

Snow and Glaciers: Water Resources in the Maipo Basin

Stephanie Joyce, Middlebury College

Introduction

Provision of adequate water resources is becoming a worldwide problem aggravated by increasing population, migration to urban centers and anthropogenic global warming, with demand growing and supplies shrinking. The Metropolitan Region of Chile, which contains Santiago, the capital city, and over 40% of Chile's 15 million inhabitants, is especially vulnerable because of its heavy reliance on the snow and glaciers of the Andes Mountains for current water supplies. Despite the importance of snow and glaciers as water resources in this area, thus far they have received remarkably little attention from both the government and the scientific community. Lack of information has provoked a great deal of speculation and public misinformation, especially in the national press, about the current and future sources of water for the region. A November 3, 2008 article in a national newspaper, *La Tercera*, suggested that the Glaciar Echaurren, a 0.4 km² glacier, supplies 70% of Santiago's water and that it would disappear within the next 50 years to due global warming (Acevedo, 2008). Similar articles have been published in the *La Nación* (Mitchell, 2009) and *El Mercurio* (Zúñiga, 2009) in the past six months. The alarming nature of the story extended it beyond a national audience, reaching the public and policy makers worldwide through international press coverage. There is no evidence to support any of these claims, although the news provokes concern about the dearth of available information about Maipo Basin snow and glaciers and their contribution to water supplies. Existing information is primarily technical in nature and disparate, not offering an overview of the water resource availability issue. This dearth of information contributes to the overall confusion surrounding the issue, especially regarding water availability and reliability. The purpose of my research is to synthesize relevant information about regional climate change, snow and glacier trends in the Basin, water usage, and associated political decisions.

Geography

The Maipo Basin extends from 32°55'N to 34°15'S and from 69°55'W to 71°33'W, covering the entire Metropolitan Region and a small portion of the V Region, joining more than 15 rivers and streams (Cade-Idepe 2004). There is some variability in the estimations of its total area, but most studies cite figures between 15,000km² and 15500 km². The primary tributaries of the Basin are the Volcán, Colorado, Olivares, and Yeso rivers, all of which join with the Maipo River in the High Maipo Basin, subsequently flowing towards the central valley and the southern periphery of the capital city. The Mapocho River, which brings water from the north towards the capital represents another major tributary, joining with the Maipo River to the west of the city (see map 1). The Mapocho River's major tributaries are Estero Yerba Loca, Estero Arrayán and Río Molina.

The Metropolitan Region is located in the central-north zone of the country, which is characterized by its Mediterranean climate, receiving maximum precipitation during

the austral winter (May-August). This wintertime precipitation constitutes about 80% of the total annual precipitation and above 2500 meters normally falls as snow. The amount of precipitation increases towards the Andean Cordillera due to a strong orographic effect, which, along with a decrease in temperature, allows for the formation of mountain glaciers in the region (Dirección Meteorológica de Chile, 2009).

The Metropolitan Region encompasses strong topographic relief with the Andean Cordillera rising to over 6000 m to the east and the Pacific Ocean located only 10 kilometers from its westernmost boundary. Santiago, at an average elevation of 560 m a.s.l., is located in the central valley, between the Coastal mountain range, rising to 2338 m a.s.l. at Morro Chache and the Andean Cordillera. Since the prevailing winds are westerly, the coastal mountains and the Andes receive more precipitation than the central valley.

According to the 2002 census, the Metropolitan Region of Chile was home to 40% of the total population (INE 2002), and it continues to grow. An average of 10,155 building permits were issued per year between 2003 and 2007 for the construction of homes in the greater Santiago area (Corporación para el Desarrollo de Santiago 2008). Together with a great part of the country's population, the Metropolitan Region has a significant concentration of agriculture and industry. Even though the Metropolitan Region has only 2% of the total land area of Chile it is responsible for almost 15% of the agricultural GDP (ODEPA 2005) and more than 40% of the total GDP (Banco Central de Chile 2003). This high density of population, intensive agriculture, and industry requires a large water supply and careful planning to ensure its continuing availability.

Water Demand

According to a study contracted by the National Water Board (DGA) in 2007, by summing the consumptive and non-consumptive water demands in the Metropolitan Region, the total demand for human ends is 256.3 m³/s, (Ayala, Cabrera and Associates Ltda. 2007, see table 1). The consumptive demands come primarily from agriculture, industry, and households, while the non-consumptive demands are from hydroelectric power generation and tourism (e.g. enough water for vessels to transit, scenic value etc) as well as use of the river to dilute contaminants (e.g. maintaining a certain minimum necessary to disperse contaminants).

