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Beyond city limits: Using a basin perspective to assess urban adaptation to climate change

The case of the city of Santiago in Chile

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Abstract:

This paper describes the challenges and solutions/opportunities for urban water supply systems in adapting to climate change. We present a conceptual model to assess the adaptation options available both within and beyond city limits by considering the basin in which the city is located. While the options available within the city are common to all cities in the world, their potential use differs according to their respective vulnerabilities. The portfolio of options outside city limits varies for each city depending on the location of the city within the basin and its relation to other water users. Drawing upon this framework we present the case of Santiago, the largest city in Chile, with more than 7 million people and producing almost 40% of the nation's total gross domestic product. The main source of water supply for this city, the Maipo River, is expected to have reductions in water availability due to less precipitation and higher temperatures linked to climate change. Different adaptation options within and outside the city are being considered for the city of Santiago and other water users. Next steps involve articulating a basin-wide climate change adaptation plan that is able to recognize and deal with both challenges and opportunities froma basin perspective.

Keywords:

Adaptation, Basin, Santiago de Chile, Urban water supply

1. Introduction

Urban centres nowadays hold more than half the world's population (United Nations, 2012), and much of the gross domestic product (GDP) of most nations is concentrated there (World Bank, 2008). Most of the population in wealthy nations live in urban areas, and rapid urbanization is also occuring in low and middle-income nations as they experience rapid economic growth and associated increasing needs for critical resurces such as water and energy. According to the last IPCC report on Impacts, Adaptation and Vulnerabilities (IPCC, 2014), rapid urbanization has been accompanied by rapid growth of highly vulnerable communities associated with low adaptive capacity.

Future demographic projections suggest that the global population will keep growing this century (United Nations, 2006), and that the world´s population living in the largest agglomerations will be exposed to the direct impacts of climate change. According to the Urban Chapter of the latest IPCC assessment (2014) some of the urban risks related to climate change include storm surges, heat stress, extreme precipitation, inland and coastal flooding, landslides, drought, increased aridity, water scarcity and air pollution. Drought can have many effects in urban areas, including increases in water and electricity shortages. Rising sea levels, storm surge and heavy rainfall could have large effects on populations and infrastructure (Nicholls, 2004), while saline intrusion as a result of sea level rise could also constrain groundwater availability and quality. Climate change also creates several challenges for air quality, drinking water, food security and shelter (WHO/WMO, 2012 and Barata et al. 2011).

Water and sanitation systems affect the health and well-being of households, while also influencing urban economic activities, energy demands and the rural-urban water balance (Gober, 2010). Climate change will affect the operation of these systems including decisions related to long-term planning and investment in infrastructure (Fane and Turner, 2010), and may also exacerbate conflicts between water users (Roy et al., 2012). Under these scenarios, assessing climate change impacts and the different adaptation options for water supply systems is neccessary.

In the next section of this paper, we offer a conceptual framework to assess these adaptation options considering both a city and a basin-wide perspective. Using this framework we present in Section 3 an assessment of the water supply adaptation needs for the city of Santiago in central Chile. We finish this paper with discussions on the challenges and opportunities of climate change adaptation that arise with the proposed basin perspective.

2. Conceptual model to assess threats and adaptation options for urban water supply

As mentioned earlier cities are and will continue to suffer from many climate related threats. Of these, threats to water supply are a major concern especially for cities in semi-arid regions. We propose in this section a systematic approach to assess the potential adaptation options for water supply systems. The approach first looks at the city as an isolated system. In Figure 1 we represent different components of water consumpton in a city (eg residential, industrial, and parks and green spaces). Some of these consumers could be aggregated within the service provided by a single water utility or could have their own water supply system. This dual represention is very common, for example, with large industrial consumers who often rely on their own water supply systems (surface or groundwater). When considering the residential sector we can recognize a continuum between the centralized water supply system which is the norm in most industrialized cities and the decentralized water supply system more common in the developing world.

In terms of the water supply options, we depict three types of sources in Figure 1:

1. External diversions/extractions (most typically river diversions),
2. Groundwater extraction within the city
3. Reuse of effluents from wastewater treatment plants.

The flow between the source of water and its consumption is mediated by a series of pipes and pressurizing systems that create the desired characteristics of water flow (continuity, quality, pressure, etc.) at the point of use. In the distribution system there are typically inefficiencies ($\eta 1$) that can be estimated as the difference between the water extracted (from many sources) and water finally used.

