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ESTABLISHING THE POSSIBLE IMPACT OF CLIMATE CHANGE-RELATED PHENOMENA UPON THE SUPPLY OF WATER FOR HUMAN CONSUMPTION TO CHILE'S SANTIAGO METROPOLITAN REGION

Coordinator: Manuel Cermerón Romero.

Authors: Marcelo Bravo Fortune, Raúl Flores Audibert, Raúl Galindo Urra, René Garreaud Salazar, Eleonora Muñoz Morales, Alejandra Serey Amador, Maximiliano Viale

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EXECUTIVE SUMMARY

Climate change is acknowledged to be one of the most complex global environmental challenges facing society. A number of studies are in agreement that Chile is a country vulnerable to this phenomenon, with the medium- and long-term forecast for Central Chile being that the global increase in greenhouse gases will entail rises in temperature and a reduction in wintertime precipitation, negatively impacting the availability of water resources in the country.

This aim of this study, carried out by University of Chile, the Federico Santa María Technical University and the Aquae Foundation, is to determine the impact on human water supply management in the Santiago Metropolitan Region of Chile associated with the possible effects of climate change. More specifically, the study has focused on the availability of water and on the occurrence of extreme high turbidity events. It is important to note that, in recent years, the Maipo river basin, the main source of drinking water for the Santiago Metropolitan Region, has suffered from a series of meteorological and climatic events that fall outside the normal patterns of recent decades and that can be summarised as follows:

- From 2009 to date, Central Chile, including the Santiago Metropolitan Region, has suffered from generalised drought conditions that have had a marked effect on agriculture and, to a lesser extent, the supply of water to the public.

- Unusual increases in turbidity during the summer season, with a direct impact on the operation of drinking water production plants, where the most recent recorded event caused problems in the supply of water to more than one million customers (four million people) for around 24 hours.

According to our analysis, the high turbidity events can be broken down into two types:

- Heat-related events: caused by an increase in air temperature, which speeds up melting in the basin and the transportation of sediment due to this mechanism, with a good linear relationship between flow anomalies and turbidity.

- Rainfall-related events: these are characterised by the occurrence of convective storms over the higher parts of the mountains, with intense precipitations of short duration and a small spatial scale, causing differing degrees of mass wasting, thereby increasing turbidity in the river. In these cases, the air temperature falls or remains stable and there is a possible decrease in the thawing process, which is not compensated for by the contribution from the rainfall, causing a drop in flow levels.

A range of studies indicate that precipitation over the Andes in Central Chile during the summer period is usually associated with convective activity. The localised nature of this meteorological activity prevents the current rain gauge network from detecting a large amount of this precipitation. Nevertheless, given that this convective activity is often associated with lightning discharges, one alternative would be to make use of WWLLN (World Wide Lightning Location Network) records to detect activity in the area studied. Another complementary variable that could be useful in improving forecasts of convective precipitation (and, potentially, alluvia in the Maipo River) is the wind's zonal aspect (east-west), insofar as it is the wind from Argentina that carries the damp air capable of climbing the Andes and feeding these storms.

Taking advantage of the analysed association between summer storms and easterly winds, and given that the wind is a large-scale variable much better represented in global and regional atmosphere models, it is possible to gain an indirect understanding of convective activity projections under climate change scenarios. Under an RCP8.5 concentrations scenario (strong emissions of greenhouse gases), it can be seen that the Santiago Metropolitan Region is in an intermediate area, meaning that there is no clear indication for construing either an increase or decrease in convective activity (and, accordingly, in extreme turbidity events) over the Maipo River.

Another phenomenon of importance in the region's water management and supply is drought. In the last four years, Central Chile has been affected by low precipitation levels, whose individual values do not in themselves constitute extraordinary events: however, the duration of the precipitation shortfall does.

To analyse the future outlook for these events, a series of simulated precipitations has been taken into account for Central Chile (33°S 71°W) using IPCC 2013 global models, normalising them based on their respective long-term averages and assuming an RCP8.5 concentrations scenario. The results, expressed as the number of three-year or longer droughts, double in the near future and increase more than tenfold in the distant future.

A detailed study of the mass wasting mechanisms that would cause extreme turbidity events indicates that conditioning factors favouring their creation (the land's own geomorphic features) must be combined with triggering factors that modify the pre-existing stability of the land and help set off the events (including meteorological causes, amongst others). Flow-type wasting is characterised by continuous movements in which the rupture surfaces are not preserved and the moving mass is strongly internally deformed, behaving in a similar way to a viscous liquid of water-saturated material.

To analyse these phenomena, a risk assessment is usually carried out, involving, on the one hand, a potential threat (hazard) assessment and, on the other, one of the downstream impact on the infrastructure and population in general (vulnerability). At a stage prior to the assessment of these characteristics, it can be useful to provide a preliminary identification of the areas susceptible to the occurrence of threats, and this was done in this study. The methodology used to do this was that suggested by Lara (2007), which allows for the establishment of a 'susceptibility index (SI)' based on the sum of the weighted scores for different conditioning factors.

The study area, as well as two assessment units, was defined in those sectors in which flow-type events were confirmed on the dates on which the Maipo River recorded high turbidity levels (21 January and 8 February 2013).

Applying this methodology gives rise to zoning maps (for both areas analysed) showing units with SI values of between 0-24 and 25-49, i.e. of low and medium susceptibility, and SI values of between 50-74 and 75-100, meaning high and very high susceptibility, respectively. These values seem to indicate that the high turbidity events that have taken place in the Maipo river basin will doubtless continue to occur. The greater or lesser likelihood of their occurrence will depend upon an analysis of triggering factors such as precipitation intensity and accumulated precipitation, originating in summer and winter storms.

The main impact that each of the analysed phenomena—turbidity and drought—may have on the supply of drinking water to the country's Metropolitan Region, based on the results of the meteorological and geological studies carried out, can be summarised as follows:

- Impact due to a decrease in water flow rate: acquisition of water usage rights; the use of alternative water sources; economic impact (investment and higher operating costs); disputes over use; eventual rationing; and impact upon corporate image.

- Impact due to high turbidity: economic impact (investment, repair and operating costs) and impact on corporate image.

The strategic focus, allowing the climate-related phenomena of drought and turbidity described in this document to be tackled, is designed to achieve the implementation of a range of actions to mitigate, adapt and manage risks to minimize the possible impact of climate change on the supply of water for human consumption in the Greater Santiago area. Within this focus, worthy of particular note are the actions aimed at increasing the use of alternative water sources, implementing steps aimed at improving efficiency in the use of water resources, guaranteeing the availability of raw water of acceptable treatment quality, and improving information related to key parameters in the basin to provide an improved overall understanding and anticipate turbidity events.

The analyses and results of this study will, in addition to increasing knowledge of the impact of climate change with regard to water availability and high turbidity levels, help ensure proper and advance planning of mitigation works by the water utility company, demonstrating its commitment and concern for the future sustainability of the service it provides its customers.

KEYWORDS

Climate change, drinking water supply, drought, turbidity, water resources management, mitigation and adaptation, mass wasting, susceptibility index.

1. INTRODUCTION AND GOALS

The supply of water for human consumption to Chile's Metropolitan Region, which includes the country's capital, Santiago, and its six million inhabitants, is carried out in a way that ensures that water reaches everyone in accordance with the conditions and standards for quantity, quality and availability established in applicable legislation.

The main sources of raw water for the water company Aguas Andinas, which supplies close to 89% of the Region's population (SISS, 2013), are the Maipo and Mapocho rivers, with the secondary sources being the natural aquifers found within the concession area. In 2013, total annual demand for drinking water from Aguas Andinas stood at 708 hm3 (Aguas Andinas, 2014), around 80% of which was supplied using the surfaces waters of the Maipo and Mapocho river basin.

The normal supply of water to the population may be affected by events and/or circumstances that hinder and, taken to extremes, prevent the production of drinking water. This is the challenge that Aguas Andinas has had to face in recent times, due to the droughts affecting the Metropolitan Region over the last four consecutive years (2010-2013) or due to alluvial phenomena occurring in recent years that, in the summer of 2013, caused stoppages in the supply of drinking water on two occasions, with one of these events leading to supplies being cut off for almost 24 hours.

It is difficult to attribute the aforementioned drought and alluvial events to climate change. Nevertheless, one cannot disregard the conclusions of studies using global future climate circulation models, which indicate that Central Chile will experience a significant decrease in rainfall (of between 15 and 30%) and a rise in temperatures (of between 2 and 4°C), particularly in mountainous areas.

Given this, proper drinking water supply management calls for systematic planning of preventative actions and the definition of courses of action should they occur, and necessarily requires the asking of questions with regard to the probability of these kinds of phenomena occurring.

In light of the above, and considering the impact of these phenomena and the context of climate change in which they occur, the University of Chile, the Federico Santa María Technical University and the Aquae Foundation have decided to join forces and leverage their experience to draw up this study, whose goal it is to establish the possible impact on the management of the supply of water for human consumption in Chile's Santiago Metropolitan Region.

The study will help us understand the effect of climate change on the availability of water and the occurrence of extreme high turbidity events, allowing for proper advance planning of mitigation works by the water utility company, demonstrating its commitment and concern for the future sustainability of the service it provides its customers.

2. THE CONTEXT

2.1 The regional context, the Maipo river basin and water resources

Chile's geography offers a unique variety of climatic conditions and distribution of water resources scattered over 200 basins of a relatively small size (globally speaking), given the short distance between the Andes mountain range and the Pacific Ocean. Within this climatic diversity, two precipitation patterns can be distinguished (World Bank, 2011): one with precipitations concentrated in the summer (in the north of the country) and the other with precipitations distributed predominantly in the autumn-winter period, in the rest of the country (centre and south).

In terms of water availability, according to the 'Diagnosis Report on the Management of Water Resources in Chile' (Informe de Diagnóstico de la Gestión de los Recursos Hídricos de Chile, World Bank, 2011) total mean runoff stands at 53,000 m^3 per person per year, a fairly high value compared with the world average of 6,600 m^3 per person per year and well above the 2,000 m^3 per person per year regarded as the threshold for sustainable development. However, these average values do not reflect the varying realities along the length of the country, given the aforementioned climatic diversity, in which values of less than 800 m^3 per person per year are obtained from the Metropolitan Region northwards, whilst the south sees more than 10,000 m^3 per person per year.

This situation is critical in the case of Central Chile and, in particular, the Santiago Metropolitan Region, which is home to almost half of the country's population and economic activity and whose balance between the availability of and demand for water is borderline, as can be seen in Figure 1.

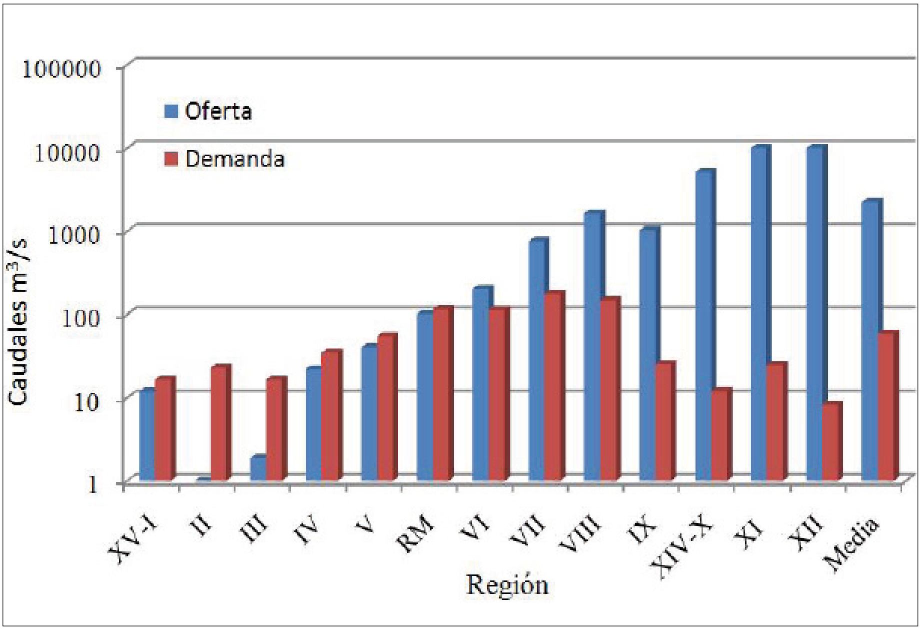

Figure 1. Balance between the availability of and demand for water resources (World Bank, 2011)

In a climatic context, the Maipo River basin is found in a temperate area, with average precipitations of 320 mm (Aguas Andinas, 2011) concentrated in a very short winter season, and with a long, dry summer season. The average flow rate of the Maipo River, as measured at the El Manzano river gauging station, has record highs and lows of 234.8 m^3/s and 37.1 m^3/s respectively (Aguas Andinas, 2010). In terms of runoff, the river is of the rainfall/snowmelt type and is characterised by great seasonal variability in its flow rates, with annual maximums being seen in the month of December. Additionally, the basin features three large surface water storage and control systems: the Negra and Lo Encañado lakes and the El Yeso reservoir, all with an operating storage volume of 220 hm^3 (Aguas Andinas, 2011). Furthermore, the Maipo river basin contains, according to the Directorate-General for Water's registry, around 1,000 glaciers, with a surface area of 380 km^2, whose contribution to the basin's hydrology is currently the object of study. The basin of the Río Maipo station in El Manzano has an approximate surface area of 5,000 km^2, and so the area with glaciers covers less than 10%.

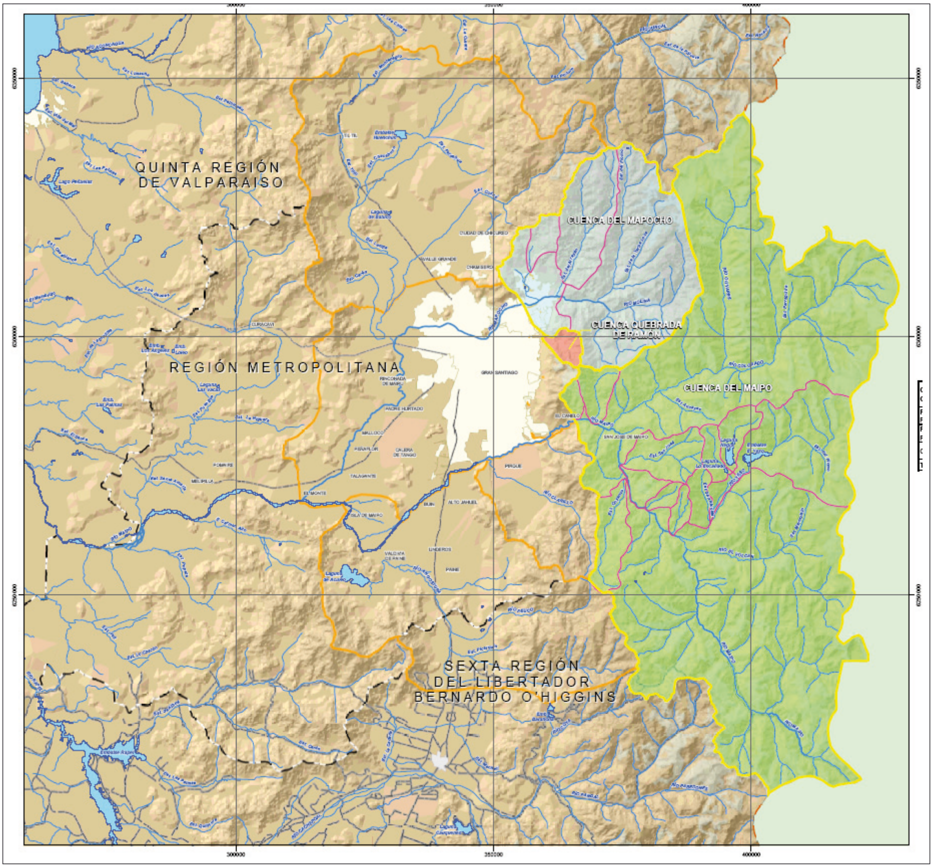

Figure 2 shows the location of the Maipo river basin and the main rivers making it up (Aguas Andinas, 2010).