In 2007 the demand for potable water was 18.5 m³/s (Ayala, Cabrera and Associates Ltda. 2007), a figure that represents 124% of 2000 potable water consumption, reported by Brown and Saldivia (2000) as 14.9 m³/s in their National Report on the Management of Water. Brown and Saldivia (2000), projected the demand for 2005 at 19.5 m³/s (615.1 H m³/year) or a meter per second more than reported 2007 demand. The projections by Ayala, Cabrera and Associates (2007) for 2017 are somewhat greater than the projections of Brown and Saldivia (2000) for 2025, the former being 23.4 m³/s and the latter between 20.2 and 22.0 m³/s, depending on the per capita increase of water demand and population growth scenario.

Demanda de Agua en la Región Metropolitana de Chile
Actual y Proyecciones Futuras
Caudal por uso en metros cúbicos por segundo (m³/s)

Año	Agro-pecuaria	Agua Potable	Industria	Minería	Forestal	Energía	Receptor Contaminantes	Turismo	Caudal Ecológico	Total
2000		14.9	4.01 [^]			114				133
2005		19.5	5.24 [^]							
2007	82.5	18.5	10.4	0.481	0.096	129	15.4	0.002	50.4	307
2017	80.5	23.4	15.4	1.37	0.16	129	15.4	0.002	50.4	316
2025		21.1	15.4 [^]							
2032	80.5	24.8	27.6	1.99	0.16	129	15.4	0.008	50.4	330

Tabla 1: Elaboración propia usando datos de Ayala & Cabrera (2007) y Brown y Saldivia (2000)
[^] Dato base corresponde a 1995, industria y minería calculado juntos

Table 1: Metropolitan Region water demand, current and future projections. Runoff is reported in cubic meters per second. Table was elaborated using data from Ayala, Cabrera and Associates (2007) (base year 2007) and Brown and Saldivia (2000) (base year 2000). [^] Base data point is 1995, industry and mining are calculated together.

Despite having estimates on the demand predictions, it is difficult to draw conclusions about future water availability, especially in the long-term, for a variety of reasons that will be examined in detail in this paper.

Snow-climate-water interaction

The hydrological regime of the Metropolitan Region is nivo-glacial, which means that the majority of its water comes from the melting of snow and glaciers. The time of peak discharge is during spring and summer, which coincides with the period of highest demand for irrigation and residential consumption. Masiokas et al. (2006) report that from 1951 and 2001, the average water contribution from snowpack and glaciers between November and February was 55.8% of the annual total in the central Andes. Variations in annual snow accumulation in the Basin (measured in snow water equivalent) can account for >85% of the interannual variation in the runoff of the Maipo River (Masiokas et al. 2006), which suggests that less than 15% is the product of glacial runoff and rainfall at low altitudes. However, during dry years glacier melt can provide up to 67% of the total runoff of the Maipo River according to a study conducted by Peña and Nazarala in 1987.

According to Masiokas et al (2006), within the central region of Chile and Argentina, between 28°S and 36°S, which includes the Metropolitan Region, there are only 30 snow courses (fixed routes with stakes for snow measurement) with historical records, and of these, only six have a record longer than 30 years with less than 10% of the data missing. There is only one snow course within the Maipo Basin that fulfills these requirements, the Laguna Negra (33°40S, 70°08W, 2768 m a.s.l.), which has a record since 1965 (Masiokas et al. 2006). This points to the need for increased monitoring of snowpack to obtain reliable baseline data.

The average snow accumulation for Laguna Negra between 1965 and 2004 was 573 mm snow water equivalent (Masiokas et al. 2006). There is significant annual variability in precipitation within the Metropolitan Region, with deviations of 6-257% from the average snow accumulation (Masiokas et al 2006). This high annual variability makes planning a challenge, as it is due to a number of meteorological factors that are difficult to predict. It has been demonstrated that there is a significant correlation between the ENSO (El Niño Southern Oscillation) phenomenon and precipitation in central Chile (Escobar y Aceituno 1998, Quintana y Aceituno 2006, Masiokas et al. 2006). There is consensus that El Niño events are correlated with high precipitation years, while La Niña events tend to produce dry years. However, according to Masiokas et al. (2006), the ENSO phenomenon is not capable of explaining more than 44% of the annual snow variability, with the other 56% is attributable to a variety of complex interactions that have yet to be studied in detail. The group of measurements from the six snow courses with relatively complete 30-year records show a slight, but statistically insignificant, positive trend of 3.95% per decade ($p=0.543$) in snow accumulation during the period 1951-2001, which confirms high annual variability but does not indicate any general trend in central Chile (Masiokas et al. 2006). Even though the high variability in annual snow accumulation tends to cause variability in runoff, it is partially compensated for in the Maipo basin by glacial runoff, which tends to increase with decrease in precipitation (Hock et al. 2005).

