http://www.scar.ac.cn
Sciences in Cold and Arid Regions
2013, 5(1): 0027–0034
DOI: 10.3724/SP.J.1226.2013.00027

Effect of climate change on drinking water supply in Santiago de Chile

Gerardo Ahumada *, David Bustos, María González

Department of Civil Engineering, Universidad de Chile, Santiago, Chile

*Correspondence to: Gerardo Ahumada, Department of Civil Engineering, Universidad de Chile, Santiago, Chile. E-mail: ga-humada@ifarle.cl

Received: October 30, 2012 Accepted: January 20, 2013

ABSTRACT

Climate change is likely to increase the occurrence of floods and flashfloods that affect Santiago de Chile's drinking water supply system throughout the 21st century. A relationship between flashfloods in the Maipo River—Santiago's main raw water source, drainage area in the Maipo Alto Sub Basin and precipitation 48 hours previous to the event was found. Despite having legal guidelines to guarantee continuity and stability in water supply, Chilean law does not specify the maximum admissible magnitude of an event. A 12% drop of average monthly flow at Maipo en El Manzano Station was estimated for the 2035–2065 period due to climate change, meaning water suppliers would not be able to meet 90% monthly water supply security, required by Chilean law. Water suppliers would need to increase their current allotted quota of the Maipo River, from 24.5% to a percentage between 26% and 30% to comply. If the 0 °C isotherm keeps increasing its elevation through the 21st century, more intense floods could occur because of additional drainage area granted by the elevation of the snow line, even if precipitation does not suffer a significant change. In order to withstand a five day turbidity event, 2 m^3/s of groundwater, or any non river source, should be temporarily incorporated to the emergency drinking water production.

Keywords: climate change; drinking water; water availability; floods; water supply security

1 Introduction

The motivation of studying emergencies in drinking water supply from a climate change and anthropogenic approach comes from the importance that the World Health Organization (WHO) has given to a safe and reliable drinking water supply to the population, because of its positive impact in public health, development and quality of life. WHO has also stated that climate change is one of the defining challenges of the 21st century (WHO, 2009), given its nature of global phenomenon that is likely to pose more threats than opportunities. It is necessary that governments, agencies, organizations and communities gain awareness of the link between climate change and negative impacts in their sanitary services.

Drinking water supply security should be considered a high priority problem by countries, and the subject will be studied with a local approach, aiming to design a set of measures that help improve the current conditions in which Santiago's drinking water supply system withstands emergencies associated with floods, sediment transport and droughts, under the premise that such events may occur more often in the middle-term. As a result of such measures taken into effect, it is expected that the frequency and duration of drinking water shortages due to emergencies triggered by drought or unfeasibility of treatment of raw water, as a result of massive sediment transport or sudden high turbidity, are shortened, mitigated or even prevented.

The general objective is to provide a set of mitigation and safety measures for Santiago's drinking water supply system, focusing on the challenge of climate change. The specific objectives are:

(1) Analyze current threats and identify the emergencies they might trigger.

(2) Define different middle-term scenarios of climate change for the emergencies identified.

(3) Assess the physical security of the main drinking water supply facilities and structures in Santiago.

(4) Propose different mitigation and safety measures for the water supply system in Santiago.

2 Methodology

A bibliographical review was carried out to assess the possible impacts in the sanitary area; a general description of the basin was made, and the evolution and/or present state of precipitation, temperatures, elevation of the 0 °C isotherm, land use and fluviometric parameters were studied. Water flow recorded by Maipo en El Manzano Station (33°36'S, 70°23'W; 890 m a.s.l.), which drains the Maipo Alto Sub Basin and is also close to the Toma Independiente intake, one of Aguas Andinas' main sources of raw water, was analyzed. Also, a simulation of monthly water supply-demand balances were made for possible future scenarios (2035–2066 period), taking into account drinking water and irrigation demands versus water supplied by the Maipo River and the Yeso Dam.

Relationships were found between maximum instant flow and drainage area, provided by the hypsometric curve of the basin and elevation of the 0 °C isotherm data from Santo Domingo and Quintero stations (32°74'S, 71°33'W, 8 m a.s.l. and 33°38'S, 71°38'W, 77 m a.s.l., respectively); and precipitation records from Santiago Quinta Normal Station (33°26'S, 70°41'W; 520 m a.s.l.).