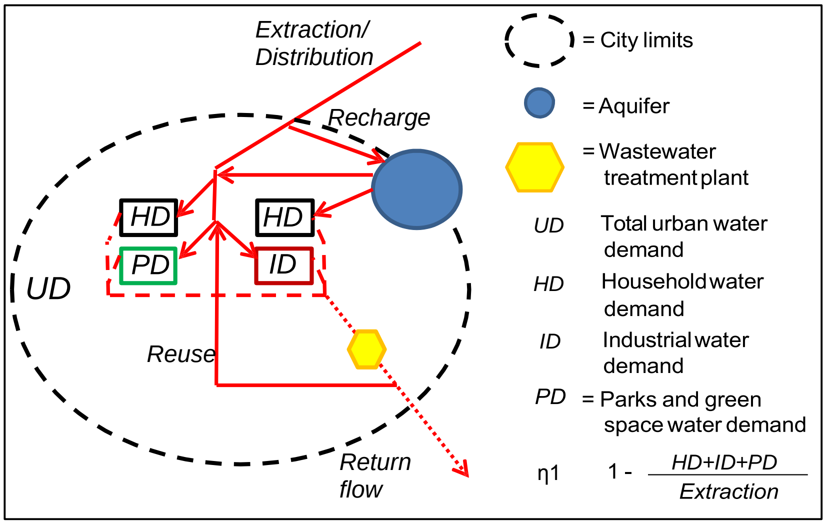

Figure 1. Simple schematic representing an urban water supply system

Consider now the climate threat of a reduction in water supply availability. This can be reflected above by a reduction in the amount of water flowing into the city from the external source. It could also be represented by a reduction of groundwater table levels beyond a sustainable threshold. For simplicity, we stick with the first scenario for which there is a series of solutions. On one hand there could be a reduction in total water consumption, but sustaining the desired output (e.g. industrial output, green lawn, washed clothes). This option improves water use efficiency (η2). Another type of adaptation option is associated with the distribution system where leakages that typically occur can be reduced by improving the physical and operational characteristics of the network (water distribution efficiency η1). Finally we can consider water supply options that fall within the boundaries of the city. The most typical of these options is groundwater extraction that is normally used as a (more costly) backup option for water supply in the formal system. The sustainable use of this option can be complemented by artificial aquifer recharge close to the location of groundwater pumping wells. And finally a way to improve overall water distribution efficiency is centralised wastewater reuse, an option that is gaining popularity. All these options have been explored and are under study in several cities around the world (IPCC, 2014).

Let´s extend the analysis now beyond the city limits to consider a basin framework. From this perspective, the city is one of many water users, as represented in two new schematics (Figure 2). In these schematics we consider two possible locations of a city within the basin. In the first case (Basin type A) the city is located close to the headwaters, and in the the second (Basin type B) the city is located near the outlet. In both cases we consider different water users such as agriculture and hydropower generation.

We also recognize possible connections to other sub- basins that could potentially have different climate conditions uncorrelated to the basin in which the city is located (consider large interbasin transfers).

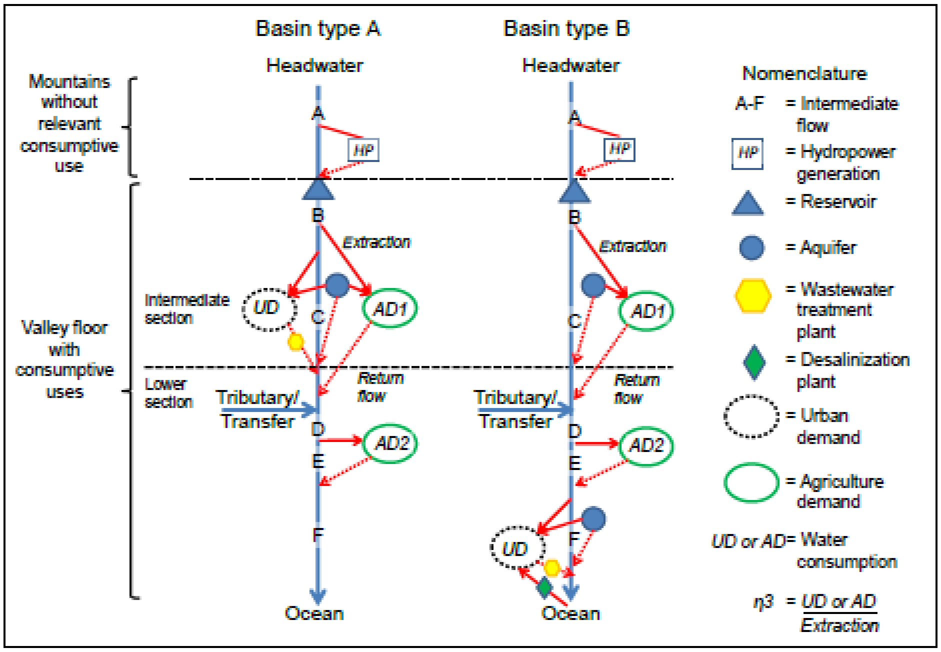

Figure 2. Schematics representing urban water supply system within a basin perspective