Ice-climate-water interaction

The cryosphere (composed of all water on Earth that is in a naturally-occurring solid state) is a crucial resource for a variety of reasons, among them the fact that it contains up to 75% of the world's freshwater resources (Bates et al. 2008). The majority is stored in the two large ice sheets of Antarctica and Greenland. However, the smaller reserves represented by the world's mountain glaciers have a much more immediate impact on human settlements because of their vicinity and direct contribution to industrial and potable water provision wherever runoff contributes to inhabited river systems. Such is the case of the Maipo Basin, where glaciers can represent a significant contribution, especially during dry years as they represent an important regulator of the runoff effect of annual variability in the snowpack (Peña and Nazarala 1987).

The two primary types of mountain glaciers in the Maipo Basin are debris-free glaciers (known as glaciers) and rock glaciers. Glaciers form through the accumulation and sintering of snow, that first transforms to firn and later to ice as overburden pressure increases. This transformation can take from a few years to a few decades in glaciers, depending on climatic and geometric factors such as precipitation, temperature, and aspect. Firn-ice transition can accelerate notably by the occurrence of melt-freeze events.

In contrast to glaciers, rock glaciers are not only composed by clean ice, but have large accumulations of detritus joined by ice, being composed of between 40-60% rock and 60-40% ice. Rock glaciers flow downslope due to the softness of the ice, although their velocity is less than that of clean glaciers. For both types of glaciers, the accumulation process occurs during the wet season and the melting of snow and/or ice occurs during the summer period, and is increased at lower elevations. Despite annual melt and accumulation cycles, the initial formation of a glacier requires centuries if not

millennia when accumulation exceeds melt, which only occurs during periods when lower temperatures prevail. For that reason, glaciers are a water *reserve*, and once gone, they are irreplaceable at human time scales.

Scientists refer to a year when there is less snow accumulation than there is melt as a year of negative mass balance (for a specific glacier) because what was lost was not replaced. A year of equilibrium is one in which the same amount melts as snow accumulates, and there is no change in the net mass of the glacier. When more snow is gained than melts, then there is a positive mass balance. So, for every year it is possible to classify a glacier as having either a mass balance that is negative, positive, or in equilibrium. Several years of negative mass balance lead to the so-called retreat of the glacier, when parts at lower elevations disappear. Some factors that can cause glacial retreat over the course of several years are higher temperatures and lower precipitation. A period of positive balance results in the advance of the glacier, when the glacier is forced downslope by the weight of ice and snow faster than it is melting at the front. A glacier in equilibrium does not retreat or advance.

Mountain glaciers represent a complex system of interactions between a number of factors, so the hydrological contribution of a glacier to a river system varies according to several timescales depending upon the climate conditions, physical transport mechanisms, and mass of the glacier itself (Hock et al. 2005). These timescales can involve diurnal variability, seasonal variability, annual variability, and multi-annual variability. The diurnal variability of glaciers is important because runoff can triple during a single warm day without any precipitation. Seasonal variation refers to the difference between winter runoff, which tends to be insignificant, and summer runoff, which can be voluminous. With regard to annual variation, basins with 40% glaciation tend to have relatively little annual variability in water discharge. Basins with less glaciation, like the Maipo Basin, are more acutely affected by snowmelt runoff peaks and lows during spring melt and the winter season. However, years when there is more precipitation and thus a larger snowpack tend to result in less glacial contribution to runoff and greater storage, and consequently positive glacier mass balance. In this way glaciers act as regulators of runoff, contributing more when there is less snowpack and storing for drier years when there is sufficient snowpack.

Glacial runoff increases with temperature, along with a decrease in glacial mass until the glacier reaches a 'critical mass'. Initially the hydrological contribution to runoff with respect to its mass is an inverse relationship, but it later drops off sharply after reaching its critical mass (Corripio 2007, Casassa et al. 2009). In other words, the first response of a glacier to a rise in temperatures is an increase in river discharge, corresponding to greater ice melt, followed by a decrease when the glacier is so reduced in size that it can no longer feed the river system with substantial runoff.

Glaciers of the Maipo Basin

A fluviometer record for the Maipo Basin has existed since the middle of the 20th century, but data about glaciers is as scarce as data about snowpack. Cedomir Marangunic carried out the only detailed inventory of glaciers in the Maipo Basin in 1979 on behalf of the National Water Board (DGA) based on aerial photography of 1955-1956. Earlier, Louis Lliboutry (1956) performed a preliminary inventory based on aerial

photography of 1944-1945. The DGA is currently conducting a new inventory with results for mountain glaciers expected at the end of 2009, but the results will not be comparable to previous studies because of differences in image resolution (Gonzalo Barcaza Sepúlveda, personal communication). Alexander Brenning conducted another inventory in 2003/2005 with the purpose of estimating the number of rock glaciers in the basin. Brenning (2005) estimates that the number of rock glaciers is 7:1 in the Basin, in comparison to Marangunic's 1:1 estimate. Brenning's estimation of the total area of glaciers doubles that of Marangunic (1979), although he uses a statistical approach and not a direct inventory like Marangunic.