In recent years, the Maipo river basin has experienced a series of climatic events falling outside the normal patterns experienced in past decades, whose two main features are:

- From 2009 to date, there have been generalised drought conditions in Central Chile, including the Metropolitan Region, which have had a significant impact on agriculture and, to a lesser degree, the supply of water to the public, thanks to mitigation actions and the redistribution of surface and groundwater resources.

- Unusual increases in turbidity during the summer season with a direct impact on the operation of drinking water plants. These events reached their peak in January and February 2013, forcing plants to be operated with minimal or zero flows for more than 30 hours and leaving more than one million clients (four million people) without a water supply for around 24 hours.

Although similar events have been seen previously, their duration and frequency in recent years has caught the attention of both the management of the company responsible for supplying drinking water and researchers at Chile's universities and research centres.

2.2 Climate event-related problems: the historical background

As noted in the preceding point, the Chile's Santiago Metropolitan Region is located in a temperate area, with precipitation concentrated in a limited number of months, making it highly vulnerable to drought events. Additionally, it is found in an area strongly influenced by climate phenomena with year-on-year variability, such as the El Niño Southern Oscillation, associated with Pacific Ocean currents and which have traditionally caused extreme event cycles of flood and drought (e.g. Montecinos and Aceituno, 2003).

With regard to annual precipitations and their annual distribution, the 2009 to 2013 period shows figures below the historical average in Central Chile, with a great impact on surface water resources. Figures 3 and 4 show the mean annual flow rate figures recorded by the Río Terrazas station of the DGA, displaying annual figures lower than the average for the 1961-2013 period over the course of the last four years (2009-2013).

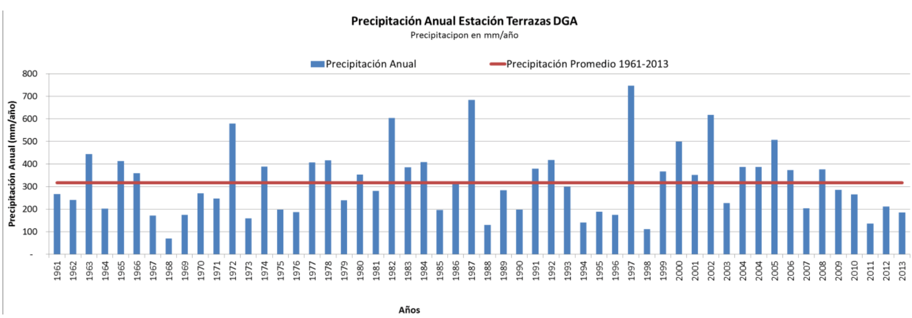

Figure 3. Annual precipitation at the DGA Río Terrazas station (prepared by the authors based on DGA data).

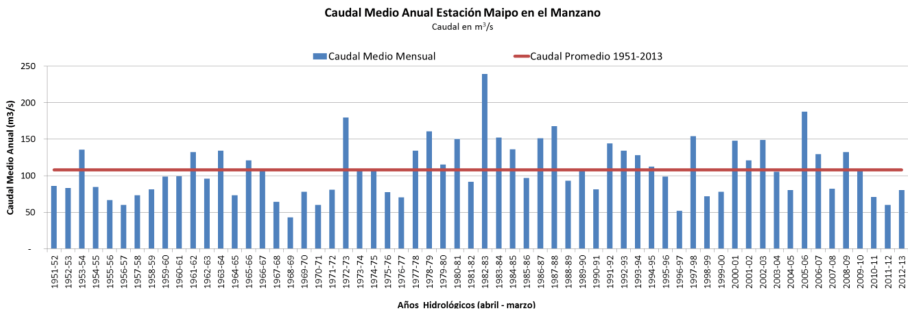

Figure 4. Mean annual flow rate at the Río Maipo station in El Manzano (prepared by the authors based on DGA data).

Turbidity in the Maipo River is one of the critical operating parameters for the drinking water plants supplying the Greater Santiago area, which, as noted previously, depend to a significant extent on surface water from the Maipo River. The plants have an operating range with a maximum turbidity limit of 5,000 NTU, above which the process must be stopped. Although values above this threshold have occurred historically, their frequency and duration have increased in recent years, as can be seen in Figure 5, which shows the average turbidity of the Maipo River (measured in independent samples) for the period from January 1990 to March 2014. The figure indicates mean daily values above the 5,000 NTU threshold in 1997-1998 and an increase in these events beginning in 2008 and, more markedly, from 2012.

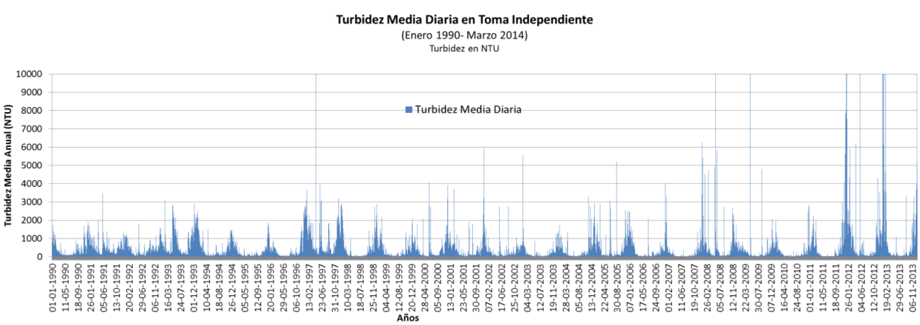

Figure 5. Mean daily turbidity, independent samples, Maipo (source: Aguas Andinas).

The increase in maximum values can also be seen in the maximum daily turbidity recorded from 2008, the year of the first recorded event of turbidity levels exceeding previously recorded levels, which caused the first supply stoppages and which led to a series of studies and actions to improve the infrastructure's capacity to respond to events of this type. Nevertheless, in the following years, the phenomenon became more recurrent, reaching new record turbidity levels in January-February 2013 in two events that led to a new supply stoppage. Recorded peak daily turbidity levels for the 2012-2013 period are displayed in Figure 6, showing how the maximum figures were recorded on 21 January and 9 February 2013, at 160,000 and 382,000 NTU, respectively.

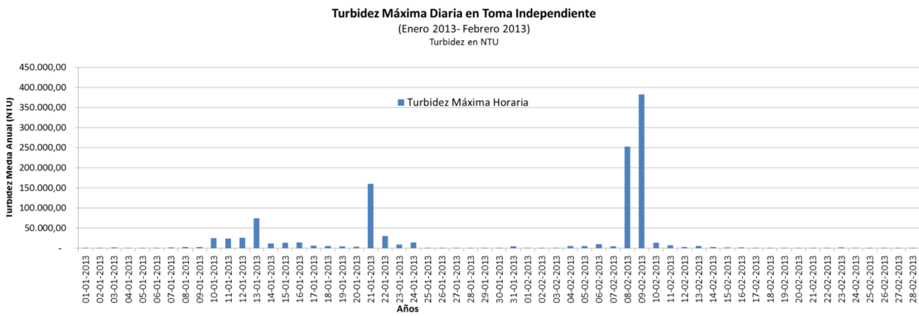

Figure 6. Maximum hourly turbidity from independent samples in the Maipo River, January-February 2013 (source: Aguas Andinas).

The causes of these phenomena and the frequency with which they occur are currently the object of study both internally within the company and by research bodies associated with local universities, particularly the link with global climate change trends of anthropogenic origin, whose main effect is an increase in atmospheric carbon dioxide concentrations and which, according to IPCC studies (2007) have increased the planet's average temperature by 0.8°C over the course of the 20th century. More particularly, in Chile, there is evidence of warming in the valleys and cooling in coastal areas, To sum up, this report has been produced against a backdrop of:

- Climate change, with adverse effects on water resources in Central Chile, according to future scenario studies based on IPCC analyses.

- A current drought scenario arising in a period (2009-2013) with annual precipitation figures lower than the historical mean, with an impact on surface water resources, according to flow rate records.

- An increase in extreme turbidity evens in the Maipo river basin, particularly in the summer, with record maximums recorded in January and February 2013.

3. AN ANALYSIS OF THE METEOROLOGICAL AND CLIMATE-RELATED PHENOMENA AFFECTING THE MAIPO RIVER BASIN

3.1 The relationship between turbidity and flow rate

There is great seasonal variation in the Maipo River's flow rate and turbidity. Peak values are recorded in the Southern Hemisphere's summer months (December to March), with generally low values in autumn and winter, all this being associated with the meltwater characteristic of Andean rivers in Central Chile (Cortes, Vargas and McPhee 2011). There are also winter peaks that provide an exception to this general rule, associated with rainstorms, which are generally short in duration (2-5 days). This behaviour can be seen in Figure 7.

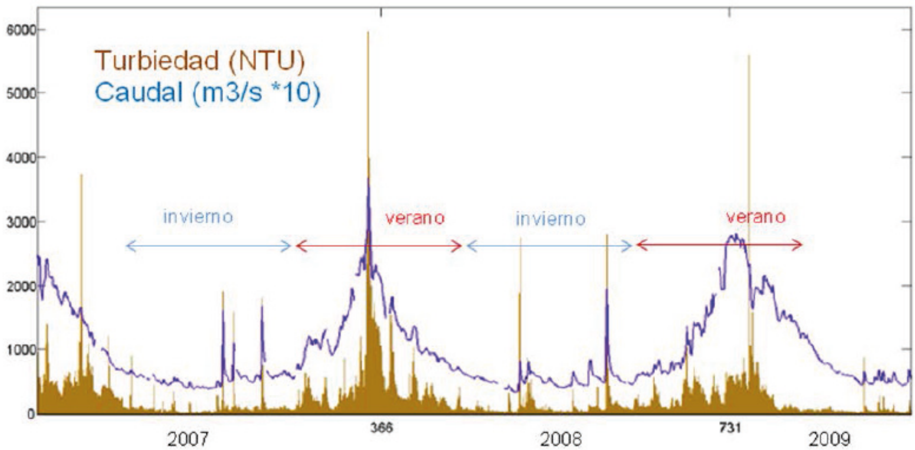

Figure 7. Daily flow rates (blue line, in m^3/s * 10) in the Río Maipo station in El Manzano and turbidity rates (brown bars and in NTU) in independent samples taken by de Aguas Andinas.

Despite this seasonal similarity, on a daily basis, both variables exhibit an extremely non-linear relationship, as can be seen in Figure 8. This shows how high turbidity levels (above 1,000 NTU) can occur across the daily flow rate values (from 50 to 700 m^3/s). In other words, the high turbidity events taking place in the Maipo River do not occur only in high flow rate conditions caused by the wasting and suspension of sediments, but also due to the potential injection of high sediment loads in low flow rate conditions associated with alluvial events. It can also be seen how the monthly averages for the December-January-February (summer) quarter are generally the highest.

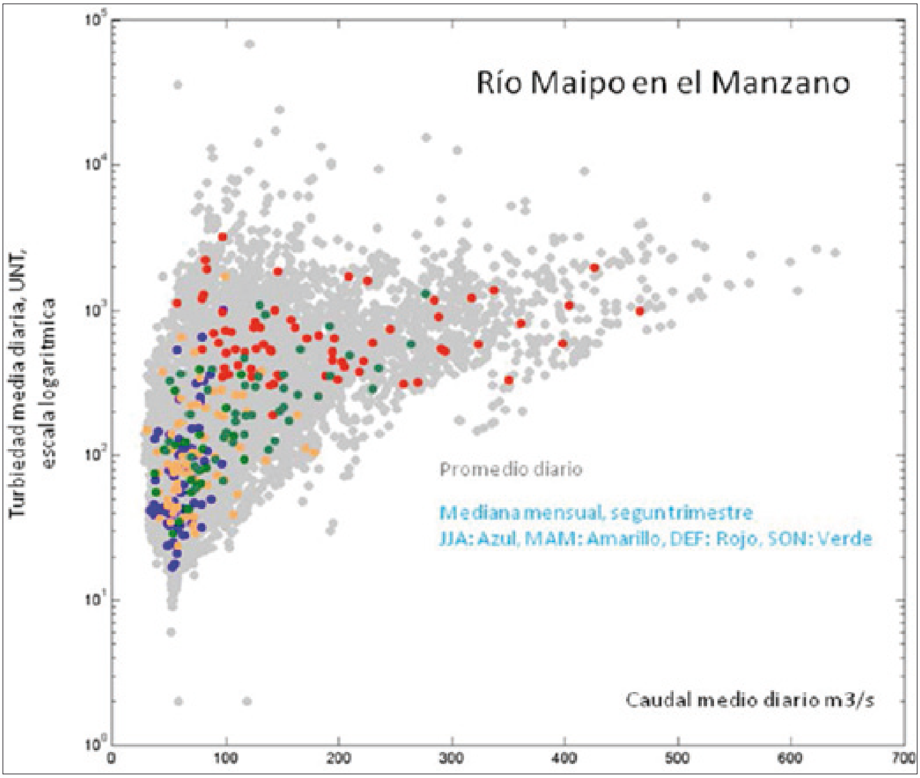

Figure 8. Scatter plot showing daily flow rate values taken at the Río Maipo station in El Manzano and turbidity levels taken through the Aguas Andinas independent sample (grey circles) for the period from 1990 to 2013. The coloured circles show the average for each quarter.

3.2 Local meteorological conditions

In this section, we will be analysing the meteorological conditions associated with high turbidity events (HTE) in the Maipo River, beginning with conditions at a local level. To do this, we shall take as our example the summer of 2007-2008. Figure 9 shows the time series for turbidity (the red line), flow rate (blue line), daily precipitation in Lagunitas (the Blanco river basin, at an altitude of 2,700 m, grey bars) and the air temperature at a level of 700 hPa above Central Chile (around 3,000 m high, the green line). Superimposed above the seasonal flow rate, temperature and turbidity cycle are events in which turbidity increases markedly, associated with a simultaneous increase in flow rate and a rise in air temperature one or two days previously. One example of this type of event is marked as HTE1 on 2 December 2007. In such cases (identified with a vertical red line) the marked warming of the troposphere boosts thawing, increasing the river's flow rate and, in turn, the transportation of suspended solids, boosting turbidity.

However, there are other HTE (such as HTE2, identified with a vertical blue line) that are not accompanied by an increase in flow rate or temperature, but rather by a decrease in these variables. Such events appear to be linked to precipitation in the mountains, at least that recorded at the Lagunitas station. The approach of a low-pressure system in the middle levels of the atmosphere during these events explains the increase in cloudiness, falling or constant air temperatures and a possible decrease in the thawing process, which is not compensated for by the contribution of rainfall, causing a fall in flow rates. Nevertheless, localised precipitation occurring over a short timespan (from minutes to 2-3 hours) could create different degrees of mass wasting, thereby increasing turbidity in the Maipo River.