Now let´s consider the same situation depicted before whereas we foresee a reduction of surface water availability for urban demand but consider now the adaptation options available outside the city limits. Imagine for the sake of simplicity that after urban and agriculture consumption happens in different locations in the basin the only available water left in the river is that needed to supply instream flow requirements. If the reduction in water availability affects only some periods of time (within or between years) an option could be to build a reservoir that could dampen the temporal effects of that reduction. This is an option that is available for both cases A or B. However, the next portfolio of options available are different in cases A or B. The only option left for case A would be a reduction in water that is made available to the close-to- headwater agriculture sector. In the case of type B basin we recognize at least three more options:

1. A further reduction in agriculture water deliveries that includes also the irrigated areas located in the lower portions of the basin
2. Increasing water flow in the interbasin transfer or tributary
3. Taking water directly from the ocean through a desalinization plant

Technically all these options are also available for case A, but there is a clear energy/economic cost to pump water upwards against gravity hence for sake of argument we consider that these are not available options.

The main message we want to convey here is that when looking at a basin scale there seems to be a broader set of water supply adaptation options when a city is closer to the basin outlet than the headwaters. There are, however, other important considerations. For example, in terms of water supply quality the costs of water treatment in case A should be less than in case B, where there is a contribution of pollutants within the return flows of all users upstream of the city. Also in terms of contribution of flow (and nutrients, sediments) from inland to the ocean it is expected that they are larger in case A as compared to case B. This analysis considers that “water use efficiencies” are typically relatively higher in urban as compared to agricultural settings. Other important considerations will be discussed at the end of the paper.

In the next section we apply this conceptual framework to understand climate change threats and adaptation options for the city of Santiago located in the Maipo Basin in central Chile.

3 Water supply adaptation in Santiago and the Maipo Basin in Central Chile

3.1 General context

Santiago is the largest city in Chile. Located at the foothills of the Andes Mountains, it is home to nearly 7 million people and produces nearly 40% of the nation’s total GDP. The 250 km Maipo River runs from the Andes Mountains to the Pacific Ocean, and supplies 70% of the drinking water for Santiago. The river’s average flow is around 90 m3/s (DGA, 2003) and it has a snowmelt-dominated regime, with streamflow peaks occurring in late spring (December). Consequently, and since precipitation in this region is low (320 mm/year) and constrained to the winter period (June to September), water supply for Santiago is strongly dependant on snow accumulated in the mountains each season. The Mapocho River also supplies drinking water for Santiago. In addition to the Maipo and Mapocho Rivers, the El Yeso Reservoir - with a capacity of 220 million m3 (Mm3) and several pumping wells - further supports the water supply system. The Maipo and Mapocho basins are located in the heart of the semi-arid highly variable climatic region in Chile. Standard deviation of annual precipitation is roughly half the average amount and since 2009 there has been an extended drought with precipitation levels never reaching average values during the 5 year period.

The average per capita consumption in Santiago is 150 L/day, although consumption can reach more than 600 L/day when considering high income neighborhoods (SISS, 2009). Water use within Santiago is mainly residential, accounting for 73% of total water consumption. The remaining consumption is associated with industrial, commercial, parks and other uses. Aguas Andinas, the city's largest water utility, is responsible for producing drinking water and managing water supply for 90% of the city's population (SISS, 2012). The remaining 10% is served by Servicio Municipal de Agua Potable Alcantarillado, a municipal water utility which operates in one specific district. The system as a whole – considering both water utilities - produces more than 400 Mm3 per year. There are two wastewater treatment plants at the west side of Santiago, where 100% of the wastewater is treated and then returned downstream to the Mapocho River.