The hypsometric curve was approximated with a second order polynomial regression (R^2=0.999):

$$y = \begin{cases} 0.00049x^2 - 0.972x + 510.9, \\ \qquad \text{when} \quad x \in [855 \text{ m}, 3500 \text{ m}] \\ 0.00000023x^3 - 0.0037x^2 + \\ \quad 19745x - 31018.8, \\ \qquad \text{when} \quad x \in [3500 \text{ m}, 5600 \text{ m}] \end{cases} \tag{1}$$

where y is the drainage area (km^2) of the sub basin and x is the elevation of the 0 °C isotherm (m) given by Santo Domingo and Quintero stations.

Maximum instant flow of a flood was modeled with a multiple linear regression (R^2=0.67):

$$Q=9.97P+0.388A-0.0059PA-44 \tag{2}$$

where Q is the maximum instant flow (m^3/s) at Maipo en El Manzano Station, P is the precipitation recorded 48 hours before the event (mm) at Santiago Quinta Normal Station, and A is the drainage area (km^2) of the sub basin.

3 Description of the study area

Because of the scope of this work, it is only relevant to understand the first and highest section of the Maipo River Basin, hereinafter Maipo Alto Sub Basin, which is drained by the rivers Maipo, Yeso, Colorado, Colina and Olivares; and ends at the confluence of the rivers Maipo and Colorado. The importance of this 4,859 km^2 basin resides in the fact that it feeds two of the most important intakes used for tap water production in Santiago: Aguas Andinas' Toma Independiente and the Sociedad del Canal de Maipo intake (Figure 1).

The Maipo Alto Sub Basin's elevation ranges from 890 m a.s.l. (Maipo en El Manzano Station) to 6,570 m a.s.l. (Tupungato Volcano, on the border with Argentina) in approximately 60 km from west to east. The altitude difference allows the coexistence of two different climates: below 3,000 m a.s.l. there is Temperate Hot-Summer Mediterranean climate, and above 3,000 m a.s.l. there is Cold Highland climate. Because of this, rivers are mostly fed by rain during the wet season (April–September), and by snow from the Andes during the dry season (October–March).

The Yeso Dam (33°39'S, 70°4'W; 2,568 m a.s.l.) is a reservoir with a capacity of 250,000,000 m^3. Aguas Andinas owns 400,000,000 m^3/a in eventual rights, which can be used in case of scarcity.

Santiago de Chile (33°27'S, 70°42'W; 567 m a.s.l.) is located within the broader Maipo Basin and is also the country's largest and most important city in terms of commercial, educational, cultural, governmental, industrial and financial activity. With nearly six million inhabitants (INE, 2008), it is home of roughly 36% of Chile's entire population and although the Maipo River does not cross the city, its major tributary, the Mapocho River, does.

4 Water supply in Santiago

Aguas Andinas is the largest tap water supplier in Santiago, with approximately 85% of the market under its control. Its 11,365 km of subterranean pipes and 835,000 m^3 of water storage capacity are in charge of providing fresh water to the city. To guarantee continuity and stability in water supply, the "Ley General de Servicios Sanitarios" (General Law of Sanitary Services) has a set of quality and continuity guidelines for water supply that Aguas Andinas has to comply with. Valid reasons to limit, reduce or interrupt the service include droughts, earthquakes and maintenance. Chilean laws and norms (DS N° 1199/04, NCh. 691/98, NCh. 2369.Of2003, NCh. 777/1.Of2008) also indicate the extra capacity water tanks must have in order to address or withstand emergencies such as fires, blackouts, and pipe damage; and indicate the minimum requirements to resist earthquakes without incurring structural damage. With regards to water intakes, the law says they must be designed to resist a 100-year Return Period flood.

Despite all the guidelines stated above, Chilean law does not specify the maximum admissible magnitude of an event, or mentions risk management related to turbidity events.