Marangunic's inventory counts 647 glaciers that make up the Maipo Basin, covering an area of 421.9 km² (Marangunic 1979, Valdivia 1984, Rivera 2000). According to this figure, glaciers cover 2.8% of the Basin's total area (using a figure of 15,157 km²), with 49.6% classified as clean glaciers and 50.4% as rock glaciers. Medium sized (1.00-9.99 km²) glaciers dominate, representing 47.8% of the Basin's glaciers. The Equilibrium Line Altitude (ELA) or the highest summer firn line, is estimated for the region at 3792 m a.s.l., but varies between 3508 m and 4081 m. Marangunic estimates the volume of water contained in the mountain glaciers within the Basin by assigning an average thickness relative to the surface area together with an ice density of 0.8 g/cm³ and a 50% ice content for rock glaciers. This method yielded a value of 30.65 km³ of water stored in glacial ice, with an estimated 10% margin of error.

The number of glaciers could be more than one order of magnitude higher than Marangunic's estimate according to Alexander Brenning's (2005) estimates. With the addition of several thousand previously unconsidered rock glaciers the extent of glaciers could reach an estimated area of 791 km² or approximately 5% of the total Basin area, almost twice that estimated by Marangunic. Within this area Brenning proposes that rock glaciers compose 312 ± 64 km², mountain glaciers 412 km² and dead ice (not moving), 67 km². According to his analysis clean glaciers are most prevalent above 4250 m while rock glaciers are more prevalent between 3500-4250 m (Brenning 2008). There are no glaciers below 3000 m in the Basin. Brenning agrees with Marangunic that the ELA is at 3800 m a.s.l., varying between 3600 m a.s.l and 4000 m a.s.l (Brenning 2003). In his 2003 paper Brenning proposes that using the same technique of area-thickness correlation and a density of 0.8 g/cm³ as Marangunic (1979), the clean glaciers in the Basin represent a water volume of approximately 28 km³. Rock glacier volume is calculated as 2.7 km³ based on various assumptions about rock glaciers, which are a recently studied phenomenon and therefore have characteristics yet to be measured. In his 2005 paper Brenning does not give an estimate for the volume of water contained in clean glaciers but does a recalculation (using a statistical method) to include new rock glaciers that suggests water content might be up to 3.5 km³ in the Basin's rock glaciers.

The only glacier within the Basin with a historical mass balance record is the Echaurren North Glacier, which has been measured consistently since 1975 (Escobar et al. 1995, DGA personal communication). Echaurren North was selected for its facility of access, rather than for its representational value within the entire Basin. Several factors limit using Echaurren data for accurately modeling glacier behavior in the Maipo Basin. It has a very small surface area (0.4 km²), especially in comparison with the other glaciers of the Basin, of which 75% are larger (Marangunic 1979). Also, it is located at a very low altitude with minimal elevation change (3650-3880m), whereas the majority of

the mountain glaciers are located above 4000 m (Brenning 2005, Marangunic 1979). Additionally, because its entire aspect is south-facing it does not allow for analysis of the impact of aspect on accumulation and ablation. Thus the extrapolation of Echaurren data to the whole Basin could introduce significant errors into the estimation of a representative mass balance. The mass balance data for the Echaurren North Glacier appears to reflect more the amount of wintertime precipitation and to a lesser degree the temperature of the melt season than it does the larger scale climate changes within the Basin.

Nevertheless, taking those factors into account, the measurements from Echaurren North Glacier show a negative trend in the glacier's mass (DGA personal communication). The National Water Board calculates that Echaurren North has a cumulative mass balance between 1974 and 2009 of -747 centimeters water equivalent (DGA, personal communication), calculated using the standard equation of accumulation (in cm of water equivalent) minus ablation (in cm of water equivalent) (Kaser, Fountain and Jansson 2003). The average accumulation per year during the same period is 271 cm and the average ablation -293 cm, making an average mass balance of -22 cm per year. Despite the large annual variability and a near-equilibrium balance in 1975-1993 and in 1998-2009, there is clearly a negative trend in balance in the period 1993-1998. This is in agreement with other glacier studies in central Chile, such as the study of the Aconcagua Basin just north of the Maipo Basin, conducted by Bown et al. in 2008, that reports a net area loss of 0.6 km² per year in the last 30 years, suggesting that glaciers in the Maipo Basin may not be an exception. A cursory comparison of Masiokas' snow data and the mass balance of Echaurren North suggests that there is a correlation between years of low winter precipitation and increased mass loss, but any general conclusion requires more detailed analysis.

