorities and interests of different water users.

By bringing into consideration these diverse factors, impacts will be better represented and planning options will be bounded to real possibilities, within a more defined framework, and by addressing not only management goals but also management actions. This should be the appropriate path to establishing different options of dynamic planning which combine and switch strategies over time according to well-defined criteria.

ACKNOWLEDGEMENTS

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