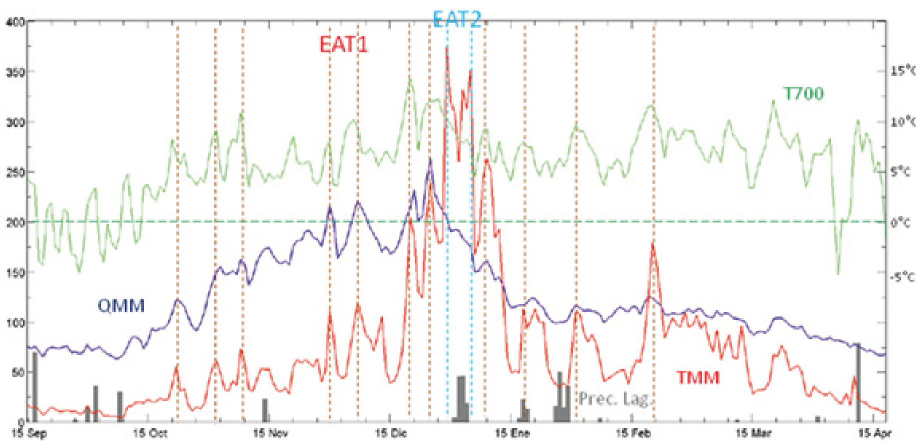

Figure 9. Daily time series for the summer of 2007-2008 for the flow rate (blue line, in m3/s) and turbidity (red line, in NTU/100) at the Río Maipo station in El Manzano, together with daily precipitation in Lagunitas (Blanco river basin, altitude 2,700 m, grey bars, in mm*20) and air temperature at a level of 700 hPa above Central Chile (an altitude of some 3,000 m, green line).

It is possible to study how temperature and precipitation-related hydrometeorological forcing affects turbidity events in the Maipo River in the summer by including them in a graph of flow rate and turbidity anomalies (deviation from seasonal mean). In Figure 10, each circle represents a summer day in 2002, 2005, 2008 and 2010, which are also coloured in accordance with the temperature anomaly and have a dot added if precipitation was recorded. In the graph, two groups of events can be seen, called (for the purposes of this study) heat-related and rain-related.

Heat-related events are characterised by a good linear relationship between flow rate and turbidity anomalies. What is more, days of higher flow rate and turbidity tend to be warmer and those with lower values for both parameters cooler. These events of increased turbidity would thus be caused by a rise in temperature, speeding up thawing within the river basin and sediment transport by this mechanism.

Furthermore 'rain-related' events are more extreme in nature (note the change in scale in Figure 10), are not associated with marked increases in flow rate and also do not necessarily occur on the hottest days. The approach of a low-pressure system in these events explains the falling or constant air temperatures, a possible decrease in the thawing process and an increase in cloudiness leading to precipitation. This precipitation is, in the majority of cases, produced by ordinary convection cells, which cause moderate precipitation rages, in very isolated areas of the mountain range (especially in the higher reaches, where there are no seasons), and over a short period of time (from minutes to a few hours). This convective, localised nature of the precipitation would not be enough to give rise to a marked increase in flow rate, but would cause different degrees of mass wasting, thereby increasing turbidity in the river.

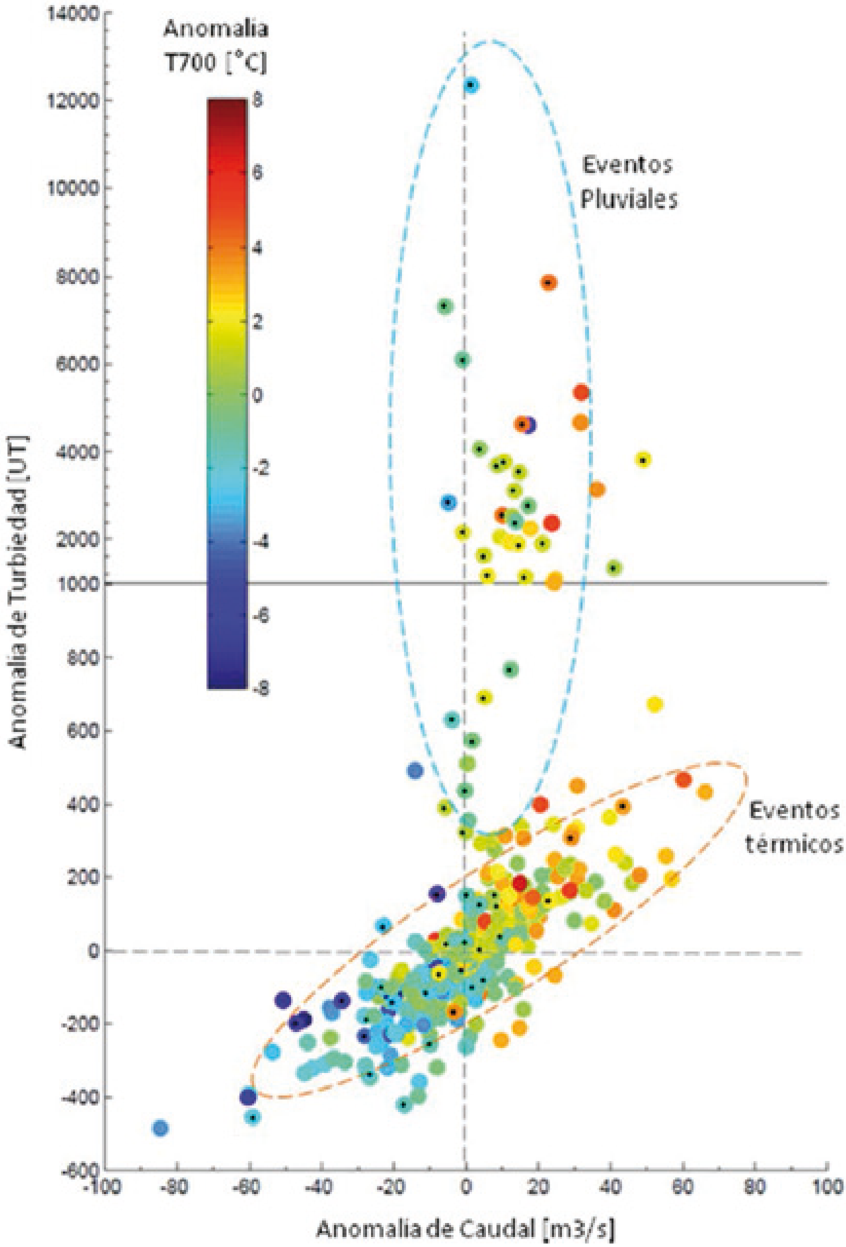

Figure 10. Dispersion diagram of daily anomalies in the flow rate of the Río Maipo station in El Manzano against turbidity in samples taken by Aguas Andinas independent sampling in the summers of 2002, 2005, 2008 and 2010. The circles are coloured in accordance with the temperature anomaly at a level of 700 hPa (an altitude of around 3,000 m) and a dot has been added if precipitation was recorded at the Lagunitas station (Blanco river basin, altitude 2,700 m above sea level).

It is these most recent events that we wish to study, in that they have caused the most extreme turbidity levels, right at the time of greatest demand for drinking water in the summer months.

3.3 Synoptic analysis

Different studies (Viale and Garreaud 2014; Garreaud and Rutllant 1997) indicate that summer precipitation over the Central Chilean Andes is usually associated with convective activity, when pockets of air are raised by thermal currents, boosted by lower pressure and weak winds at mid-level in the atmosphere, to their free convective layer. This activity has a clear daily cycle, and can give rise to intense (1-10 mm/h) albeit short-lived rainfall.

One limiting factor is humidity (usually very low in the Chilean sector). Nevertheless, the presence of a high pressure centre in central southern Argentina creates a weak easterly wind, responsible for carrying damp, warm air able to cross over the Andes and end up feeding the convective storms in the mountains' higher reaches, which move towards the Chilean sector, causing precipitation. The associated configuration is summarised in the conceptual model shown in Figure 11.

Given the above, one variable of particular interest in forecasting convective precipitation (and, potentially, alluvia in the Maipo River) is the zonal component of the wind (U, east to west) over the barrier of the subtropical Andes. There is no linear or even strict relationship (not every case of an easterly wind $U < 0$ entails convection), but is still a useful tool for analysis, since, unlike other meteorological variables (such as rain itself), wind is a better-forecast large-scale variable.

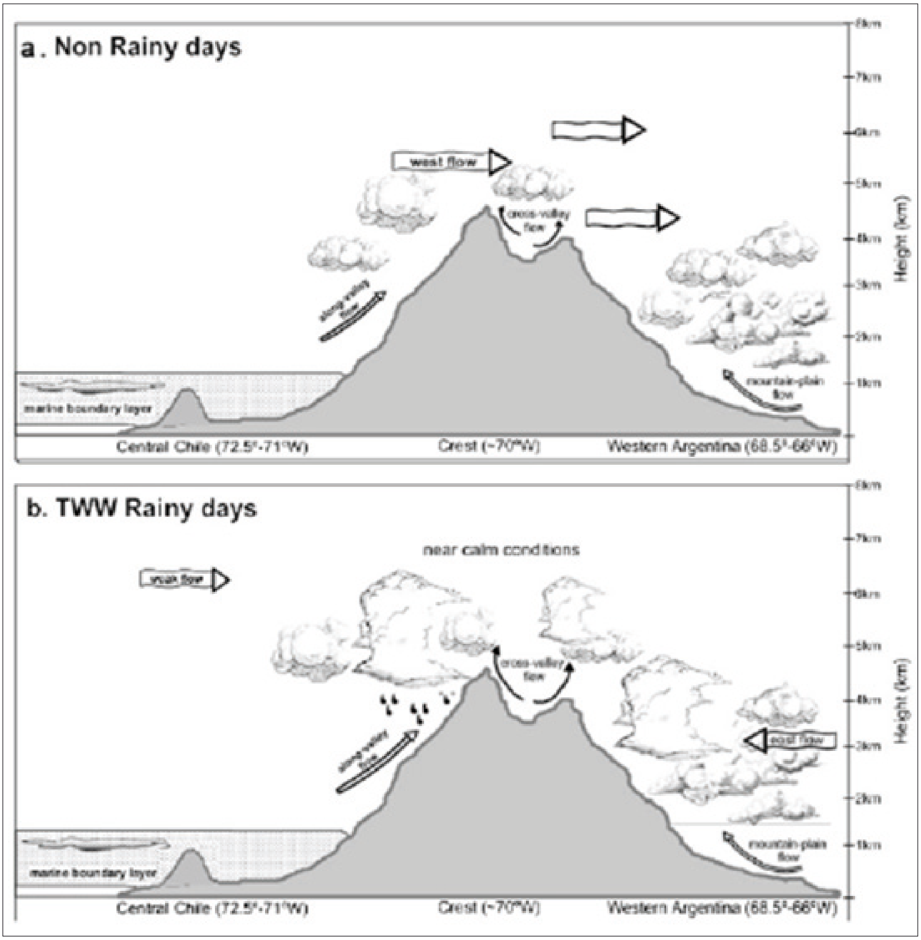

Figure 11. (a) Conceptual model of average flow conditions over the subtropical Andes (Santiago, Chile latitude). (b) The same for easterly flow summer storms, which predominate in this season (adapted from Viale and Garreaud, 2014).

3.4 Using lightning discharges to estimate convective activity

The localised nature of convective activity means that the current rain gauge network is unable to detect a large amount of this precipitation. Nevertheless, given that convective activity is often associated with lightning, one alternative is to take advantage of the records of the WWLLN (World Wide Lightning Location Network, http://www.wwlln.net) to detect said activity in the area studied. The WWLLN is made up of more than 60 land stations that record electromagnetic radiation to permit, by means of triangulation, the plotting, in space and time, of lightning discharges.

The summer of 2013 saw the largest turbidity events ever recorded in the Maipo River series. Daily turbidity values reached 16,000 NTU on 21 January and 65,000 NTU on 8 February. According to one study (DICTUC, 2009), peak values were probably five to ten times greater than the daily average, underlining the extraordinary concentrations of sediment affecting Aguas Andinas' Maipo River abstractions.

Figure 12 shows the time series of the average daily values for flow rate and turbidity in the Maipo River and the air temperature over Central Chile at 700 hPa for the period from November 2012 to March 2013. Superimposing onto these series the days in which most lighting flashes were detected over the basin of the Río Maipo station in El Manzano (orange bars), presumably associated with convective precipitation in the region, one can clearly see the rain-related nature of both events, due to electrical activity and the fall in temperature and flow rate during them.

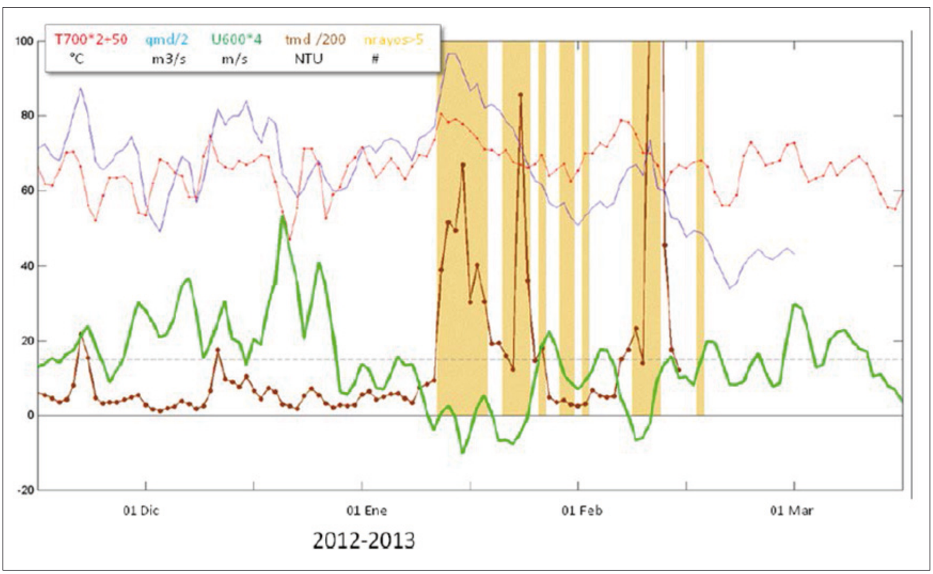

Figure 12. Daily time series of flow rate at the Río Maipo station in El Manzano (blue line), turbidity in Aguas Andinas independent samples (light brown line), temperature at 700 hPa (red line) and zonal wind at 500 hPa (green line). Units of measurement and scale factor noted above. Orange bars indicated days of electrical activity in the basin.