The rock glaciers within the Maipo Basin have received more attention since Brenning's work in 2005, but the extent of their contribution to runoff continues to be largely unknown. Brenning points out the significance of rock glaciers, noting their relative abundance and concentration below the current ELA. Maipo Basin rock glaciers tend to be smaller, varying between 0.01 and 2.0 km² with an average of 0.04 km² (Brenning 2005). Clean glaciers predominate above 4250 m, while rock glaciers are more prevalent between 3500 m and 4250 m, meaning that they may contribute more water during the summer but also might be more susceptible to climate changes, especially during warming trends (Brenning 2005). Brenning mentions that an important element of rock glaciers is their more consistent hydrological contribution to river outflow compared to clean glaciers because they have slower melt rates and primarily subterranean flows (Brenning 2003). If Brenning's statistical findings can be corroborated, rock glaciers play a much more important role in the hydrological system of the Basin than was previously thought.

Despite the uncertainty about the number of glaciers and the area they cover, both Marangunic's and Brenning's inventories show that glaciers are an important source of water, with both authors agreeing more or less on the total water volume. Marangunic estimated that there is 30.64 km³ of water in the Maipo Basin glaciers while Brenning estimated that they contain 31.5 km³ (the sum of the 2003 estimate of clean glaciers and the 2005 rock glacier estimate). For comparison, potable water consumption in 2007 was 0.58 km³ (Ayala and Cabrera 2007). At the end of dry summers the glaciers of the Maipo

Basin represent an important variable, with a contribution of up to 67% of the monthly runoff, as modeled for the driest year on record, 1968/1969 (Peña y Nazarala 1987). Even in less extreme years these authors report that their contribution is significant, although less, with between 4 and 34% of the monthly discharge recorded between the months of December and February for the period 1981-1986. More recent studies of their contribution do not exist, so it is not clear whether their contribution has increased in recent years.

Even though there is no clear trend of increase or decrease in flow rates in rivers throughout the country, the Maipo River, measured at the fluviometric station Maipo en El Manzano, has had a mean annual discharge increase of $0.93 \text{ m}^3/\text{s}$ per year, significant at the 0.05 level between 1954 and 2003 (Masiokas et al 2006). Given that there have not been significant increases or decreases in precipitation reported for the Maipo Basin in recent decades (Quintana and Aceituno 2006), it is possible that increased flow rates are due to greater ice melt, as there has been a warming trend of $+0.28^\circ\text{C}$ per decade in the region (Falvey and Garreaud 2009). It is, however, difficult to extrapolate these conclusions to the entire Basin, since the fluviometric station Mapocho en los Almendros did not have a significant change in runoff during the same period of 1950 to 2007 (Casassa et al. 2009), even though it is only 25 kilometers from Maipo en el Manzano (see map 1).

There is a general trend toward the retreat of glaciers in Chile's central zone (Rivera 2000, Casassa et al. 2006) and a rise in the equilibrium line altitude (Carrasco et al. 2007), which suggests that glaciers in the region are losing mass at an accelerated rate. However, it is not possible to make a direct connection between mass loss and higher runoff because mass loss can occur through evaporation and sublimation as well as liquid discharge. In order to accurately determine glacial contributions to the increased runoff, it would be necessary to install fluviometric stations that could measure the discharge of several key glacial streams or rivers as close as possible to the ice sources.

The Climate

Predictions for climate change

The Intergovernmental Panel on Climate Change (IPCC) announced in 2007 that 1) warming of the climate is *unequivocal* and 2) the majority of global temperature increase since the middle of the 20th century is *most likely* due to the observed increase in anthropogenic greenhouse gases emissions (IPCC 2007). Global warming brings with it a whole host of changes, not only for temperature but also precipitation, sea level, spread of diseases, reduction in biodiversity and water reserves, to name a few.

In recent decades the whole world has experienced an average temperature increase of 0.74°C (IPCC, AR4, 2007). This increase has been greater in some regions and smaller in others, with the Arctic, central Asia and the Antarctic Peninsula being the most affected. Chile has warmed at different rates in the different regions of the country, but in general the temperature has demonstrated a positive warming trend of 0.14°C - 0.38°C per decade since 1933, with the most pronounced increases occurring recently (Rosenblüth et al. 1997). The Andean Cordillera has been subject to greater increases than the coastal regions, with measurements at Lagunitas ($30^\circ04'\text{S}$, $70^\circ15'\text{W}$, 2600 m)

and El Yeso (33°09'S, 70°05'W, 2400 m) of +0.28°C per decade (Falvey and Garreaud 2009). In the region between 30°-34°S, which includes the Maipo Basin, precipitation does not appear to have changed significantly in the last 30 years (Quintana and Aceituno 2006), however projections for the future are grim.