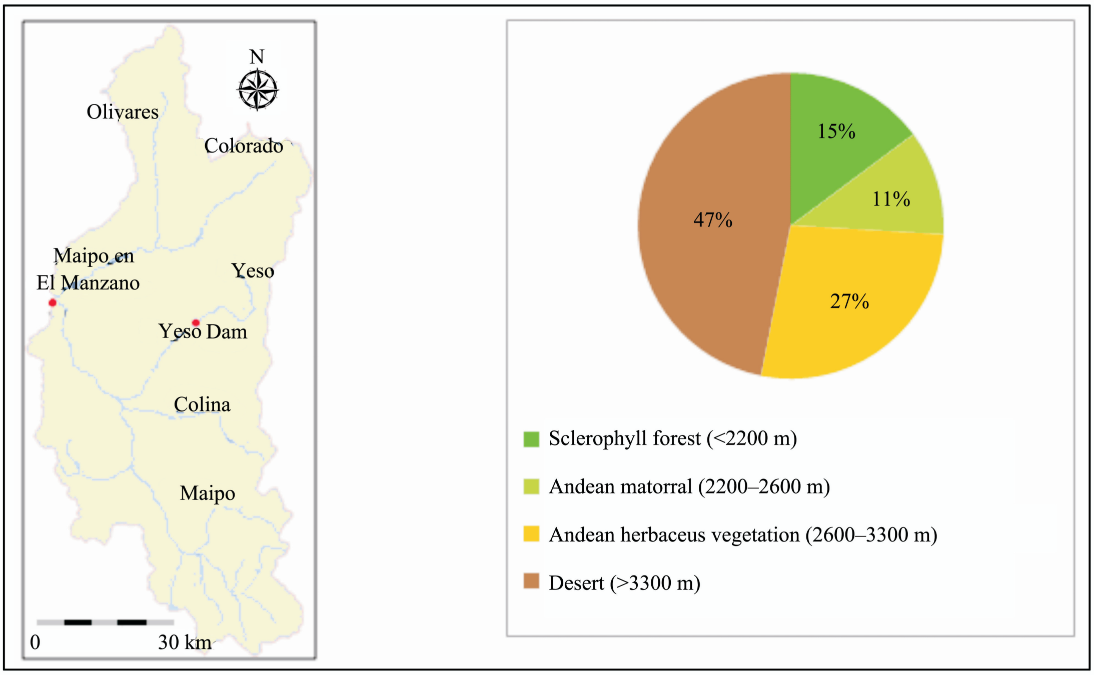

Figure 1 Maipo Alto Sub Basin and its vegetation

5 Water availability in the Maipo Alto Sub Basin

González (2010) found an average monthly flow correlation between Maipo en San Alfonso (33°44'S, 70°18'W; 1,108 m a.s.l.) and Maipo en el Manzano stations for the 1946–2009 period (R^2=0.938):

$$Q_{EM} = 1.2978 Q_{SA} + 12.553 \tag{3}$$

where Q_{EM} is the average monthly flow (m^3/s) at Maipo en El Manzano and Q_{SA} is the average monthly flow (m^3/s) at Maipo en San Alfonso Station.

Based on projections by the study "Economía del Cambio Climático en Chile" (CEPAL, 2009), which estimated average monthly flow for the 2035–2065 period at Maipo en San Alfonso Station, and assuming the correlation stated above would remain valid for the next 70 years, a 12% drop of the average monthly flow at Maipo en El Manzano Station was estimated for the 2035–2065 period due to climate change (Figure 2). This drop would reduce the quota allotted to Santiago's drinking water suppliers, who currently control 24.5% of water rights in the Maipo Alto Sub Basin (24.5% of the river flow).

Figure 3 presents the historic (1946–2009) and projected (2035–2065) average, average maximum and average minimum monthly flows.

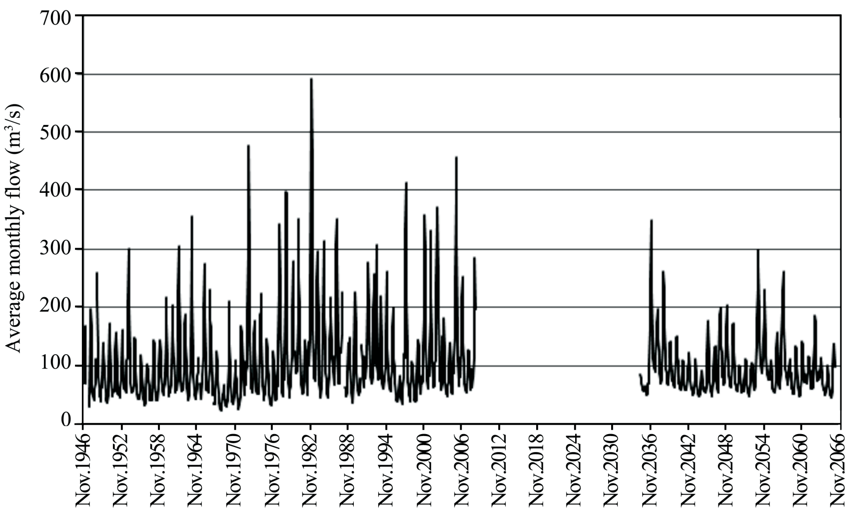

Figure 2 Historic (1946–2009) and projected (2035–2065) average monthly flow, Maipo en El Manzano Station