Considering the location of Santiago within the Maipo Basin and the framework presented earlier, we can classify this as a Basin Type A (Figure 2 and Figure 3). Other activities using water in the Maipo River Basin are agriculture, hydropower and mining, which are all very relevant economic sectors in the region and in Chile. With an area of 136,000 ha, irrigated agriculture is the main user of water in the basin (INE, 2007). Irrigation efficiency is considered low (50%) due to the predominance of furrow irrigation, which implies high return flows back to the river. There are 11 hydropower plants in the basin which are all run-of-the-river plants. In total, average use of water is 115 m3/s (DGA, 2007) with a generation potential of near 350 MW. Water demands regarding mining activities are mainly related to one copper mining site located upstream in the San Francisco River (upper Mapocho). Finally, there are recreational and environmental demands in different stretches of the rivers in the basin. All of these features are represented in Figure 3.

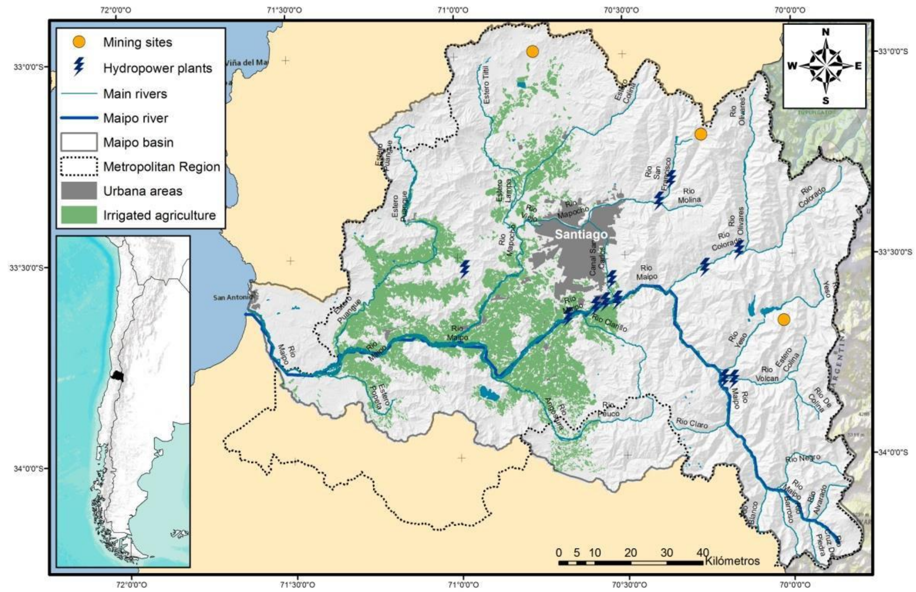

Figure 3. The Maipo River Basin.

The Maipo Basin is a system in evolution with the growth of Santiago being a critical component of this process. In the 1970s, the city had less than 3 million people. In 40 years since then that number has more than doubled to nearly 7 million people. And although daily per capita water consumption has been reduced from an average of 350 to 150 L/day, the increase in population has triggered an increase in aggregate consumption from 350 to 400 Mm3 (see Figure 4).

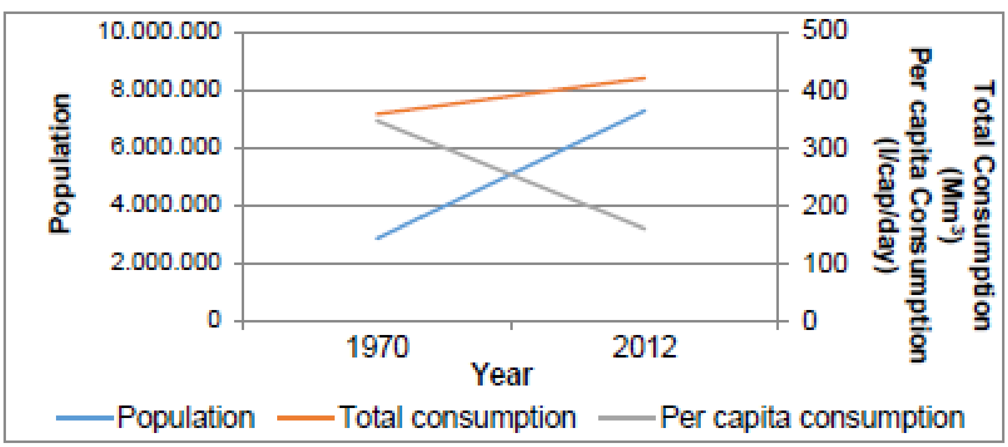

Figure 4: Evolution of Santiago's population and water consumption (SISS, 2012; OPRU 1972)

This increase in population has a spatial footprint in the basin with an important increase in hectares covered by urban land use in the last 40 years as shown in Figures 5 and 6.