Using global climate change models, the IPCC has developed future global climate scenarios based on historical changes together with greenhouse gas emissions predictions. These models at the global scale have been 'nested' recently (2006) by the University of Chile to establish predictions at a regional/national scale. The University of Chile adopted two IPCC emissions scenarios, SRES A2 and SRES B2, to conduct their analysis. Emissions scenario SRES A2 describes a world with high and sustained population growth and slow technological and economic development. Emissions scenario SRES B2 describes a world with an increase in population that peaks mid-century and reduces thereafter with moderate economic development and emphasis on local solutions to economic, social and environmental sustainability. There are other emissions scenarios but these two represent sufficiently different situations along a spectrum of possibilities so as to be useful in examining the effects of climate change on Maipo Basin glaciers.

Under both scenarios Chile warms considerably before the end of the 21st century, although there are significant differences between the results under the different scenarios. Under scenario A2 mean annual temperatures will rise 2°-4°C above the current average, depending on the region of the country, with temperatures reaching up to 5°C of deviation from the current average in some zones of the Andean Cordillera during the summer months. The predictions for scenario B2 are not as drastic, but still point to the possibility of changes in the average temperature of up to +4°C in some regions during the summer and average changes of +1°-3°C (UdC 2006). The Metropolitan Region is within the area of change between 3°-5°C under scenario A2 and 1°-4°C under B2, depending on the season (UdC 2006).

Together with rising temperatures, changes in precipitation are expected. The summary indicates that, "In the central region of Chile there is a generalized loss of precipitation under scenario B2 with the exception of the autumn season at latitudes below 33°S. The loss is on the order of 40% at low elevations, gaining in severity towards the Andes range in summer but easing during autumn and winter under scenario B2" (UdC 2006, p5, my translation). The prediction for a point at 32°S and 72°W, off the coast of Valparaíso, indicates that wintertime precipitation will average around 30 millimeters at the end of the 21st century, in comparison to an average of 150 millimeters (UdC 2006). It is important to reiterate that, as the summary states, the decrease in precipitation will be more severe towards the Andes, which is where the vast majority of wintertime precipitation, and approximately 80% of overall Metropolitan Region precipitation, currently accumulates in the form of snow.

Effects of climate on water

Globally climate change is expected to significantly reduce the extent of snow and ice cover worldwide over the coming century. The predicted decreases in precipitation and increases in temperature would suggest that the trend holds true for the Metropolitan Region. In June 2008 the IPCC released a special technical report on water resources

worldwide (Bates et al. 2008) that indicates some of the principal changes expected and their impact on human infrastructure. According to a global water resource model, Water GAP, developed by Alcamo (2003), the Metropolitan Region of Chile appears within the “very high stress” range, classified as less than 1000 m³ of water availability per person per year or a “withdrawal to availability ratio” of greater than 0.8 (Bates 2008, Figure 1.1), meaning that more than 80% of the available water flow is in use. Brown and Saldivia (2000, Table 15) anticipate water availability in the Metropolitan Region at 544 m³ per person per year in 2025, assuming projected population growth and no change in water availability. This last assumption is most probably wrong since precipitation is predicted to decrease and glacier yields will change under a warmer climate. A water availability of 544 m³ fits with Alcamo’s “very high stress” classification. The Metropolitan Region is also classified as having a “freshwater resource vulnerability that is very likely to impact sustainable development” (Bates 2008, Figure 3.4). Considering that Santiago is the political, economic, and industrial center of the country, these preliminary reports would appear to have wide reaching implications.

Currently agriculture in the Metropolitan Region relies heavily on irrigation, with 1320 km² irrigated or approximately 9% of the Basin, using a total area of 15,157 km² (Brown and Saldivia 2000). Water shortages clearly affect crops, reducing their quality and quantity. The Metropolitan Region also relies heavily on hydroelectric power for electricity generation, with six hydroelectric dams installed in the area with a total generating capacity of 274 MW (Brown and Saldivia 2000). Maintaining or expanding hydropower could become a problem, especially when there could be competing demand due to the conflicting temporal demand highs of water consumption and electricity generation from a limited water supply, if the population of Santiago continues to grow and industrial expansion continues.

In order to mitigate the effects of climate change on water availability, there is a need for coherent, reliable data on water resources as well as greater emphasis on resource management, reductions in the emissions responsible for global warming, increased efficiency in water usage, and possibly the development of alternative water sources.

Politics of Glaciers and Snow

The data previously presented indicate that glaciers and snowpack may provide increasingly essential water resources for Chile in the 21st century, and as such their effective management is a crucial component in mitigating the possible impacts of climate change in Chile. Effective management requires knowledge of the relevant variables and enforced policy decisions. Although broad-based knowledge of the relevant variables is scarce, interest in their study and protection has increased in recent years, with corresponding changes in their management by the government.