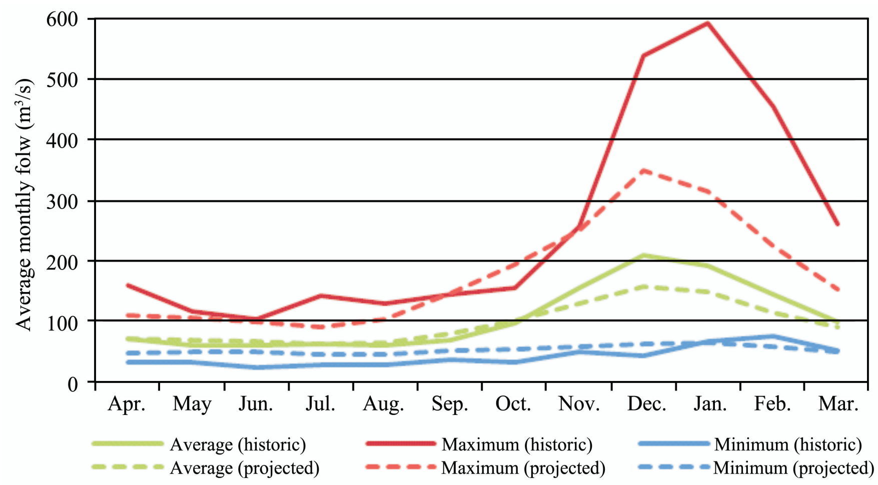

Figure 3 Average monthly flow, Maipo en El Manzano Station

As mentioned before, a 12% drop was projected for the average monthly flows. Maximum monthly flow estimations decrease by 35%, the effect being most noticeable from December to March, and minimum average flow estimations increase by 27%. While the minimum average flow increase could be attributed to an elevation of the 0 °C isotherm, thus granting wet season rain more drainage area, the abrupt drop in maximum summer flow could probably be related to glacier shrinkage and less melted Andean snow available during the dry season, a subject that will be discussed latter. The reason flows are larger during the dry season in both historic and projected series is that most of the rainfall during the wet season is stored as snow, only becoming available when it melts, during the dry season.

Under the circumstances discussed above, and also considering natural growth rate, domestic consumption changes and irrigation demands, water suppliers would not meet the 90% monthly water supply security, required by Chilean law. Ninety percent monthly water supply security means at least 90% of a month's days must comply with 100% of consumer's drinking water demands.

Figures 4 and 5 below present assumed future changes in population and domestic consumption.

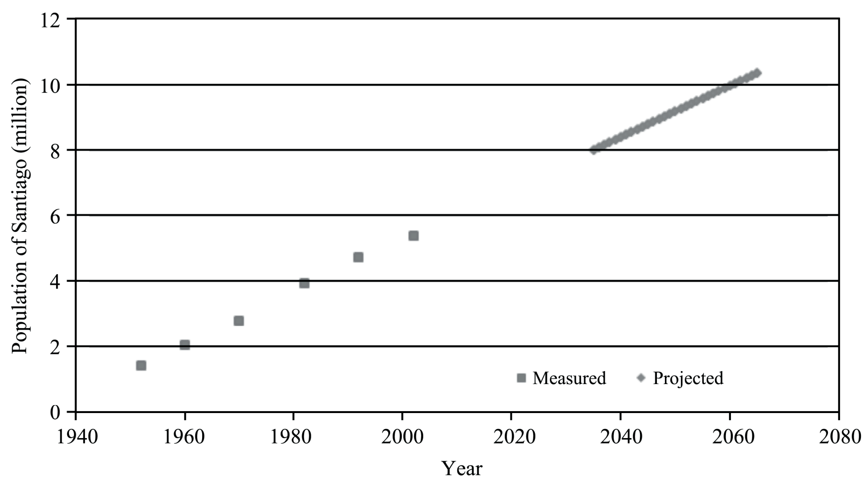

Figure 4 Measured and projected population of Santiago de Chile

Figure 5 shows "proposed" and not "projected" domestic consumption because the projected values were too low and unlikely to occur. The proposed values were based on measured values, but imposing that domestic consumption would never decrease from 180 L/(cap·d) during the 2035–2065 period.