Figure 13 shows the electrical activity during the event of February 2013. Each dot marks the location of a lighting flash detected by the WWLLN on 7, 8 and 9 February. On the 7th and 9th, it can be seen that the majority of the flashes are in the Argentine sector (the usual situation), whilst on the 8th there is a high density of flashes in the Chilean sector, coinciding with the day of greatest turbidi

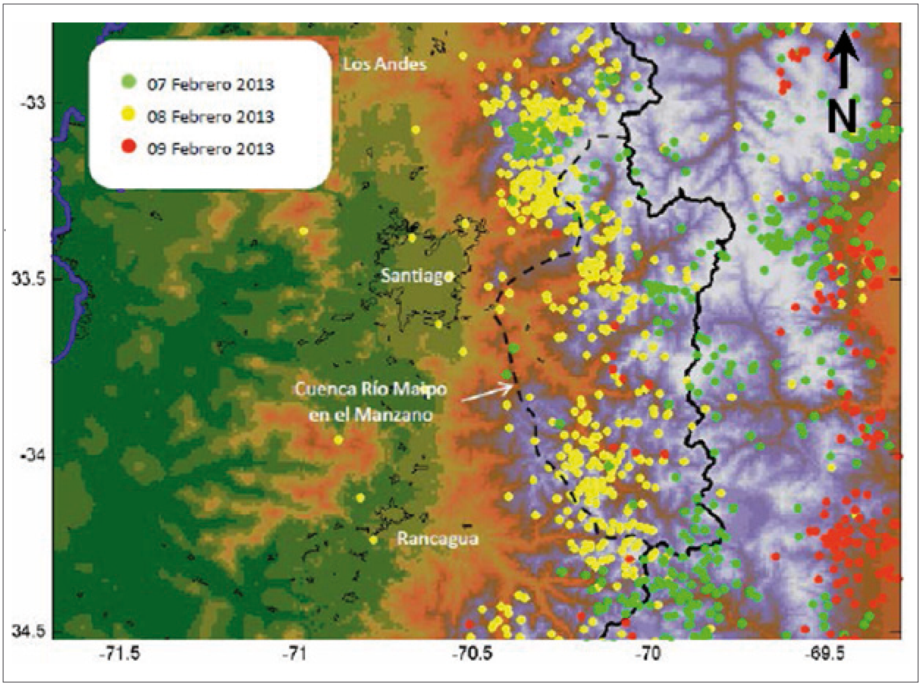

Figure 13. Location of lightning flashes detected by the WWLLN on 7, 8 and 9 February 2013 superimposed over a topographic map, marked with political borders and the boundaries of the Río Maipo en el Manzano station basin.

3.5 The outlook for high turbidity events in a changing climate

This document has stressed the fact that extreme turbidity events are not necessarily solely due to an increase in temperature, but rather also due to the occurrence of localised convective storms, which may cause mass wasting somewhere in the Maipo basin. So, the gradual rise in temperatures expected for the rest of this century does not in itself entail an increase in extreme turbidity events.

A more robust response calls for the establishment of the trend in the occurrence of convective storms in the region. Nevertheless, due to the inherent difficulties in modelling this type of small events, it is not possible to clearly forecast this trend using numerical models. However, taking advantage of the analysed association between summer storms and days with easterly winds, and given that the wind is a large-scale variable much better represented in global and regional atmospheric models, it is possible to gain an indirect understanding of forecasts of convective activity under climate change scenarios.

Figure 14 shows the difference in the zonal wind average for the Southern Hemisphere's summer months (December, January and February) between the turn of the century until now based on an RCP8.5 concentrations scenario (strong greenhouse gas emissions). It can be seen that the Metropolitan Region is in an intermediary area, so there is no clear indicator pointing to either an increase or decrease in convective activity (and hence extreme turbidity events) over the Maipo River.

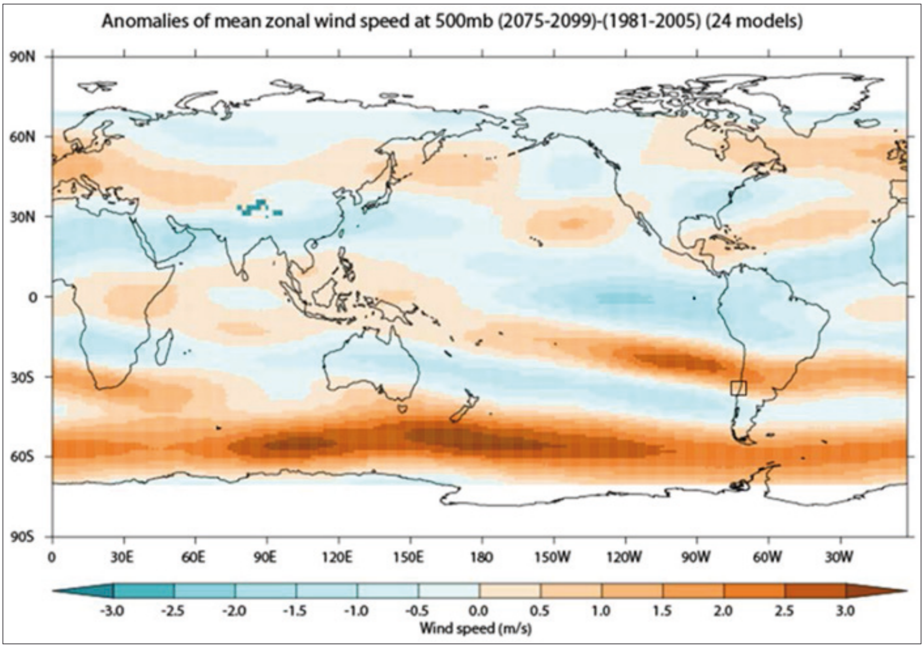

Figure 14. Difference in zonal wind average at a level of 500 hPa between future scenario (2075-2099, under RPC8.5 concentrations conditions, similar to current rate) and current situation (1981-2005) based on CMIP5 simulations carried out for the fifth IPCC report, 2013. The area of interest is marked with a black square.

3.6 Drought analysis and prediction

Another significant phenomenon in the management and supply of water in the region is drought. Over the last four years, Central Chile has been affected by a decrease in precipitation, whose average values do not, in themselves, constitute extraordinary events, but the duration of the shortfall certainly does. Looking at the series from the Quinta Normal rain gauge station in Santiago de Chile in Figure 15, over the last 150 years of records, there have never been four consecutive years below 70% of the historical average, although there have been cases of three years. Additionally, in recent years, drought conditions are initially estimated to recur every 50 to 100 years.

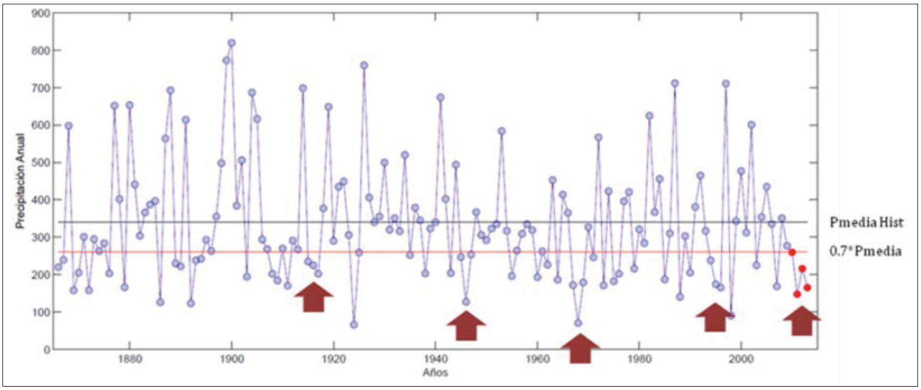

Figure 15. Annual precipitation series at the Quinta Normal station (Santiago, Chile).

To analyse the future outlook for these events, we have taken into account the series of simulated precipitations for Central Chile (33°S 71°W) according to IPCC 2013 global models, normalised in accordance with their respective long-term means and assuming an RCP8.5 concentrations scenario. Figure 16 shows how the models are in agreement on a gradual drop in precipitation compared with the historical period, with a mean decrease of 10% in the near future (2000-2040) and 25% in the distant future (2040-2080).

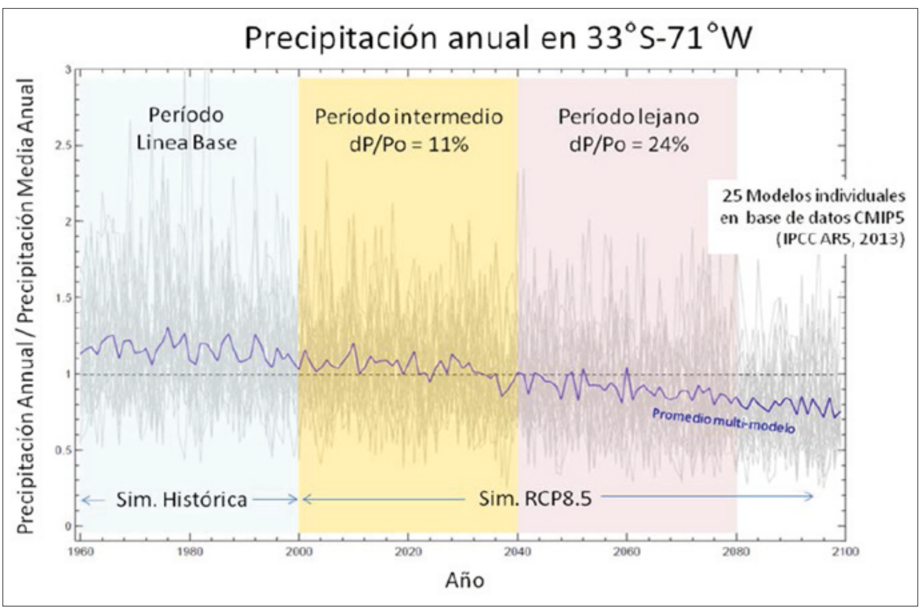

Figure 16 Annual series for precipitation over Central Chile, obtained from CMIP5 models. The series for each model (in grey) is normalised by its long-term mean. The blue curve is for the multi-model mean.

To study the expected increase in drought events similar to the current one, the following procedure was applied to each period and model contained in the above figure: 1) a stationary condition was assumed; 2) a two-parameter gamma distribution was adapted to annual precipitation; 3) a 1,000 year synthetic series was generated, and 4) the number of droughts ($p \cdot P^*$, where $P^* = 0.7$ Pp (precipitation) historical mean) and their duration in years was counted.

Table 1 shows the results, expressed as the number of droughts of three or more years per 1,000 years, which confirm that the historical simulations give values similar to those observed (from two to four droughts), a number which doubles in the near future and that increases more than seven-fold in the distant future.

Table 1. Number of droughts per 1,000 years in different periods of time, per CMIP5 models under an RCP8.5 scenario and adjusting the gamma distribution to generate synthetic series.

Number of droughts per thousand years	1960-200	2000-2040	2048 2080
Number of years with drought	96 ± 12	170 ± 18	320 ± 25
Number of biannual droughts	17 ± 4	34 ± 8	96 ± 15
Number of droughts of 3 or more years	3 ± 1	6 ± 2	21 ± 5

4. THE SUSCEPTIBILITY OF SLOPES IN THE MAIPO RIVER BASIN TO MASS WASTING

The previous chapter contained an analysis of the non-linearity of the relationship between flow rate and average turbidity, which indicated that high turbidity can occur not only in association with high flow rates (carrying sediment), but also due to mass wasting events commonly called alluvia.

The high turbidity events of January and February 2013 in the Maipo river basin, in addition to causing damage to infrastructure and blocking roads, affected the public with the closure of drinking water plants. An analysis of their causes is thus required to be able to grasp the likelihood of them occurring more frequently in the medium and long term.

The characteristics of the Maipo river basin make it very difficult to carry out preventative actions against high turbidity events due to mass wasting. Nevertheless, we see the need to carry out a risk assessment involving, on the one hand, the potential threat (hazard) and, on the other, the downstream impact it will have on infrastructure and the general public (vulnerability).

The danger or hazard is directly related to the probability of occurrence of the event within a specific area and timeframe, and to the ability to control and predict this event.

Prior to studying the danger of mass wasting, it is often useful to first identify the areas susceptible to the occurrence of the threat. This chapter therefore contains a summary of the susceptibility to mass wasting of the slopes of the Maipo river basin, associated with the possibility that an area is affected by a specific process, generally expressed in qualitative and relative terms.

4.1 The theoretical framework

The term 'mass wasting' refers to downslope movements of soil, rocks or a combination of the two, in which gravity is always present as a factor. These earth movements arise due to the progressive weakening of the materials, combined with geometric terrain conditions (such as steep slopes) and are in general triggered by earthquakes, intense rains or changes in the terrain's natural geometry (either natural or caused by man). The term 'mass wasting' refers to downslope movements of soil, rocks or a combination of the two, in which gravity is always present as a factor. These earth movements arise due to the progressive weakening of the materials, combined with geometric terrain conditions (such as steep slopes) and are in general triggered by earthquakes, intense rains or changes in the terrain's natural geometry (either natural or caused by man).

- **Conditioning factors and trigger factors**

  The different wasting processes can be broken down by the material moved, the characteristics of the movement, whether or not there is geological structure control or the predominant fault mechanism.

  Each of the indicated types of mass wasting has its own characteristics, although there are factors related to the nature, structure and composition of the terrain that favour environments in which wasting processes can occur. These factors, which include the slope gradients and rugged topography of the terrain, the quality of the materials, the degree of weathering, the presence or absence of vegetation, the presence of water and the existence of human intervention, amongst others, are called conditioning factors.

  Similarly, there are factors that have altered or modified the terrain's pre-existing stability, such as buildings, roads, earthquakes and intense rains, which can help trigger an event: these are called trigger factors.

More particularly, the triggering of mass wasting due to meteorological and climate-related factors, of chief interest to this study, is fundamentally related to the duration, intensity and distribution of precipitation and with the prevailing climate. Additionally, the mechanism capable of causing wasting is associated with the degree of saturation of the materials and with a temporary increase in fluid pressure, which causes instability.

- **Flow-type mass wasting**
  In studies of this type, susceptibility can be estimated based on the inventory of phenomena recorded in an area, which is made independent of the time variable and of the calculation of the probability of occurrence by means of a summing of factors favouring the creation of the phenomena. In this sense, there are numerous studies, historical precedents and press clippings telling of flow-type events in the Metropolitan Region's mountain and pre-mountain area, and so these are the events upon which this study will focus.

  Flow-type wasting is characterised by continuous movements in which the rupture surfaces are not preserved and the displaced mass is strongly internally deformed, behaving much like a water-saturated viscous liquid (Varnes, 1978). Such events can be classified based on the type of material involved and the amount of water present. So, one can find debris flows, where the majority of the solid matter is composed of thick particulate material; earth flows, whose material is the finest fractions of the soil, which is not saturated, and sludge flows, composed mainly of fine material and fine sand, which is totally saturated.

  An analysis of flow-type events in the Metropolitan Region's Pre-Andes area by Hauser (1985) showed a clear relationship between such wasting and intense precipitation, more than 60 mm in 24 hours in winter. Making an estimate based on an event occurring in 1980, the author indicated that, in the case of summer rains, 5 mm of rainfall per hour would be enough to trigger flow events. Similarly, highly intense precipitations in a short period of time, as well as precipitation of medium intensity over prolonged periods of time, could be considered trigger factors (Padilla, 2006).

4.2 The events of summer 2013 in the Maipo river basin

According to records consulted, 21 January and 8 February 2013 saw the appearance of a series of debris flows channelled by tributaries of the Maipo and Volcán rivers and in the San Alfonso stream (Moreiras and Sepúlveda, 2013).

These reports (Moreiras and Sepúlveda, 2013; SERNAGEOMIN, 2013), indicate that, in both cases, the trigger would have been the intense and highly localised precipitation attributed to summer convective storms, where a mass of damp easterly air flowed over the Andes and intensified the behaviour of the South Atlantic High.

There is an acknowledged shortage of rain measurement information on these mountains, which makes it impossible to gain a clear understanding of the rainfall rate that triggers these events. According to the measuring stations available to the Directorate-General for Water, a body reporting to the Chile's Ministry of Public Works, maximum precipitation of 11 mm per day was recorded on 21 January (at the El Yeso station) and 6.8 mm per day on 8 February (San Gabriel station) in the Maipo Basin. Unconfirmed reports from the area would indicate that this precipitation would have occurred in a short period of time and could have exceeded the value of 5 mm/h set by Hauser (1985) as a trigger factor for causing flows. It should also be noted that the first event would have been caused by precipitation over a greater area than the second, such that the precipitation accumulated in the area in the short period of time between the two events (soil saturation) would have had an influence on the recording of flow-type mass wasting on 8 February (25-day rainfall phenomena impact, Padilla, 2006).