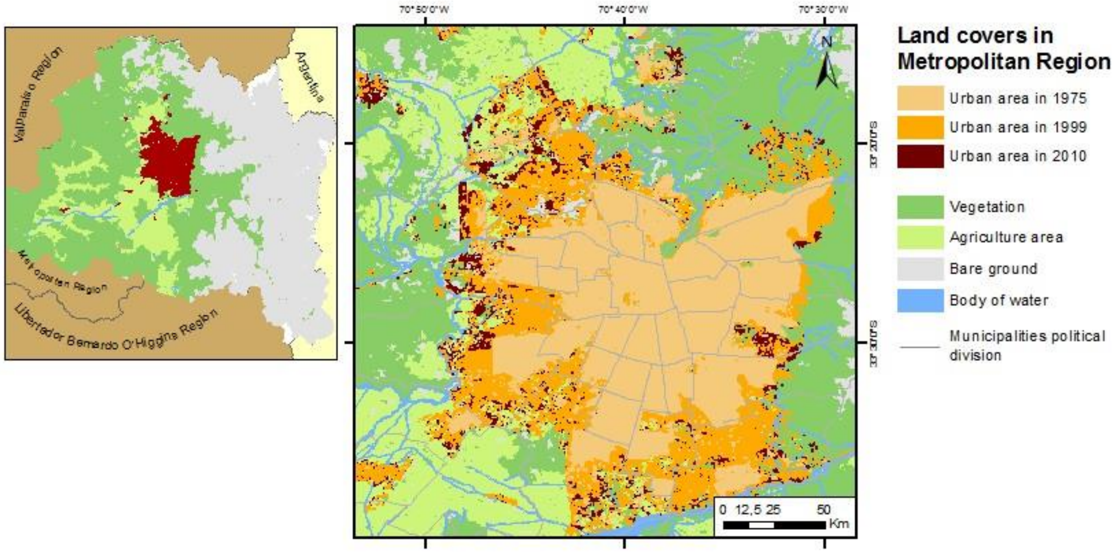

Figure 5: Land cover in the Santiago Metropolitan Region (based on Puertas et al. 2014)

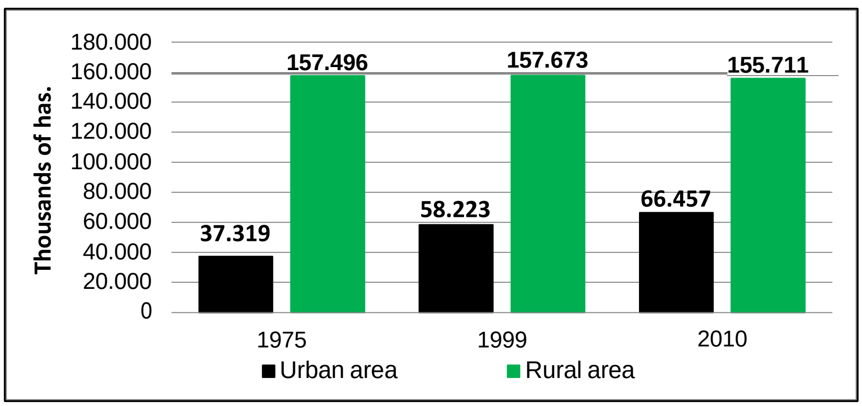

Figure 6. Historic land use trends in the Maipo Basin from1975 to 2010 (Puertas et al. 2014)

Santiago has doubled in surface area over the last 40 years. And this growth has occurred at the expense of agricultural land located on the outskirts of the city. However, total agricultural land has stayed at similar levels within the basin due to replacement of natural vegetation surface. Total water consumption in the agriculture sector has diminished over time. Maintaining productive land has been possible due to a steady increase in the prominence of efficient irrigation technology. As can be seen in Figure 7, drip irrigation accounted for less than 10% of total irrigated land in 1997. Ten years later, it has increased to more than 30% and this trend is expected to continue in the future, especially with a more fruit/vineyard oriented crop mix.