Considering the estimated water availability and Santiago's possible future needs, the following scenarios (Table 1) were devised for analysis:

Domestic consumption in 2000 was 260 L/(cap·d), but since then it has been steadily decreasing: in 2008 it reached 244 L/(cap·d), which translates to an average domestic consumption of 16.5 m^3/s, or total demand of 23.6 m^3/s if water losses are taken into account.

A monthly supply-demand balance was made with each scenario and, in order to assure an average percentage of demand supplied around or above 95%, water suppliers would need to increase their current allotted quota of the Maipo River (24.5%) to 26% for the best scenario and to 30% for the worst scenario. Since such increase would require drinking water suppliers to buy quota from other owners, such as growers who currently use theirs for irrigation purposes, it would have an impact in agriculture and land use in the Maipo Alto Sub Basin, and would also increase the production cost of tap water (US$370,000 per year for the best scenario and US$2,200,000 per year for the worst scenario), but should ensure the 90% monthly water supply security required by law, and should also keep it above 80% consumers' drinking water demand in months when it cannot be met.

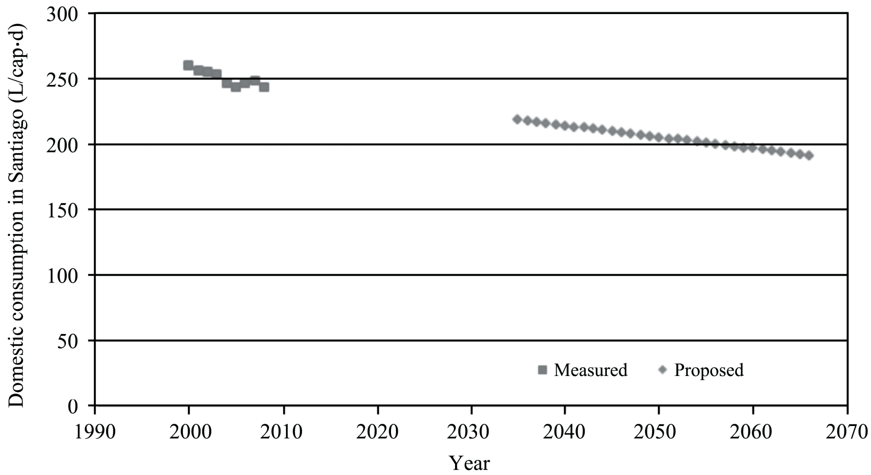

Figure 5 Measured and projected domestic consumption in Santiago de Chile

Table 1 Possible future scenarios, 2035–2066 period

Variable	Best scenario	Worst scenario
Irrigation demand	Proportional to current situation.	Constant demand: 150.2 m^3/s (current monthly maximum, equal to maximum irrigation intake capacity).
Yeso Dam initial state	Initial state: full (250,000,000 m^3).	Initial state: empty.
Drinking water demand	Progressive decrease in domestic consumption: from 219 L/(cap·d) in 2035 to 192 L/(cap·d) in 2066, and 20% water losses in distribution.	Constant domestic consumption: 219 L/(cap·d) and 30% water losses in distribution.

6 Floods

April–September instant flow records (wet season, hourly basis) from Maipo en El Manzano Station were reviewed (Table 2). Of the whole set of records analyzed, two subsets were clearly distinguished: the 1947–1967 and 1968–2009 periods. The first one was characterized by empty or incomplete records, with days or even weeks without any data; and the second one had more consistency and a better frequency on its measurements.

Table 2 Instant fluviometric records, Río Maipo en El Manzano Station

Period	Complete or partially complete monthly records
1947–1967	43.3%
1968–2009	92.9%

A "partially complete monthly record" is an incomplete monthly record that lacks five days of measurements, at the most (roughly 85% of days with measurements), but no more than three days in a row without any measurements.

Given the fact that only 43.3% of the monthly records of the 1947–1967 period are complete or partially complete, it is likely that many floods or flash floods triggered by rainfall were not recorded by the station, making the whole subset inaccurate with regards to maximum monthly instant flow.

In broad terms, floods studied between 1968 and 2009 whose 0 °C isotherm were below 3,000 m a.s.l. had approximately 10 m^3/s of instant flow per 100 km^2 of drainage area, while those whose 0 °C isotherm were above 3,000 m a.s.l. had approximately 40 m^3/s of instant flow per 100 km^2 of drainage area (Bustos, 2011). These numbers are by no means absolute, but they give an idea of the effect produced by high altitude rainfall—generally more intense than its lower altitude counterpart—that takes place on low infiltration and high runoff soils, usually covered by a layer of snow that can be partially melted during the event. If the 0 °C isotherm keeps increasing its elevation through the 21st century, more intense floods (instant flow greater than 1,000 m^3/s) could occur because of the additional drainage area granted by the elevation of the snow line, even if precipitation does not suffer a significant change.