According to the above reports, the events on these dates would not have occurred in isolation, but would have taken place in a number of gorges and tributaries. Indeed, according to the results of the technical inspection carried out by SERNAGEOMIN, on 21 January, flows would have occurred in the San Alfonso, El Manzano and El Volcán gorges, as can be seen in Figure 18. This same figure also shows the debris flows arising on the night of 8 February and located in small tributaries of the Colorado River and en route to the Los Maitenes and Alfalfal stations. The rainfall in the Colorado Valley would have activated a series of gorges that are Maipo River tributaries along a 14-km stretch, measuring from the Aucayes gorge until the Colorado Rivers outlet into the Maipo.

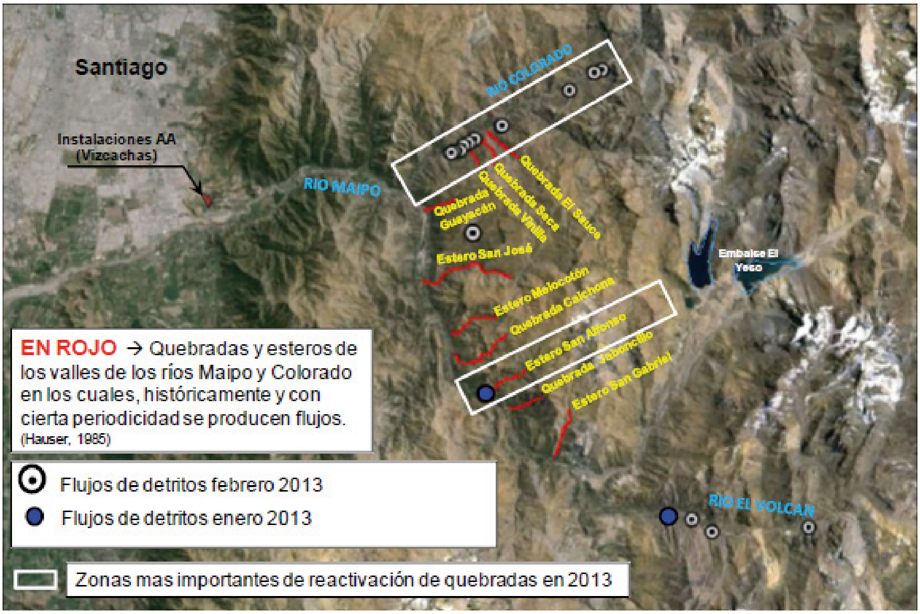

Figure 17. Mass wasting occurring in January and February 2013 in the areas under study, plus gorges in which flows have occurred in the past (source: UFSM own work).

Given this background and the goal of this study, the area of interest is focused to the southeast of the city of Santiago, covering the Maipo river basin and its main tributaries, the Colorado, Yeso and Volcán rivers. This area is outlines in white in Figure 18

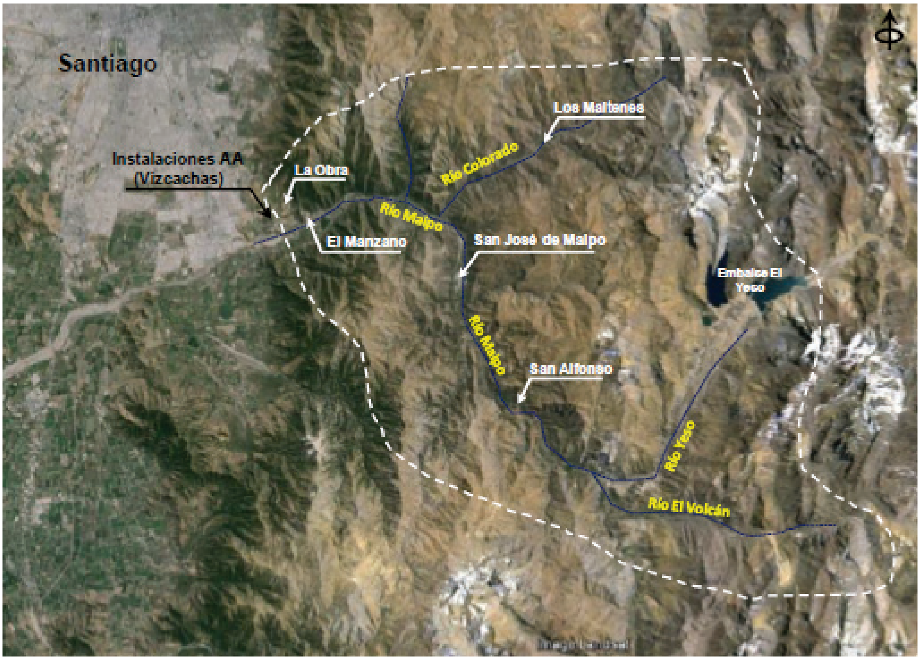

Figure 18. General view of area of study (source: own work based on Google Earth image).

4.3 Methodology employed to establish susceptibility

The methodology applied in this study is that suggested by Lara (2007) and permits the establishment of a susceptibility index (SI) based on the sum of the weighted sources for different conditioning factors. The methodology's ranges and values are defined based on importance and influence on the occurrence of mass wasting, providing an SI ranging from 0 to 100% for each unit of analysis. Critical mass wasting areas will be those with an SI of greater than 50.

The susceptibility study of the area analysed has followed the three stages defined in the methodology:

- A first, off-site stage aimed at 'characterising the area of study' based on an analysis of bibliographic information and previous studies in the area, which also helps define the scope of the work and the specific area to be assessed.

- A second stage of 'onsite field inspection', aimed at characterising the units present in the area of study, performed by means of observation (geological, geomorphic, geotechnical, hydrological, hydrogeological, of vegetation and of onsite description of soils and rocks).

- A third stage of 'assessing susceptibility', which consists in establishing SI values by applying tables with weighted conditioning factors for different units of analysis, based on geological and geomorphological criteria. Table 2 shows the conditioning factors and the maximum weighting taken into account for flows.

Table 2. Conditioning factors assessed for flow susceptibility and maximum weight (Lara, 2007)

FACTOR		%
GEOMORPHOLOGY	Slope gradients	35%
	Drainage channel slope gradient	
	Narrowness of drainage channel	
	Exposure to sun	
GEOLOGY AND GEOTECHNICS	Geological/geotechnical characteristics of the material	35%
	Humidity and saturation	
CLIMATE-VEGETATION	Accumulation of snow	10%
	Vegetation cover	
ANTHROPIC	Obstruction of drainage canal	10%
	Artificial destabilisation of slopes	
BACKGROUND	Alluvia noted in the valley	10%

Set out below is a summary of each of the stages followed in this methodology, placing the emphasis on the outcome of the application.

4.3.1 Characterisation of the area of study

Geomorphologically, the area of interest can be characterised as belonging to the Andes mountains, which, in this area, reach altitudes of more than 6,000 metres above sea level. It is a young range whose heights decrease towards the west. This unit contributes the greatest amount of material that fills the intermediate depression, which is mainly carried by the Maipo and Mapocho rivers. The slopes surrounding the Maipo, Yeso, Colorado and Volcán rivers have heights approaching 1,000 m, and gradients of between 30 and 50°, occasionally exceeding 55°. Current watercourses have low gradients (of less than 10°) mainly made up of fluvial and alluvial deposits, the product of prior activity in the courses (in some cases, earlier alluvia).

The geology of the area of study was obtained from the studies by Thiele (1985) and Fock (2005). In general terms, these define volcanic and stratified clastic rocks belonging to the Abanico and Farellones (Cenozoic) formations, which are highly deformed. To the east are the formations of the Damas River (continental sequence and volcanic rocks) and Colimapu (sequences of sedimentary rocks and volcanic insertions), both Mesozoic. There are also intrusive bodies (mainly granite and granodiorites), the most important of which are those of La Gloria, San Gabriel (Upper and Middle Miocene) and La Obra (Lower Miocene). Amongst the Quaternary deposits (alluvial and colluvial, amongst others), worthy of particular note is the presence of mass wasting in the main gorges in the area of interest.

Hydrologically, the area has been described in previous chapters: the Maipo River, in its upper watershed, has a drainage basin of around 5,000 km2, which starts in wetlands on the slopes of the Maipo volcano and has as its main tributaries the Volcán, Yeso, Colorado and Olivares rivers (from south to north).

With regard to hydrogeology, the DGA's hydrogeological map shows that just one aquifer is to be found in the mountainous region, specifically in the Volcán and Yeso rivers. This groundwater reserve, called the Santiago aquifer, stretches from the mountains to the outskirts of the town of Talagante, some 120 km away, with a size of some 10,000 million cubic metres. Following the Maipo River downstream, another aquifer is found in the Volcán River sector, where it joins the Maipo River.

Based on the characterisation of the area of study and having identified the mass wasting analysed in this work as being of the debris flow type, Table 3 defines the following significant conditioning factors:

Conditioning factor	Description
Geomorphology	Active gorges or those in areas of reactivation of previous mass wasting.
	Existence of steep slopes.
	Presence of short tributary gorges, with a steep gradient, straight and narrow (or embanked).
	Incidence of exposure to sun (especially on valley slopes arranged along east-west axis).
	Presence of vegetation on the slope (differentiating slopes with greater or lesser degree of exposure to sun).
Geology / Geotechnics	Presence of mass wasting-type deposits, particularly in watercourses and gorge bases. Presence of colluvial deposits or materials at the limit of their balance..
	Areas with the surfacing of volcanoclastic deposits of the Farellones, Abanico and Colimapu formations, which are characterised by surfaces with a high degree of fracturing and/or alteration giving rise to abundant rock fragments on the surface.
	The presence of secondary alteration minerals (e.g. zeolites), which would help to accelerate weathering. The presence of zeolites also has a influence upon the geotechnical properties of the rock massif, as they have the properties of expandability and hydration.
	Areas in which the rocks of the Abanico formation have been affected by hydrothermal processes, creating greater porosity and a reduction in the final strength of the rock.
Background	Presence of recently-occurring deposits or flow backgrounds.

At this stage, there is a need to define the sectors in which the conditioning factors presented will be applied. In this regard, considering the location in which flows have occurred in the past and also the events of summer 2013, in this study, we defined the assessment of flow-type mass wasting in the Colorado River, between the Los Maitenes sector (Aucayes stream) to the northeast and its south-easterly outlet into the Maipo River. Additionally, the San Alfonso stream gorge also shows a certain degree of recurrence of flow-type events, and so has also been regarded as an area of interest for assessing susceptibility. These areas have been called Area 1 (Colorado River) and Area 2 (San Alfonso stream) and are shown in Figure 17 marked by triangles.

Lastly, we need to find the units of analysis and the working scale. In this regard, taking into account the areas of analysis and the information available, the working scale has been defined as 1:20,000. With regard to the units of analysis, the methodology recommends not exceeding 150 for each area, based on geological, geomorphological and geotechnical criteria. The units of analysis must share common characteristics, such as the mean gradient, materiality and the geomorphological conditions (for example, orientation or type of geomorphological unit).

Figures 19 and 20 show the units of analysis defined for each area. In the case of area 1 (Colorado River), 112 units of analysis are defined (1:20,000 scale), which include a differentiation of gorge-type geomorphological units and slopes of different orientation and gradient. In the case of area 2 (San Alfonso stream), 71 units were defined using similar criteria. In both cases, it should be noted that the upper limit for units of analysis is defined on the basis of maximum heights, slope gradients and watersheds.

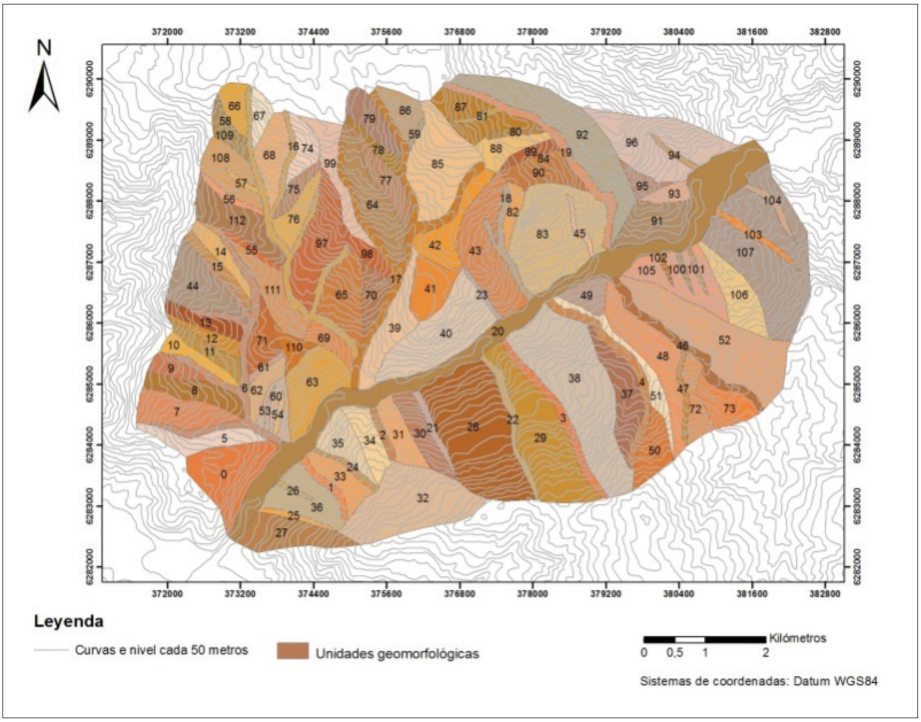

Figure 19. Units of analysis for area 1 (Colorado River), 1:20,000 scale (source: own work).

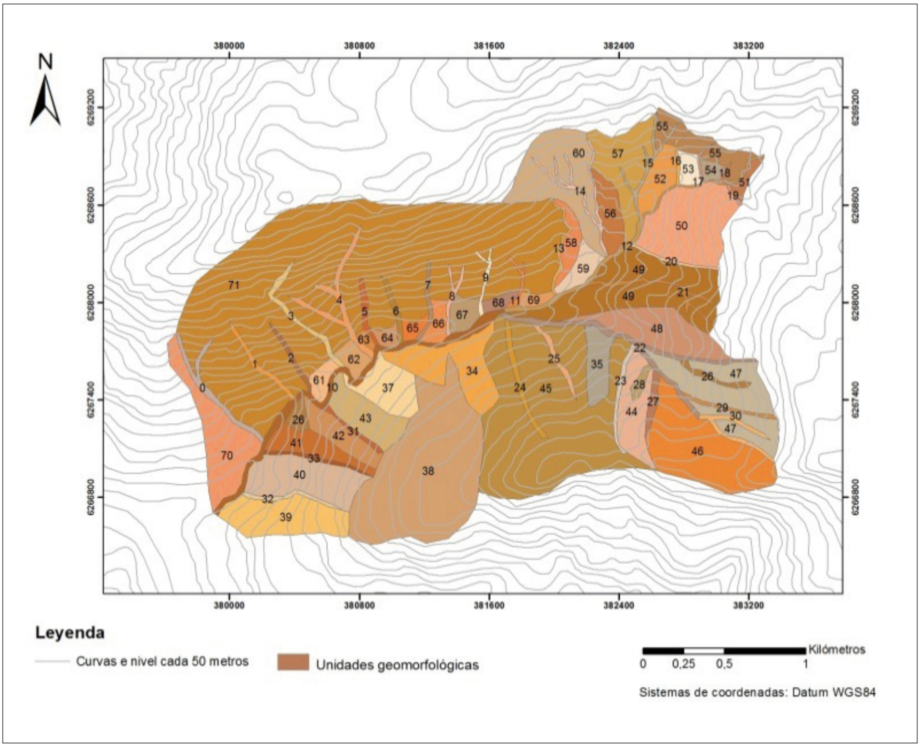

Figure 20. Units of analysis for area 2 (San Alfonso stream), 1:20,000 scale (source: own work).