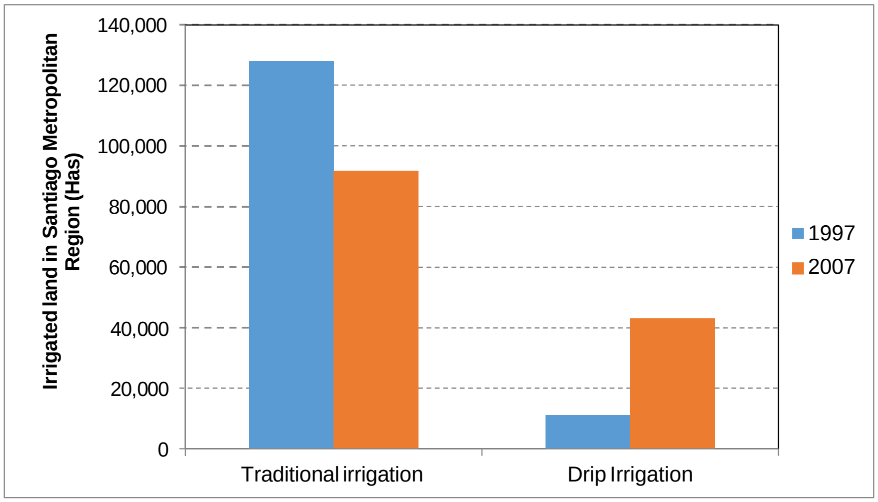

Figure 7. Changes in irrigation technology in the Santiago Metropolitan Region (INE 1997-2007)

Most of these water savings have been sold to water utilities in the urban sector. Water rights are a peculiar characteristic of Chile´s water system that grant private ownership of water regardless of its intended use and land ownership (Vicuna and Meza, 2013). Buying water rights are one of the main new sources of water that the city's water utilities have been using historically to accommodate its increasing population and prevalent dry conditions (ANDESS, 2014).

3.2 Water supply threats

Although Santiago's water supply system has been designed to high standards, important threats to performance can be identified as the consequence of climate variability and climate change and also due to a growing population. During the last 7 years, water consumption has increased at an annual rate of 1% and is expected to keep increasing as a consequence of Santiago`s growing population. In addition, climate change plays a major role as a driver of the hydrological cycle. Observed warming during the past has been associated with changing precipitation patterns, intensities and extremes (IPCC, 2011); widespread melting of snow and ice; increasing evaporation (Trenberth, 2007); changes in soil moisture and runoff (Bates et al., 2008). One of the most relevant considerations for snowmelt-dominated basins is that in a warmer world, less winter precipitation falls as snow and melting of winter snow occurs earlier in spring. Therefore regions where water supply is currently dominated by melting snow or ice are particularly vulnerable (Barnett et al., 2005).

The Maipo Basin does not escape this fate. Previous assessments on the potential impacts of climate change on the Maipo River present a future where total discharge volume could decrease between 10-40% and have peaks of river runoff from 1 to 4 weeks earlier depending on the global circulation model (GCM) projection, the GHG emission scenario and the future period considered (Meza et al, accepted). Similar runoff projections have been obtained in other snowmelt-dominated basins in central Chile (Vicuña et al. 2010). These runoff impacts are associated with increases in temperature and reduction in precipitation expected in the future as presented in Figure 8. Some of these changes are already ocurring as shown in Figure 9.

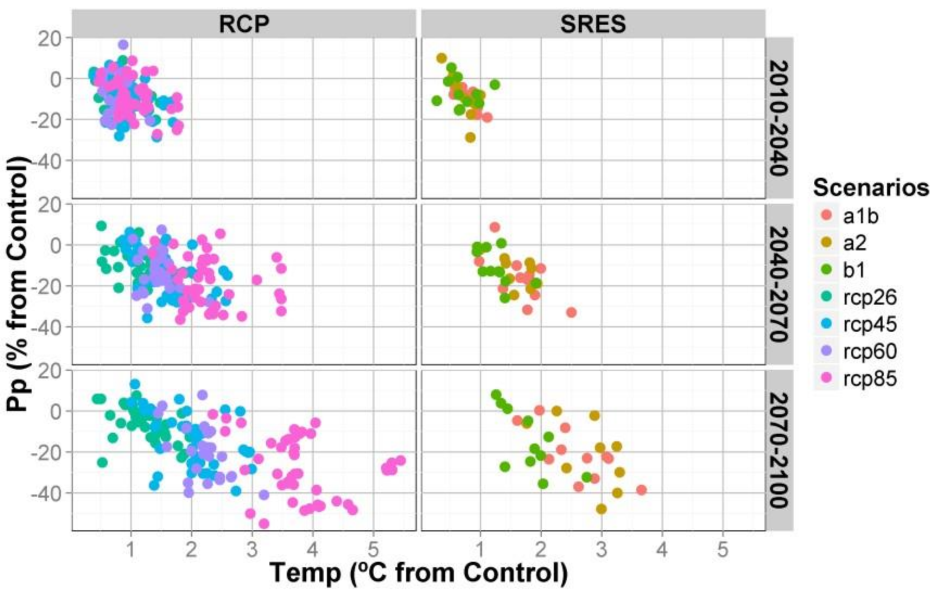

Figure 8. Representative Concentration Pathways (RCP) (IPCC, 2007) and Special Report on Emission Scenarios (SRES) (IPCC, 2013) projections for precipitation and temperature from Quinta Normal weather station located in downtown Santiago.