The phenomenon of climate change is observable in the Maipo Alto Sub Basin through the rise of the 0 °C isotherm and the equilibrium line, and among its consequences is the shrinkage of the Echaurren Glacier (33°33'S, 70°08'W, 3,750 m a.s.l.), whose last positive mass balance was reported in the late 1980's (Figure 6). Considering that the amount of rainfall has not changed significantly in Santiago in the last 100 years (Carrasco *et al*., 2005), the glacier retreat should be attributed mostly to the rise of the equilibrium line rather than the lack of snow during the winter. Moreover, if only the days with precipitation in central Chile from 1975 to 2001 are taken into account, the 0 °C isotherm has increased 12 m, in contrast with the global 152 m increase for the same period in central Chile. This is an indication that the observed warming has occurred mainly during days with no precipitation (Carrasco *et al*., 2005), which means the glacier has been able to accumulate snow normally during the wet season, but ablation has increased during the dry season.

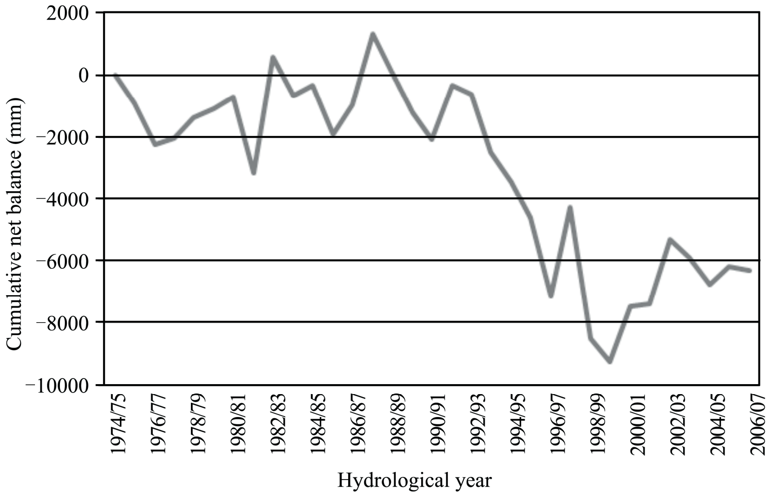

Figure 6 Echaurren Glacier mass balance (WGMS, 2009)

Elevation of the 0 °C isotherm would generate greater changes in the total drainage area during the wet season (April–September) rather than the dry season (October–March), as indicated by Table 3.

Table 3 Future scenarios of 0 °C isotherm and drainage area change, Maipo Alto Sub Basin

Items	Current situation		B2 Scenario (+350 m)		A2 Scenario (+440 m)		Intermediate Scenario (+200 m)	
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
0 °C Isotherm (m a.s.l.)	4,240	3,240	4,590	3,590	4,680	3,680	4,440	3,440
Drainage area (km²)	4,344	2,456	4,612	3,302	4,658	3,499	4,517	2,909
Drainage area difference from current situation (km²)	0	0	268	846	314	1,043	173	454
Drainage area difference from current situation (%)	0	0	6%	26%	7%	30%	4%	16%

The rise in elevation of the 0 °C isotherm for the B2 and A2 scenarios was based on estimates by Carrasco *et al.* (2005) for the 2070–2100 period and the drainage area was calculated using Maipo Alto's hypsometric curve (Figure 7). The intermediate scenario is arbitrary and it only serves as an intermediate stage between the current situation and the B2 and A2 scenarios.

These results indicate that the biggest threat to Santiago's drinking water supply would not be larger amounts of snow melt during the dry season, but less potential capacity of snow buildup during the winter. Given the relation between drainage area and the intensity of a flood, and that future scenarios predict the incorporation of high desert terrains—characterized by low infiltration, high runoff and more intense precipitation due to its elevation—to the drainage area, it is plausible that floods could become more catastrophic over upcoming years, assuming that precipitation in the Santiago area would not change significantly.