4.3.2 Field inspection

To calculate the SI for flow-type events in each defined unit of analysis, four field trips were carried out to inspect the areas affected by the mass wasting occurring in 2013, and to gather background information that would permit us to assign ranges to the different conditioning factors.

The visits were made via established access routes. In the case of area 1 (Colorado River), access was gained via the G-25 highway towards the town of San José de Maipo, from where the G-345 is taken in a northeasterly direction, parallel to the Colorado River gorge, on the southern bank. It should be noted that public access to area 1 is only available to the slopes and gorges of the southern bank of the Colorado River, and that there is no public right of way along the northern bank. To access area 2 (San Alfonso stream), the G-25 highway is taken towards the town of San Alfonso, to the intersection with the San Alfonso stream. Access to the area was gained by foot along the gorge, as far as the steep morphology allowed. In both cases, areas not visited due to access problems were analysed by means of aerial photographs and observation with binoculars.

Generally speaking, irregular deposits were observed, arranged at the bottom of tributary gorges in the form of fans, at the bottom of deep watercourses or on the banks of the main courses (the Colorado River and the San Alfonso stream) deposited by the events of 2013, and by some historical events (see Figure 21).

Figure 21. View of the mass wasting deposits on the banks of the Colorado River (source: photographic record of March 2014 field visit).

Geomorphologically speaking, the tributary gorges visited were short in nature (less than 3 km along the southern bank), straight and deep, with a channel depth-width ratio greater than 0.7, regarded as a high degree of narrowing. Figure 22 shows an example of this type of gorge.

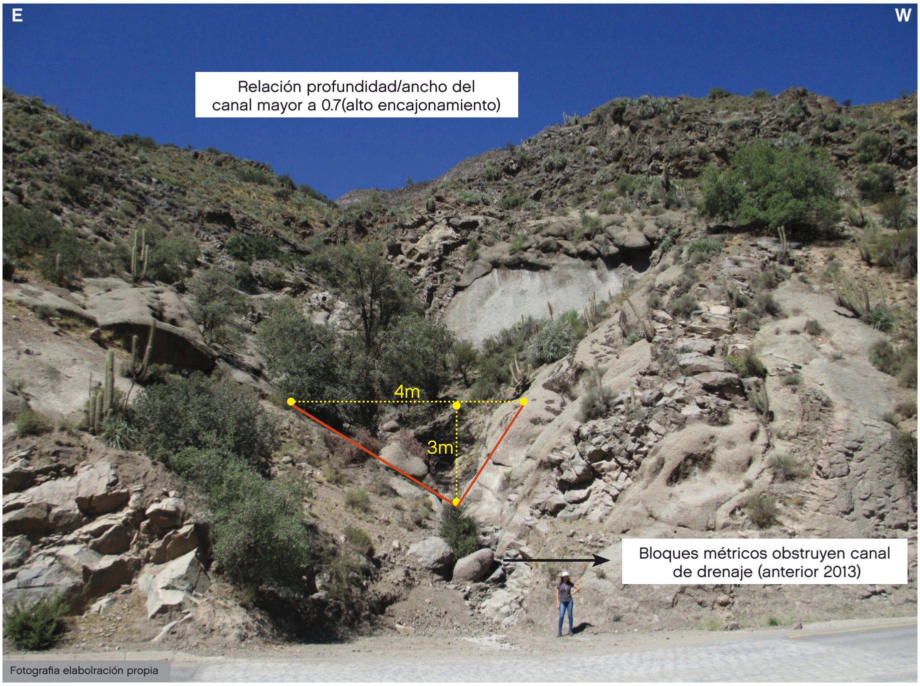

Figure 22 View of mass wasting deposits in tributary gorges of the Colorado River (source: photographic record of March 2014 field visit).

4.3.3 Assessment of susceptibility

To assess the susceptibility of each unit of analysis in the two areas of study, the adopted methodology was directly applied. The ranges assigned for each conditioning factor per unit were obtained from field observation, the bibliographic background, constructed slope models and the authors' experience of the subject.

An SI was established for the different units of analysis and the values obtained plotted using geographical information systems (GIS), the results of which are shown in Figures 23 and 24. The ranges are plotted in accordance with the proposed methodology (SI of between 0 and 24 = low susceptibility, 25 to 49 = average susceptibility, 50 to 74 = high susceptibility and · 75 = very high susceptibility).

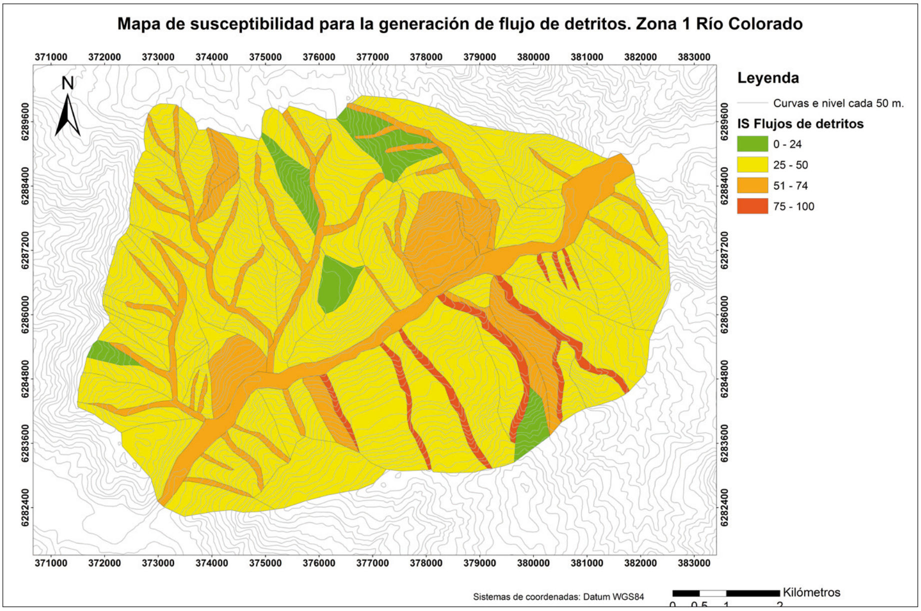

Figure 23. Susceptibility map for the creation of debris flow. Area 1, Colorado River (source: own work).

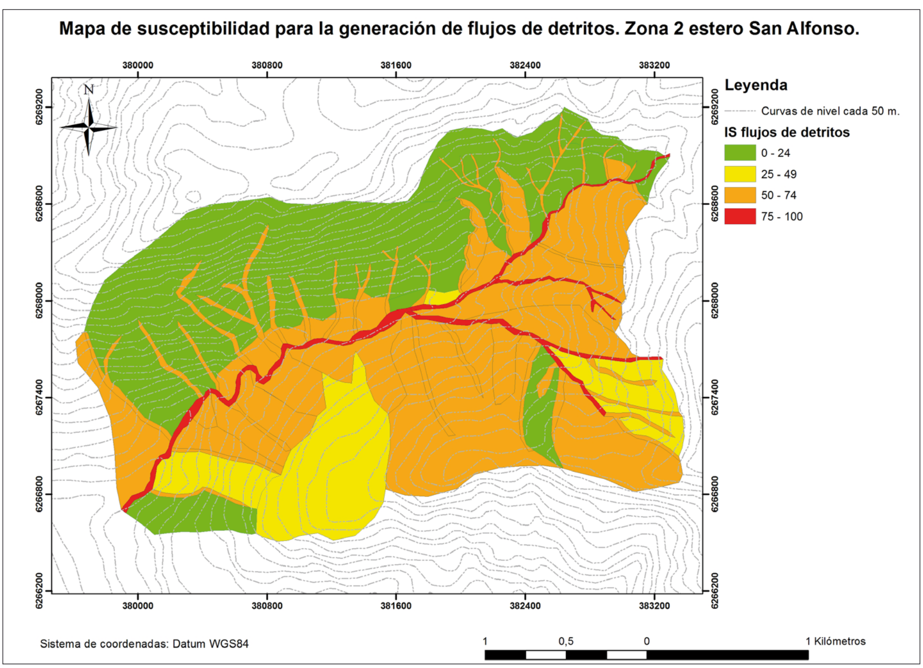

Figure 24. Susceptibility map for the creation of debris flow. Area 2, San Alfonso stream (source: own work).

4.4 Results of zoning for the areas studied

The results gave rise to zoning maps (for both areas) with units featuring an SI varying between 0 and 25, i.e. low susceptibility (green on the maps), and between 50 and 100, i.e. high to very high susceptibility (orange and red on the maps).

In area 1 (Colorado River), the units with the highest SI are found in the river's tributary gorges. Of the total of 112 analysed, 26 have a high or very high susceptibility (SI > 50). The highest SI values are found in the gorges on the southern slopes of the main watercourse (for example the Vinila, Seca and El Sauce gorges, amongst others), with values exceeding 76%.

To a lesser extent, we identified slopes highly susceptible to causing flows, adding dispersed materials, relating to surface colluvial deposits, and in which other types of mass wasting were also identified (landslide and rock fall type).

In area 2 (San Alfonso stream), of the total of 71 units, 59 displayed a high or very high susceptibility (SI > 50). The units with higher SIs were those of the main watercourse, and there were also a significant number of highly susceptible tributary slopes and gorges. The results show a general tendency of low susceptibility on the northern slopes of the San Alfonso stream, which matches the asymmetry of the slopes of the east-west facing valleys. Additionally, a significant area of low susceptibility was identified, since the dominant surface material is rock, with very low amounts of moveable colluvium or dispersed material.

To sum up, the values obtained in this study for the susceptibility indices would indicate that the high turbidity events that have historically occurred in the Maipo Basin are very likely to continue. The likelihood of them doing so to a greater or lesser degree is directly related to trigger factors, such as the intensity of the precipitation and the accumulated precipitation, originating in winter and summer storms.

What is more, identification of the conditioning and trigger factors is not in itself enough to confirm a direct link with high turbidity levels, not only due to the need for data that permits the development of a reliable model with the ability to make time-based forecasts, or due to the permanent updating of information on certain geomorphological factors (a static/dynamic look at the problem) but also because it requires a systemic focus.

Lastly, it should be noted that historical records, as well as the recently occurring events, allow us to observe that the flows are created throughout the entire pre-mountain and mountain area of Central Chile. Nevertheless, the specific places where these events occur are local, particularly associated with short tributary, steep and straight gorges, narrow main watercourses and steep slopes with available material.

Given the above, we can validly establish the existence of areas that are more susceptible than others, by weighting the conditioning factors. Applying the methodology to the areas analysed (area 1, the Colorado River Valley between the Maipo Valley and the Aucayes stream, covering 65 km^2, and area 2, the San Alfonso stream, 7 km^2) allows us to confirm the existence of geomorphological units and areas with a high susceptibility to flow generation (SI > 50), which are mostly found in short tributary gorges and the narrow stretches of main rivers, especially those with a northern orientation (on the southern bank) and, to a lesser degree, slopes with available colluvia or material from historical wasting. Comparatively, a greater number of susceptible units were identified in the San Alfonso stream (area 2). This can be attributed to the geomorphology of the valley, which is a straight and narrow gorge.

4.5 Preliminary analysis of the link between mass wasting and turbidity

Establishing areas likely to suffer from the occurrence of threats by means of the susceptibility index (SI), as part of the identification of conditioning factors associated with high turbidity events, is one of the first steps necessary to link turbidity in surface watercourses that feed treatment plants. Obviously, we also need to identify trigger factors, such as the intensity of the precipitation and the accumulated precipitation. With specific regard to the area of study, we need to understand and predict the development of convective storms occurring in the summer season in the high mountain region of the Maipo basin, as one of the predominant factors previously identified in Chapter 3 of this study.

Nevertheless, this identification of conditioning and trigger factors is not in itself enough to establish a direct link with high levels of turbidity. This requires an association, through proper identification, of potential wasting volumes on the slopes prior to the event and their granulometry, the identification of existing deposits on the banks of the watercourses and their granulometry, better precipitation, flow rate and sediment transportation measurement, not to mention turbidity measurement, amongst other aspects, within the timescale framework of each type of parameter.

Nevertheless, by way of focusing attention on the problem and as a prelude to other courses of action, it is possible to perform an analysis of some factors or parameters, which may be carried out on a reasonable engineering basis, such as:

- Estimation of the transport speed and arrival time of a mass wasting event.
- Identification of correlations between turbidity and other phenomenon variables.
- Definition of a transfer function between conditioning and trigger factors.

The parameters indicated in the preceding paragraph are expanded upon in the following pages.

4.5.1 Estimating the transport speed and arrival time of a mass wasting event

The method employed is Jacobson's (USGS, 1996), which permits the establishment of the maximum probable transport speed in rivers, using only global-level geomorphological information and river flow data measured at a station close to the area of interest:

$$V_{mp} = 0,25 + 0,02 \times (D'_a)^{0,919} \times (Q'_a)^{-0,469} \times S^{0,159} \times \frac{Q}{D_a}$$

$$Q'_a = \frac{Q}{Q_a}$$

$$D'_a = \frac{D'_a{}^{1,25} \times \sqrt{g}}{Q_a}$$

Where:
V_{mp}: maximum probable speed in en m/s
D_a: basin area in m^2
G: acceleration due to gravity in m/s^2
Q_a: annual average flow rate in m^3/s
Q: flow rate at time of forecast in m^3/s
S: mean basin gradient in m/m

For our case study (Figure 25), associated with the events occurring in the Vinila gorge and the San Alfonso stream, information from the following river gauging stations has been used:

- Colorado River, before joining the Maipo
- Río Maipo in El Manzano
- Río Maipo in San Alfonso

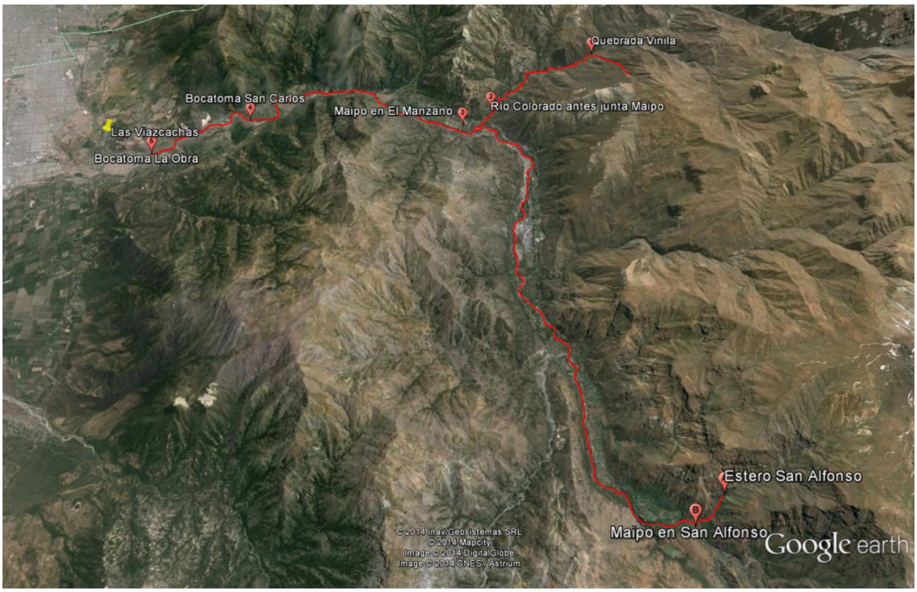

Figure 25. Area of study of transport speed: area 1, Colorado River / area 2, San Alfonso stream (source: own work).