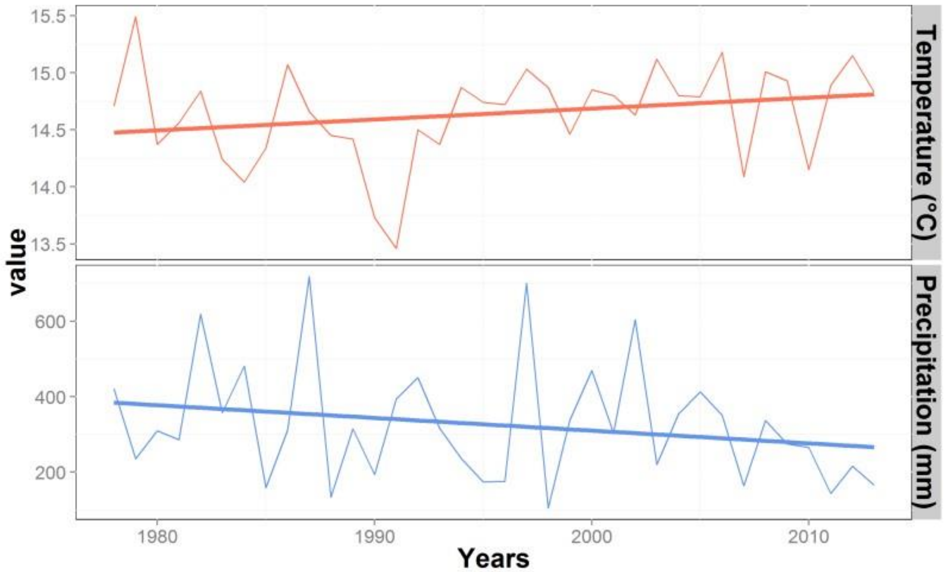

Figure 9. Precipitation and temperature historic observations from Quinta Normal weather station located in downtown Santiago

In addition to the climate and hydrologic projections presented, the consequences for Santiago`s water supply system have also been evaluated in recent publications. When comparing a mid- century period to a historic control period – with no adaptation involved - results show a decrease in the performance of Santiago`s water supply system. A decrease in continuity of drinking water service and a decrease in the minimum total urban water supply coverage associated with future periods were detected, while higher volumes of annual groundwater pumped would be needed to satisfy projected demands (Bonelli et al, accepted). Cascading uncertainties underlie these results (eg multiple emission scenarios and GCMs, long term demographic projections, scarcity of data), although they demonstrate that Santiago`s water system needs an adaptation plan to ensure water security into the future, which could have pronounced social and economic implications.

3.3 Water supply adaptation options

Considering the framework presented earlier, different adaptation strategies can be implemented to accommodate the impacts to water supply for the city of Santiago. For instance, considering measures that can be adopted within the city, potential gains in use and distribution efficiency ($\eta 1$ and $\eta 2$ presented earlier) could highly reduce Santiago's water consumption. Currently, nearly 30% of surface water extractions do not reach final consumers, mainly as a consequence of underground pipe leakages.

Therefore, one way of improving efficiency is by improving the network infrastructure. Efficiency could also be addressed from a demand-side approach, for example, through water policies that promote efficient household water consumption. According to estimations, a gain in efficiency of more than 20% is achievable with short-term installation of efficient fixtures and appliances in households and offices (Observatorio de Ciudades, 2009). Behavioral changes may reach similar gains and are most likely to result from pricing mechanisms (disincentives).

In addition, different options arise when we consider a basin perspective. One of these options is to increase the number of water rights owned by urban water utilities. Water utilities currently own 25% of the total amount of water rights for the Maipo River. This number has increased recently due to the already explained transfer of water from the agriculture to the urban sector.