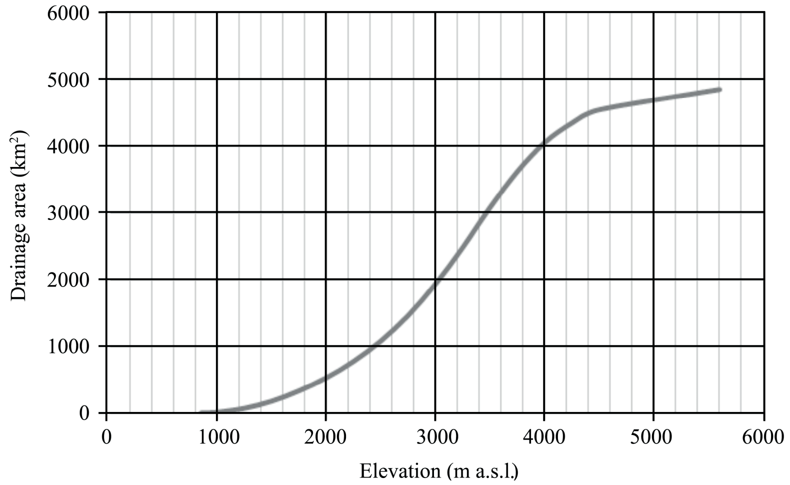

Figure 7 Hypsometric curve, Maipo Alto Sub Basin

The aforementioned projections indicate that the Echaurren Glacier's capacity to accumulate snow during the winter could be threatened by the end of the 21st century. The current equilibrium line's average winter elevation is 3,470 m a.s.l. approximately; therefore a raise of 350 m (B2 scenario) or 440 m (A2 scenario) would directly impact the glacier, located 3,750 m a.s.l.

With regards to precipitation, although there has not been a significant quantity change in Santiago in the last 100 years, the days of occurrence have decreased (Carrasco *et al*., 2005), which means rainstorms have become less often but more intense. If this trend persist though the century, the risk of floods or flashfloods could increase due to the combination of a higher 0 °C isotherm that would grant a larger drainage area; and more intense precipitation. Nevertheless, other factors also influence the magnitude of a flood, such as previously accumulated snow on the drainage area that can melt faster upon contact with rain; and the state of soil saturation, where a previously saturated soil allows less infiltration and more runoff (Dolidon, 2008).

The demand-supply balance proposed by Chile's Superintendence of Sanitary Services (SISS, 2009) for the "target turbidity event" is insufficient to appropriately address a real five day emergency in Santiago. First of all, water losses in distribution account 31% and not 15% as assumed for the target event; and second, it is unsafe to set the emergency supply equal to 80% of the average April–September demand (12.77 m^3/s) considering April and May, which concentrate most of the emergency events, have a higher demand than the autumn-winter average. Therefore, the supply-demand balance was redesigned based on actual distribution and demand conditions in order to properly withstand a 111-hour long emergency event (duration of the longest event ever recorded in Santiago) and the emergency supply was set to 90% of the maximum monthly average (April, 16.70 m^3/s). To meet these new requirements, 2 m^3/s of groundwater, or any non river source, should be temporarily incorporated to the emergency drinking water production; and 250,000 m^3 of additional reserve tanks should be built (Figure 8).

7 Conclusions

Climate change will probably increase the number and frequency of emergency events—floods, flashfloods and turbidity events—throughout the 21st century. Chilean laws and institutions have already made efforts to address security in drinking water supply, though an emphasis should be encouraged with regards to threats triggered or influenced by climate change, such as turbidity events caused by a sudden elevation of the 0 °C isotherm. In order to improve the quality of measurements, and increase the efficiency and resiliency of Santiago de Chile's drinking water system, the following recommendations are suggested:

(1) Radiosonde measurements should be made from higher elevations, such as the Andean foothills or even at Santiago Quinta Normal Station, in order to have more accurate readings of the 0 °C isotherm in the Maipo Alto Sub Basin.

(2) Any flood study based on records from El Manzano Station should take into account data from 1968 onwards, since most of the records prior to 1968 are mostly incomplete, irregular and much less consistent than data recorded from 1968 to nowadays.

(3) Continue and encourage the conservation of the sclerophyll forest, since it is the vegetation cover with the greatest infiltration and runoff control capacities in case of flood. Currently, there are 800 km^2 of unprotected sclero-

phyll forest in the Maipo Alto Sub Basin.

(4) Aguas Andinas' tap water demand should be decreased by investing in maintenance to reduce water losses in distribution from the current 31% to 20%. This would reduce global water demand from the production system, while keeping consumers' demand unaffected.