The flow rate values at intermediary points are obtained by transposing flow rates based on the drainage area, taking into account the geomorphological similarity between basins, and the distances covered by the watercourses are obtained from Google Earth. With all this information, it is possible to establish the probable maximum speeds and post-event arrival times, where the maximum transport speeds are of the order of 2.2 m/s for sections of the Maipo River, in line with the expected values, which depend upon the assumed flow for the defined watercourses.

The arrival times are shown in Figures 26 and 27, and are of the order of 3.8 hours for area 1 and 5.5 hours for area 2.

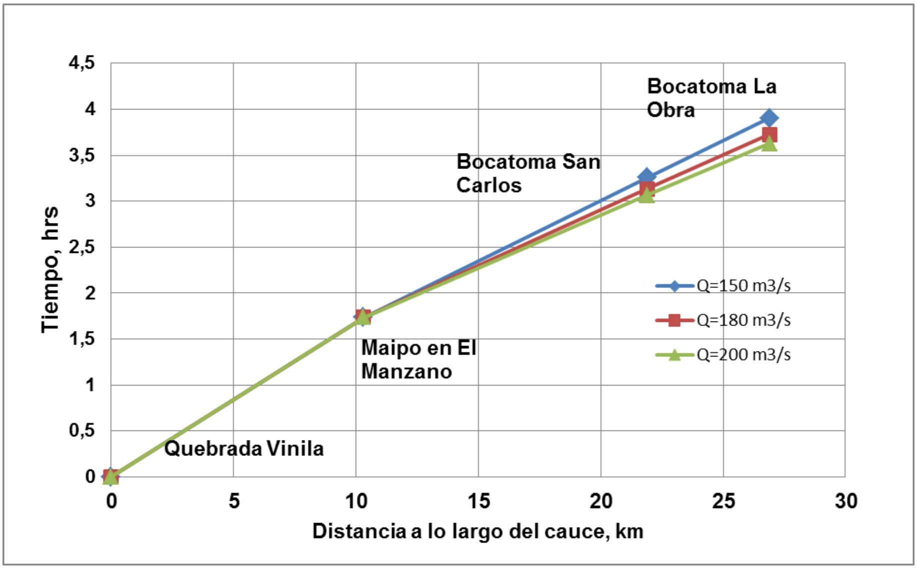

Figure 26. Estimated arrival time of high-turbidity flow at plant in area 1 (source: own work)

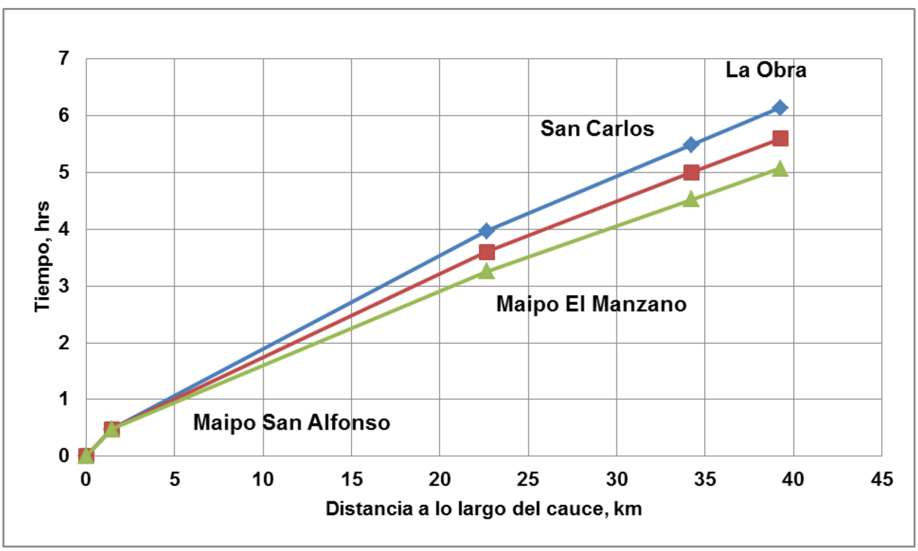

Figure 27. Estimated arrival time of high-turbidity flow at plant in area 2 (source: own work).

Although it is true that the expression used was not developed for large-scale mass wasting events, since the fluid's properties change, it would nonetheless be applicable to provide an estimate for high-turbidity events, given that it is very commonly used for calculating contaminant dispersion.

4.5.2 Spectral analysis of turbidity

One of the difficulties in forecasting high turbidity events stems from the lack of correlation between turbidity and flow rate. In this study, we evaluated the possibility of making some kind of forecast by resorting to wavelet spectral analysis (power spectrum and cross spectrum), given that the flow rate can be predicted with a good level of confidence.

As can be seen from the flow rate-turbidity spectrum (Figure 28), it is not possible to identify any representative pattern indicative of any recurrence of high correlation between the two variables throughout the measurement period. Quite the contrary: one can observe an entirely random distribution of powers, with high powers distributed throughout the scale range and time window. This confirms what we observed from inspecting the statistics: the relationship between the variables is highly non-linear and establishing some kind of prediction model is no simple task. This leads us to consider a model incorporating the physical characterisation of the processes involved, with regard to both the sediments produced by the turbidity and the hydrology of the area and its atmospheric forcing factors, and obviously some transfer function between the phenomena.

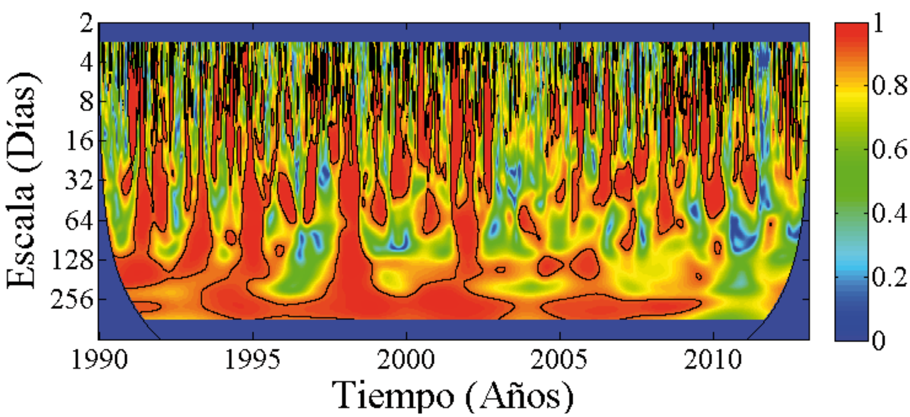

Figure 28. Crossed flow rate-turbidity spectrum (source: own work).

4.5.3 The outlook: transfer function between conditioning and trigger factors

In the 1940s, and arising from a series of analysis of data on soil erosion from stations installed in the US at the beginning of the 1930s, an equation was established for soil loss associated with a range of geomorphological and climate-related factors, called the Universal Soil Loss Equation (USLE), as indicated below:

A = R · K· L · S · C · P

Where:

A: average annual soil loss per surface unit

R: rainfall erosivity factor

L: slope length factor

S: slope steepness (gradient) factor

C: soil use and management factor

P: erosion control practice factor

This equation has evolved over the course of time (with the RUSLE and MUSLE) in line with different modifications of its purpose and the establishment of associated factors.

For example, the RUSLE (Revised USLE) retains the original purpose but incorporates new aspects such as frost processes, new calculation subfactors and new considerations of agricultural practices.

The MUSLE (Modified USLE) is designed to establish the sediment yield for a singular event, and its expression is as follows:

$$A = 11.80\ (V_Q\, Q_p)^{0.56}\ KLSCP$$

Where:

A: amount of sediment produced during a singular storm in metric tonnes, t

VQ: runoff volume in m^3

Qp: maximum instantaneous flow in m^3/s

KLSCP: the remaining factors used for the USLE

This equation is important to the subject under study because of the potential link between conditioning factors (principally of the geomorphological type), given that we possess an indicator representative of such a situation named the susceptibility index (SI), and the trigger (meteorological) factors.

5. THE IMPACT OF HIGH TURBIDITY LEVELS AND DROUGHT IN THE RIVER BASIN UPON THE MANAGEMENT OF DRINKING WATER SUPPLY

5.1 Analysis of the occurrence of this impact and its evolution over the medium and long term

Historical statistics show that drought and high turbidity are cyclical phenomena and form part of the river basin's hydrometeorological condition. Nevertheless, in recent years, both of these phenomena have displayed exceptional behaviour, associated with a longer duration of drought conditions and an increase in the frequency of extreme events (turbidity). Both phenomena have a direct impact on rivers and other watercourses, the main sources for the supply of drinking water to the Santiago Metropolitan Region.

With regard to drought conditions, although that currently affecting the basin is clearly an exceptional event, all predictions point to a trend of gradually declining precipitations, which implies an increase in the frequency of this type of shortfall. The preceding point indicated that, under climate change conditions, over the course of the next 30 years, it is estimated that drought events will double in comparison with those previously observed, in terms of precipitations and droughts of three or more years. Additionally, when taking into accounts flow rates above the 90% threshold at the Río Maipo station in El Manzano, another study estimates that there will be a triplication of these events (DICTUC, 2013).

Within the same context of flow rate availability, the effects of climate change on the hydrology of the Maipo were assessed in a study (Garreaud et al., 2009) for different emissions scenarios, in accordance with the results of the PRECIS model applied to simulations of the HADCM3 global circulation model. Figure 29 provides the example of the climatological hydrograph for the DGA's El Yeso station for a base scenario (BS) and for an A2 scenario (this latter one being now replaced by the RCP8.5 scenario), together with a variability range of 20% and 80%:

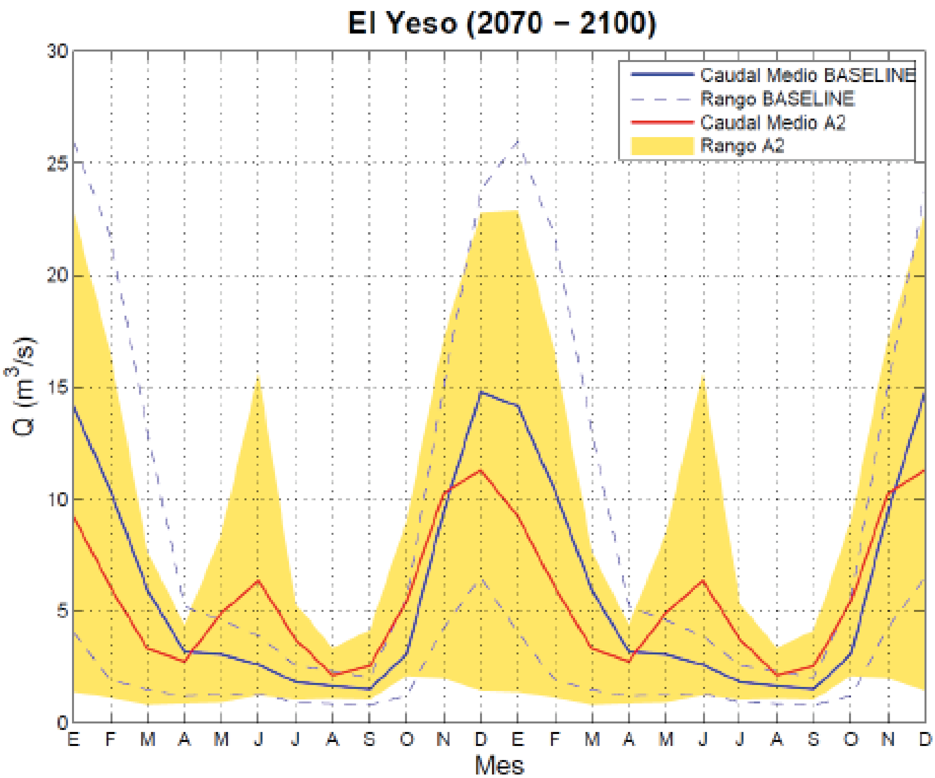

Figure 29. Availability of flow rates for the El Yeso for a base scenario and for an A32 climate scenario A2 (source: Garreaud et al., 2009).

When it comes to analysing the expected behaviour of turbidity events in the future, two focuses, pointing to two slightly different phenomena, have been used. One study, which compares observed statistics of turbidity phenomena registered above a certain threshold (DICTUC, 2014) shows how, in the period from 2008 to 2013, turbidity events have increased both in frequency and in intensity and magnitude for all thresholds (from 1,000 NTU to 3,000 NTU), in comparison with those observed for the period 1990-2008. Although this study makes no prediction with regard to future trends, a considerable increase in the mean turbidity levels to be faced by the drinking water supply company Aguas Andinas can be observed.

For its part, the study linking extreme summer turbidity with convective precipitation indicates that the Metropolitan Region is in a transition zone, meaning that there is no clear evidence pointing to either an increase or decrease in extreme summer turbidity events. It thus suggests taking them into account at a frequency similar to the current one, which does not make the phenomenon any less serious, as shown by the events of 2013 and the hydrological statistics for the last five years.

5.2 Impact types and their characteristics

Previous chapters have analysed the phenomena of drought and high turbidity levels recently occurring in Chile's Metropolitan Region. Set out below is an analysis of the main ways in which each of these phenomena may impact the supply of drinking water to this part of the country.

5.2.1 Drought-related impact types

Drought is the outcome of the accumulation of years of below annual mean precipitation. Depending upon how far below the annual mean the precipitation is, one can begin to talk of a drought after two or more years. As a point of reference, one can note that the current drought (2010-2013) has featured four consecutive years of precipitation of less than 70% of the annual mean, two of which had precipitation of less than 50%.

The problem therefore arises from precipitation, in the form of either rain or snow, below the annual mean there're and its impact upon the hydrology of the rivers and gorges in the basin. From the point of view of the supply of water for human consumption, this change in hydrology can have an impact in the two following ways:

- The need for a larger amount of water usage rights: one way of tackling hydrological changes is to resort to the market to acquire water rights.
- The need to use alternative sources of water: companies must make good the available flow rate shortfall with alternative sources. Most common these days is to replace surface water with groundwater sources but, given the limitations of the Metropolitan Region aquifer, this alternative has its limits and more research is needed to analyse other alternatives.
- Economic impact: the hydrological changes will have an impact on companies' operations, which will be reflected in investment costs, if supply needs to be increased, with investments in groundwater infrastructure or in the acquisition of more usage rights in a scenario of restricted water supply (higher demand – higher price). Similarly, operating costs will rise due the expense of exploiting this groundwater sources.

- Impact on the costs of supplying drinking water. A tremendously sensitive issue for consumers, who will be affected by the increase in prices due to the increased costs described in the preceding point.
- Disputes regarding the use of water resources: should the water shortage worsen, disputes could arise between the domestic water, hydroelectricity, industrial, mining and agricultural sectors.

- Possible rationing: although a scenario as complex as the rationing of supply is not contemplated, companies should take the necessary steps to prevent such a situation.