According to Bonelli et al (accepted), this share should reach 40% by 2050 to cope with climate change impacts and population growth. This of course directly involves other water right owners coming from any of the economic activities previously mentioned. Infrastructure strategies are also possible at a basin level. Since the use of El Yeso reservoir is mainly focused on emergency supply for urban water use when surface water availability is scarce, building new reservoirs to increase the storage capacity of the system is also a plausible choice. Again, this depends not only on the interests and priorities of several actors regarding the diversity of water uses in the basin, but also on their willingness to sell their water rights.

It is clear that, although limited due to the particular city-basin configuration (Basin type B), a Maipo Basin perspective offers adaptation opportunities that go beyond those considered only within the city of Santiago. However, there are also challenges that need to be considered. For example, Vicuna and Meza (2012) present a hypothetical numeric example (using similar schematic to that presented in Figure 2) of potential consequences of relying only on water transfers from the agriculture sector to accommodate expected reductions in headwater flow due to climate change impacts. For the agriculture sector to maintain total productivity they should increase irrigation efficiency in order to save water. Because use efficiency is typically higher in an urban setting as compared to an agricultural setting, streamflow available via return flows from these two sectors would be greatly reduced affecting downstream users, especially flow at the outlet of the basin. In their simple example, Vicuna and Meza (2012) show that with a 20% reduction in flow in the headwater the cascade of adaptation measures (mostly improvements in irrigation efficiciency at two irrigation districts) would reduce flow at the outlet of the basin by more than 80%. Users located close to the outlet of the basin would also be affected disproportionally by the implementation of these type of measures.

4. Discussion and conclusions

As cities grow, so do their environmental footprints within the basins they are located. Cities consume water and other natural resources to sustain an ever growing population. The fate of these resources suffers from multiple threats, one of them being human extraction. Another important driver is climate. According to the latest IPCC report, climate change might affect future water supply for cities due to changes in climate variables and their impact on streamflow and water availability. The city of Santiago, located in the Maipo Basin in central Chile, is one of these threatened cities. The main water supply for this city, the Maipo River, is shared by many users (the most relevant being agriculture), and according to recent climate change impact studies streamflow in this river would be reduced due to increases in temperature and reduction in precipitation.

With these scenarios at hand the need to develop strategies to adapt water supply systems for cities and their growing population is evident. In this paper we offer a conceptual model to support this process. The model differentiates between the opportunities within the boundaries of the city and those that are beyond the city extending to the water basin where the city is located. In the first group of options, we discuss the role that water consumption savings, improvements in distribution, aquifer recharge or reuse of wastewater could have in protecting against excessive extraction and climate change impacts. When we extend the analysis beyond city limits we find that the portfolio of adaptation options increases to a level that is dependant on the relative location of the city within the basin and in relation to other users. If a city is located closer to the headwater of the basin the adaptation options are less than in the case when the city is located near the outlet of the basin. In the first case, options are limited to headwater infrastructure building and reoperation and savings-transfers of water from neighboring users (eg. irrigation districts also located close to headwaters). In the second case, in addition to those options the city water supply system could rely on transfers from neighboring basins, desalination of seawater and use of savings-transfers from a larger set of users.

Using these basin-wide perspectives to assess adaptation options allows the consideration of these benefits but also of some challenges or unexpected impacts associated with the implementation of some of these measures. For example in the case of the Maipo Basin, an increase in irrigation efficiency and later selling/transfer of saved water to the city of Santiago could be a good adaptation strategy but could also affect users downstream in the basin that were using the "unutilized" water. It is also important to consider that going beyond city limits creates another series of institutional and political challenges for cities that now need to collaborate with different actors and authorities at larger geographic scales, and deal with different and conflicting priorities, needs and dynamics.

Finally, it is important to recognize that although this paper has focused on water supply issues, this basin perspective to analyze climate change adaptation options could also be extended to other types of water-related threats. One clear example is the role that ecosystem preservation close to headwaters could have on preventing floods or erosion and later water quality detriments that could affect the operation of water supply systems for cities and surrounding communities.

The city of Santiago has in recent years started the process of incorporating some of these challenges into an adaptation plan developed under the Climate Adaptation Santiago (CAS) project. Continuing and complementing this initial attempt a group of researchers working in close collaboration with different stakeholders and funded by the International Development Research Center (IDRC) are currently articulating a climate variability and climate change adaptation plan for the Maipo Basin. This plan, called theMaipo Plan de Adaptacion (MAPA) uses an integral basin wide perspective to understand the challenges and opportunities behind climate change adaptation.

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