(5) The quota allotted to drinking water suppliers should be steadily increased through the 2035–2065 period, from the current 24.5% to approximately 30%. This should ensure the 90% monthly water supply security required by law, and it should also keep it above 80% in months where it cannot be met.

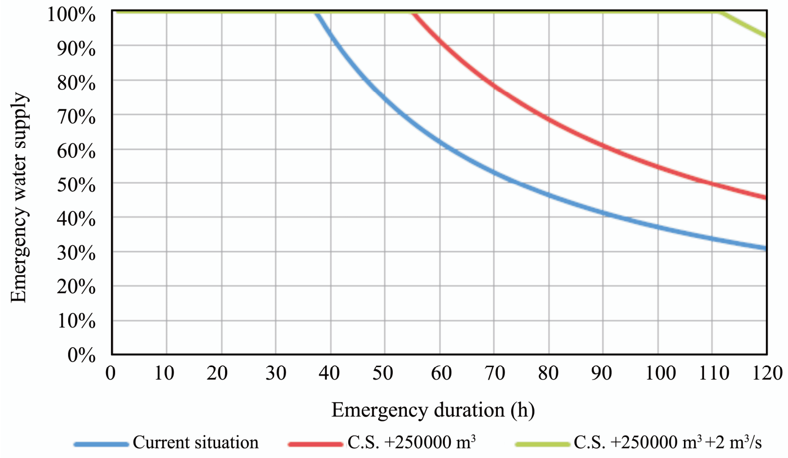

Figure 8 Water supply vs emergency duration, 90% of demand supplied

(6) 80% consumers' drinking water demand should be enforced by law as minimum minimorum in case of failure (below 90%), at least in Santiago de Chile.

(7) In order to properly withstand a five day long turbidity event, Aguas Andinas (Santiago's main tap water producer) should temporarily incorporate 2 m^3/s of groundwater, or any non river source, to the emergency drinking water production; and the construction of 250,000 m^3 of additional reserve tanks.

Finally, the biggest threat to Santiago de Chile's drinking water supply would not be larger amounts of snow melt during the dry season, but a less potential capacity of snow buildup during the wet season, considering the estimated raise of the elevation of the 0 °C isotherm and its impact on the average winter drainage area (+26% for B2 scenario and +30% for A2 scenario). While posing a direct threat to Santiago's water availability, the potentially incorporated drainage area could be used to expand the sclerophyll forest to higher grounds.

Acknowledgments:
The authors are very thankful to the Dirección General de Aguas for providing data from Maipo en El Manzano fluviometric Station and the Dirección Meteorológica de Chile for providing data from Santiago Quinta Normal Pluviometric Station.

REFERENCES

Bustos D, 2011. Cambio climático y eventos de emergencia en el suministro de agua potable en el Gran Santiago. Graduate thesis, Department of Civil Engineering, Universidad de Chile, Santiago, pp. 105.

Carrasco J, Casassa G, Quintana J, 2005. Changes of the 0 °C Isotherm and Equilibrium-line altitude in Central Chile during the Last Quarter of the 20th Century. Hydrological Sciences-Journal-des Sciences Hydrologiques, 50(6): 933–948.

Comisión Económica para América Latina y el Caribe (CEPAL), 2009. La Economía del Cambio Climático en Chile. United Nations, Santiago, pp. 88.

Dolidon N, 2008. Landslides and gullies in managed watersheds: risks, mitigation strategies, upstream-downstream linkages. Master thesis, AgroParisTech, Paris, pp. 96.

González MJ, 2010. Efecto del cambio climático en la seguridad de suministro de agua potable en el Gran Santiago. Graduate thesis, Department of Civil Engineering, Universidad de Chile, Santiago, pp. 174.

Instituto Nacional de Estadísticas (INE), 2008. Chile: Proyecciones y Estimaciones de Población, 1990–2020. Santiago, pp. 86.

Superintendencia de Servicios Sanitarios (SISS), 2009. Bases definitivas - Estudio tarifario de la empresa de servicios sanitarios Aguas Andinas S.A. Período 2010–2015. Santiago, pp. 224.

World Glacier Monitoring Service (WGMS), 2009. Glacier Mass Balance Bulletin N°10 (2006/07). Zurich, pp. 96.

World Health Organization (WHO), 2009. Summary and policy implications Vision 2030: the resilience of water supply and sanitation in the face of climate change. Geneva, pp. 41.