Changes in runoff due to variability in snowpack are currently managed through the use of reservoirs that maintain consistent supplies of water to Santiago, although it should be considered that significant decreases in snowpack and precipitation might challenge their regulatory capacities, especially with multi-year decreases. It is not clear from available studies and interviews with water officials how this possibility is being managed. Studies have shown that particulate matter, much of it produced by industry,

has a potentially serious effect on the snow albedo (ability to reflect sunlight), causing more snowmelt and at a faster rate (Tarum 1979, Drake 1981, Hansen and Nazarenko, 2003). Consideration of this potential impact currently does not appear to be taken into account when dealing with the environmental impact of factory emissions.

Glaciers have also been subject to human intervention, both direct and indirect, that has modified them significantly and irreversibly. Similarly to snow, increases in greenhouse gases cause increased glacial melt and industrial particulate matter darkens glacial surfaces and reduces the albedo of the ice (Tarum 1979, Drake 1981, Adhikary et al. 2000), both contributing to negative mass balance. According to Brenning there are rock glaciers within the Maipo Basin that are currently threatened or altered by mining, among them the Rinconada Glacier and the Río Blanco Glacier by the División Andina mine, and Infiernillo Glacier by the copper mine Los Bronces (Brenning 2008). These glaciers have supposedly been mined in some parts and used as tailings depositories in others (Brenning 2008). Clearly, mining a glacier implies a loss of the water reserve contained within it while using a glacier as a tailings pile potentially increases the risk of landslides and surging and contaminates its runoff. Further studies are needed in order to arrive at any general conclusion, but such studies would be important in order to determine the impact of mining on a limited resource.

Recognizing that there is a need for greater attention to snow and glaciers, for the first time in 2008, the National Water Board (DGA) received a budget of 625 million Chilean pesos (USD 1.2 million) to organize a Snow and Glaciers Unit to study these resources (Noticias DGA, January 2008). For comparison, the DGA's entire budget in 2008 was 11.5 billion Chilean pesos (USD 21.8 million) (Dirección de Presupuestos). The National Glacier Policy, approved in April 2009, emphasizes the importance of creating a complete inventory of the nation's glaciers, which until now has not been a national priority (see Rivera 2000). The Policy also stipulates that glaciers be integrated into the Evaluation of Environmental Impact System (SEIA), which offers a certain measure of protection against direct intervention. Previously when projects affected glaciers they only had to declare the intervention, but they were not subject to study or regulation by the government. Under the new Policy, any project that affects glaciers will have to undergo evaluation by SEIA in order to determine what the environmental and human impact will be. This does not, however, guarantee that there will not be interventions with glaciers, as SEIA reviews each application individually with reference to applicable laws, which in this case would be water laws.

It is clear that current policies are limited by a lack of prior knowledge and although there have been significant improvements in recent years, it is an issue worthy of significant further study. Director of the DGA, Rodrigo Weisner, expressed awareness in an interview that the total of six professionals within the DGA Snow and Glaciers Unit dedicated to the study of these resources was insufficient, but also reiterated that it was an improvement over the past (27 May 2009). "A few years ago we didn't have a single glaciologist working for us. Now we have six. Even with twelve or twenty-four we wouldn't have enough but we can only develop at a certain rate. More and more the National Water Board is going to start looking like the National Snow and Glaciers Board as they gain in importance as resources" (Weisner, personal communication, 27 May 2009). With regard to specific measures for facing climate change's impact on water resources Weisner expressed less certainty.

“The private companies that manage our water resources have plans for the next 15 years but after that there aren’t many specific predictions. The studies that we are conducting will give us a better idea of available resources and the demand that the Basin can support. If the results indicate that the demand is going to overwhelm the capacity due to population growth it is possible that the government will intervene to limit construction permits etc. to avoid a water crisis. But currently that is not under consideration” (Weisner, personal communication, 27 May 2009).

Conclusion

The dramatic predictions of the Chilean press have been demonstrated to be unfounded, but the point that the Metropolitan Region’s water resources are potentially at risk remains true. Drawing conclusions from the available historical data is subject to its limitations, as discussed above. However, it is clear that if climate models are accurate, there will be significant changes in the Metropolitan Region’s climate over the coming century that will require adaptation, serious mitigation measures or even population migration. Areas of special concern should be agriculture and electricity generation, which are both potentially crippled by predicted decreases in water resource availability. Protection of water resources and emphasis on increasing efficiency should become national priorities, especially for stressed basins like the Maipo. However, management decisions must be based on facts, which requires further investigation into the variables at play.