5.2.2 Turbidity phenomena-related impact types

As already noted, the waters of the Maipo River are the main source for the supply of drinking water to the Metropolitan Region, and given the background described previously, it would appear that the frequency and intensity of extreme turbidity events has been increasing over the course of recent years.

From the viewpoint of the supply of drinking water to the Greater Santiago area, the impact of these turbidity phenomena is mainly associated with production systems and their ability to treat water with a high turbidity level, and the storage capacity and autonomy of the supply network downstream of the plants. This being the case, the following impact types can be noted:

- Supply stoppages: very high turbidity levels, associated with both high flow rates in the river during the winter and localised convective events during the summer, put abstraction works at risk, as they tend to lie at the side of the river bed. The company supplying the majority of the water to the Metropolitan Region has suffered from events of this type, both at the end of the 1980s (turbidity events in winter periods) and in 2013 (turbidity events in the summer season). Both cases led to stoppages in the supply of water to the public whilst repair works were carried out.

  When turbidity levels exceed the treatment capacity of drinking water plants, to protect the facilities, they must be closed down as long as the event lasts. The greatest impact occurs when the high turbidity event continues for longer than the company's regulation system can manage, leading to supply being cut off.

- Economic impact: if high turbidity episodes occur, but can be countered by means of conventional treatments used in drinking water plants, they will entail higher costs due to the greater use of chemical inputs in coagulating and filtering processes.

Also, one should not forget the economic impact arising when damage is caused to abstraction facilities, whose repairs must be carried out under difficult conditions and great time pressure.

When supply has to be cut off, the company must incur greater operating costs due to increased use of groundwater sources, distributing water in tanker trucks and, subsequently, when supply is restored, to taking care in filling pipes and breakage problems associated with air inside them.

Lastly, there is the lower income earned during the period in which there was consumption at home. There is no legislation covering the issue in the country, but there are initiatives for the compensation of users that may come to pass, as is the case with the electricity companies.

- Corporate image: for a utility company, the harm to its image stemming from a failure to provide the service is enormous and, in the case of a water company, it could well be even worse, due to the possible relationship with public health (hygiene and feeding).·

5.3 Alternatives for mitigating the impact of drought and high turbidity phenomena

The IPCC report on managing the risks associated with extreme climate events associated with climate change (IPCC, 2012) indicates that adaptation involves any action meaning an adjustment of a natural or human systems in response to the actual or expected effects of climate change in order to moderate harm or exploit beneficial opportunities. In line with this focus, the IPCC has defined adaptation and disaster risk management approaches for reducing and managing risk in a changing climate based on six key aspects, as shown in Figure 30:

Figure 30. Adaptation and disaster risk management approaches for reducing and managing risk in a changing climate (IPCC, 2012).

5.3.1 Alternatives for mitigating drought

The outcomes of different medium- and long-term climate scenarios consistently point to a general trend of less precipitation in Central Chile and, accordingly, reduced availability of surface water resources. Section 5.1 comments in detail on these effects, but it is worth highlighting the fact that they call for significant efforts to guarantee, on the one hand, proper availability of resources and, on the other, more efficient management of water usage.

- **Increased use of alternative water resources**
  The high level of dependence on the surface waters of the Maipo river basin for supplying water for human consumption represents a medium- and long-term risk, given that studies indicate that the effects of climate

change will cause a reduction in surface water flow rates, as noted in section 5.1. It is therefore necessary to implement actions to make use of alternative water resources. Given the regional context of which the Maipo river basin forms part, advantage could be taken of the following alternative sources:

- Groundwater resources – recharging aquifers: although groundwater represents around 20% of the water resources for human consumption, the Metropolitan Region's aquifers are being exploited close to their limits. Therefore, except when trying to replace existing abstractions, the implementation of new boreholes must involve the finding of mechanisms to increase the recharging of aquifers above and beyond natural recharge rates.

Proper management of surface resources would, for example, allow for winter surpluses to be stored in aquifers to be used in times of shortfall.

- Reuse of treated water: over the course of the last decade, significant advances have been achieved in the cover provided by wastewater treatment, with a level of 99% being reached nationally. More particularly, from 2013 on, cover of 100% has been achieved in the Santiago Metropolitan Region.

This undoubtedly provides a comparative advantage and makes available a volume of water of 15 m^3/s, which is now discharged into the Maipo River and its tributaries. Although some of this volume is used for agricultural activities, its use for human supply during times of water shortages is an alternative that must be studied, in the aim of providing advanced levels of treatment for this water to guarantee that it is fit for human consumption.

It should be noted that implementing these actions also requires proper regulatory support to guarantee the quality and efficient use of such resources.

- **Efficiency in the use of water resources**
  The scarcity of water resources is without doubt a problem of the balance between the supply/availability of water and the demand for this resource for different uses. This is why, although it is important to look at the availability of water, actions aimed at guaranteeing the efficient use of this resource are also of great significance.

  According to the information contained in the Chile's National Water Resources Strategy document (Estrategia Nacional de Recursos Hídricos, Chilean Ministry of Public Works, 2012), at a national level, the consumptive use of water is, in the main, for irrigation purposes, whilst water for human consumption stands at around 6% of the total. At a regional level, the Santiago Metropolitan Region has, on average, a demand level higher than that of the availability of water resources.

With regard to efficiency in the management of water resources, and according to figures from the Superintendency for Sanitary Services (SISS, 2013), the domestic sector has a volume of non-revenue water, defined as the difference between that produced and that invoiced, of around 35% nationally and 30% for the Metropolitan Region. Given the low levels of non-revenue consumption, this indicator is fairly close to real wastage levels from the supply network itself. This is why actions designed to reduce this wastage, using good water management practices, would be of great help in reducing the shortfall between supply and demand. In any case, it is the agricultural sector that must lead such initiatives, given its high demand for water resources, in comparison with other uses.

- **Efficiency in the integrated management of water resources**
As mentioned in previous sections, the predicted climate scenario towards the end of the 21st century points to a complex balance between the supply of and demand for water resources. Given this, to achieve greater efficiency in their management, there is a vital need for the implementation of integrated water resource management mechanisms and policies, where different users can enjoy a common framework of understanding and coordination that allows them to carry out joint actions from a systemic viewpoint of water resources in the basin.

Although this is not, in practice, a measure that will allow for the direct mitigation of the effects of an adverse climate scenario, its development is essential for efficient implementation of other actions, as indicated by the world bank in its 'Diagnosis Report on the Management of Water Resources in Chile' (Informe de diagnóstico de la gestión de los recursos hídricos en Chile, World Bank, 2011), which also stresses the importance of institution-building in the field of resources management.

5.3.2 Alternatives for mitigating high turbidity phenomena

As mentioned in section 5.1, high turbidity phenomena are events of variable duration, but generally of less than 48 hours, which appear abruptly if they originate in convective storms (intense, localised and of short duration) in the high mountains during the summer, and their main impact is upon the treatment capacity of drinking water plants, which must be closed whilst the phenomenon lasts, making supply highly dependent upon stored reserves, the operational capacity for supplying groundwater reserves and the surface water sources unaffected by high turbidity rates.

In this regard, mitigation measures are aimed at both improving operational capacity and flexibility in the use of different sources and increasing reserve storage capacity.

- **Clean water interconnection and pipe laying works**
  Given the size of the Maipo river basin and its main tributaries, and also taking into account the existence of water reserves in the El Yeso reservoir and the Negra and Lo Encañado lakes, whose turbidity levels are less variable, there is a volume of water that may potentially remain unaffected by extreme turbidity events in the case of convective rainfall localised in certain areas of the mountains, and of which full use should be made.

  In this regard, infrastructure works aimed at connecting water reserves to the closest aqueducts in the mountains would allow these pipelines to be operated at full capacity to the drinking water treatment plants and guarantee a volume of water with turbidity levels within acceptable treatment limits, whilst at the same time reducing the amount of water transported by natural watercourses and thus susceptible to being affected by high turbidity.

  These measures should also include the use and boosting of the multiplicity of existing surface water abstraction points within an area large enough to mean that not all abstractions would be subject to extreme turbidity events. This last point is particularly true in turbidity events arising from convective rainfall.

- **Availability of raw water**
  One of the existing risk factors in the supply system is associated with the surface water treatment's dependence upon abstraction turbidity levels. This is particularly the case of the Las Vizcachas drinking water plant, which treats the largest percentage of surface water for the Greater Santiago area. Additionally, as noted previously, extreme turbidly events are generally short in duration, and storage of sufficient water reserves may well mean, together with other measures, that the temporary closures of abstractions in direct contact with watercourses with high turbidity levels could be dealt with successfully.

  Given the high volumes needed to guarantee supply for a 12-hour period, and the costs associated with having treated water available downstream of the plants or the construction of a high-capacity aqueduct from the plants to the higher reaches of the basin to abstract better-quality water, one more technically and economically viable alternative is to have available a volume of acceptable-quality water in the surroundings of the Las Vizcachas plant to be treated in the case of emergency and increase the security of supply.

- **Increased ability to regulate drinking water**
  Guaranteeing supply in a network as large as that of Aguas Andinas is dependent upon the regulation volumes at the head of each transport system into which the network is divided. Although this volume is defined in Chilean regulations, the regulation volumes so defined are in response to supply scenarios with stoppage events of short duration and the response capacity in the case of fires. So, to guarantee supply to specific sector, investments need to be made in regulation infrastructure to ensure a proper supply level to meet public demand during a certain period of time and to complement the raw water storage capacity.

- **Guaranteed operability of alternative supplies**
  Alternative sources are, in the main, groundwater abstractions distributed within Aguas Andinas' operating territory and represent a strategic infrastructure for dealing with turbidity events. This is why actions aimed at guaranteeing their operability during emergencies are key and must embrace aspects such as equipment maintenance, connectivity to the supply network, the activation protocol and energy supply, amongst others.

- **Monitoring of key parameters in the river basin**
  Key aspects to be considered as part of mitigation actions include monitoring river basin parameters of interest with regard to turbidity. The system is currently based on intermittent visual inspections and the taking of samples in the transport infrastructure from the Maipo River to the Las Vizcachas plant, and this, in the light of past events, is insufficient.

  A proper monitoring system could provide the ability to anticipate a convective phenomenon and provide early warning of the appearance of a turbidity event, giving operators valuable time in which to take appropriate measures (diverting water, increasing stored volumes, etc.). Similarly, it could permit the efficient anticipation and programming of the operation of plants once the intensity of the phenomenon had fallen off. However, there is a need for a specific study to establish the predictability of convective summer storms over the Andes mountains in the area studied.

6. CONCLUSIONS

Drinking water is being supplied to the Santiago Metropolitan Region within a complex and uncertain climate context, given the geographical area in which it is found. Future climate scenario forecasts, based on IPCC reports, point to adverse effects that would cause a reduction in surface water runoffs, particularly during the period from January to April, when there is the greatest demand for water for human consumption.

Historical statistics show that drought and high turbidity are cyclical phenomena and form part of the river basin's hydrometeorological condition. Nevertheless, in recent years, both phenomena have displayed exceptional behaviour, with longer-lasting shortfall conditions (drought) and an increase in the frequency of extreme events (turbidity). This affects normal drinking water supply conditions and calls for investment efforts and improvements in both public and private management.

Debris flow-type mass wasting events occur frequently in Central Chile's pre-mountain and mountain areas and have, over the course of time, had different kinds of impact upon the sector's infrastructure and, particularly, on the utility company Aguas Andinas' abstraction facilities. These events are, in the main, triggered by intense precipitation over a short period of time (associated with convective storms) in the higher reaches of the river basins, which saturates available materials, increases pore pressure and reduces shear resistance.

It is worthwhile establishing the areas susceptible to flow-type mass wasting as a first stage in what needs to be a risk assessment involving, on the one hand, assessment of the potential threat (danger) and, on the other, the downstream impact upon infrastructure and the general public (vulnerability). Calculation of susceptibility indicators is not in itself enough to establish a direct link with high turbidity levels, not only due to the need for data permitting reliable predictive models, or due to the constant updating of information on certain geomorphological features, but also because it requires a systemic focus.

No future predictions have been made of high turbidity levels in the river basin. Nevertheless, the events taking place in recent years and the high sensitivity indexes calculated in this study would seem to point to these events continuing to occur and precipitation being one of the trigger factors (and perhaps the most important one).

Studies of precipitation over the mountains of the Central Chilean Andes indicate that it is usually associated with convective activity. In this regard, one variable of particular interest in forecasting such precipitation is the zonal component of the wind (U, east-west), over the barrier of the subtropical Andes. Monitoring of this variable and its possible correlation with information on lightning available today could be of good use in making predictions. Nevertheless, a specific study is required to determine the predictability of convective summer storms over the Andes mountains in the area studied.

With regard to droughts, making forecasts within a context of climate change is a complex affair, in the sense that their number may double in the coming 30 years. What forecasts do seem to be predicting is a trend of gradually decreasing precipitation, with a knock-on effect in the hydrology of the basin's rivers and gorges.

Based the results of the meteorological and geological studies performed, both high turbidity events and drought, and lower water availability will have a direct impact upon the management of drinking water supplies and on the population of the Santiago Metropolitan Region. With particular regard to the impact on the management of domestic water supplies made by Aguas Andinas, the impact can be summarised as follows:

- Impact of reduced flow rates: acquisition of water usage rights, use of alternative water sources, economic impact (investments and greater operating costs), disputes over water use, possible rationing and the impact upon corporate image.

- Impact of high turbidity: water supply stoppages, economic impact (investment, repair and operating costs) and the impact upon corporate image.

6.1 Strategic Focus

The strategic focus permitting the tackling of the climate phenomena described in this document (drought and turbidity) is aimed at implementing a range of actions to mitigate, adapt to and manage risks to minimize the possible impact of climate change on the supply of water for human consumption in the Greater Santiago area. The following actions would form part of this focus:

- Increasing the use of alternative water resources, improving aquifer management, introducing practices such as the recharging of aquifers and taking advantage of the high cover provided by treated wastewater through its reuse.

- Ensuring the efficient use of water resources by implementing actions designed to reduce wastage, incorporating techniques and world standards for supply network wastage management.

- Achieving efficiency in the integrated management of water resources, developing coordination and understanding mechanisms amongst different users to permit the carrying out of joint actions from a systemic viewpoint of the river basin.

- Carrying out clean water interconnection and transportation works, aimed at guaranteeing the full-capacity operation of aqueducts feeding drinking water plants and boosting the multiplicity of abstraction points to ensure a volume of water in proper treatment conditions.

- Guaranteeing availability of acceptable-quality raw water with storage volumes that can ensure plant operability for a period of time that minimises the risk of water supply stoppages.

- Increasing the drinking water regulation capacity of supply systems to provide enough margin for carrying out the proper actions to guarantee continuity of supply.

- Guaranteeing the operability of alternative supplies, to provide immediately-available emergency water sources.

- Monitoring key river basin parameters to anticipate turbidity events and to programme the start-up of plants once the intensity of the phenomenon has fallen off.

On a complementary basis, and considering the need to generate more and better information to validate or correct the hypotheses and analyses contained in different studies, there is a necessity for continued progress in carrying out measurements and publishing studies. Similarly, the implementation of warning systems appears to be a requirement and, within this context, indirect systems such as lightning monitoring could potentially be of benefit, bearing in mind how complicated it is to measure direct climatological variables in high mountain areas.

Lastly, the suggested methodology of drawing up a map of the risks of mass wasting could be extended towards the headwaters of area 2 (the San Alfonso stream), prior to it being extended towards other areas of the river basin, which would complement the identification of areas susceptible to a greater incidence of high turbidity events.

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