Further research needs to be directed to creating an accurate and updated inventory of the Basin’s glaciers including their characteristics and changes, consistently tracking runoff at a number of stations within the Basin, analyzing water usage on a variety of time scales and by different sectors of the economy, and translating glacier mass balance data into relevant hydrological predictions. Only then can modeling of snowpack and glacial runoff under a variety of global warming scenarios contribute meaningfully to water resource planning efforts for the Metropolitan Region.

Equally important is the public policy aspect, which has not yet received very much attention. The dearth of publicly available information about water resources and their availability in the Metropolitan Region has led to the circulation of a great deal of misinformation and a dramatization of the issue in the media. Although the coverage has raised some awareness, the danger of the short-term ‘shock and awe’ approach used by the media is that the agencies and experts responsible for the issue lose credibility with the public when the claims are proved unfounded and their ability to effectively mobilize against future challenges is thus crippled. The dissemination of more accurate and accessible information would allow for greater involvement by the public and more long-term interest in the issue.

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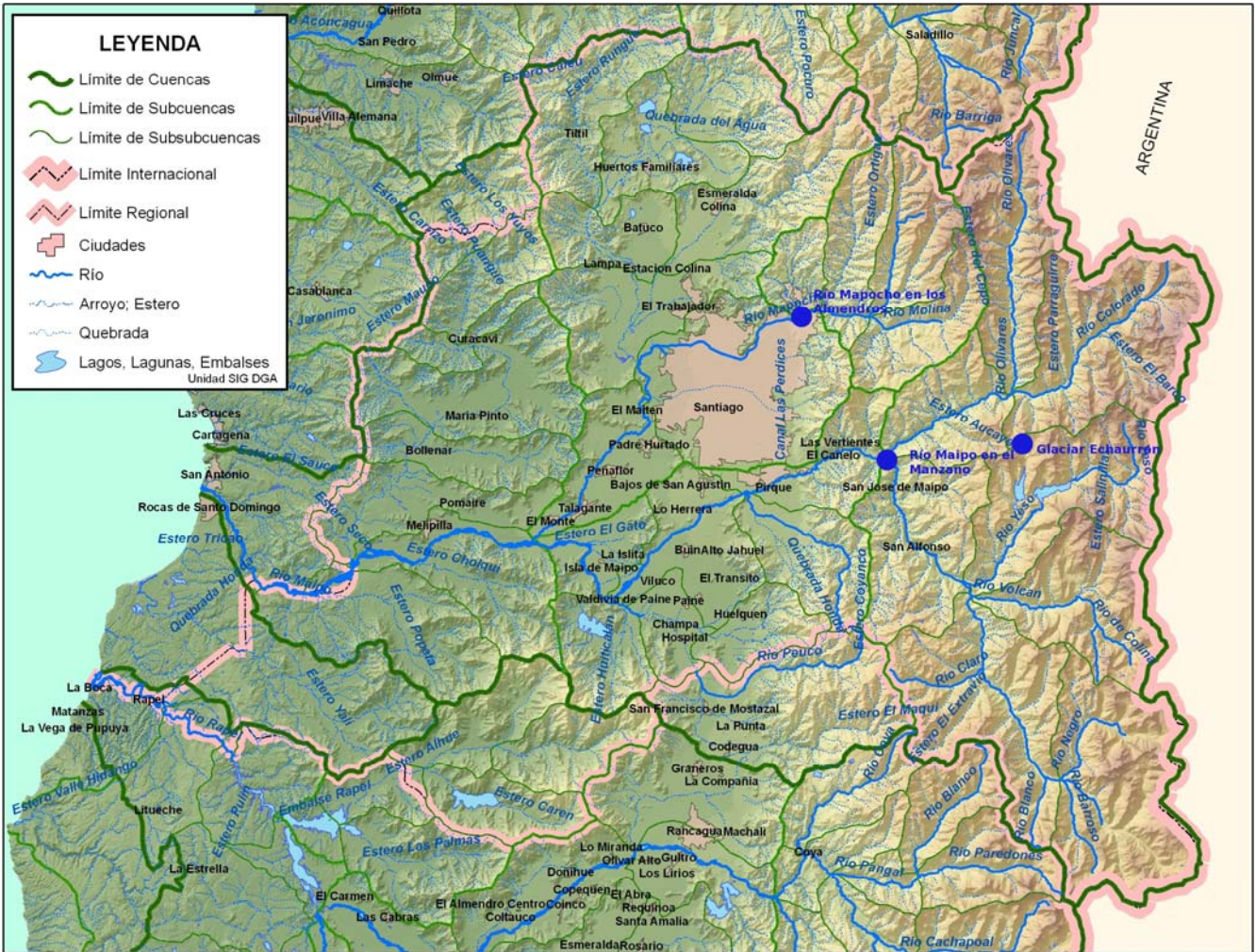
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Annex

Map 1:



Map courtesy of the Dirección General de Aguas (National Water Board)