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Contamination of surface waters by the former mining industry in the Milluni Valley (Cordillera Real, Bolivia) and the application of the water planning model WEAP

Thesis nominated to obtain the degree of
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Contamination of surface waters by the former mining industry in the Milluni Valley (Cordillera Real, Bolivia) and the application of the water planning model WEAP

Abstract

As an internship for the University College of Ghent, a study was done at the University Mayor de San Andres in La Paz, Bolivia. This study concerns the Milluni-valley in the Cordillera Real, about 20 kilometers North of the capital city La Paz. This area experiences a large contamination problem due to the waste water deriving from the Milluni-mine, which was active until 1990.

Melting water from glaciers in the mountain Huayna Potosi and water deriving from precipitation was captured and continuously used inside the mines to transport and to extract the minerals won by the miners. During the process, a lot of chemical reagents were used to improve the separation of the minerals. Finally, the waste water of the extracting process has been discharged again in the water basin of Milluni, containing remains of heavy metals and chemical reagents.

This discharged water mixes with the clear water deriving from Pata Khota, a basin where the precipitation water and the melting water from the glaciers is collected. The mixture, consisting of a large amount of contaminated water, flows by a canal to the water treatment plant Achachicala. High costs are done to neutralize the water and to convert it to drinking water.

A sampling took place to analyze anions, cations and heavy metals in 9 sampling points. The results of these analyses are discussed in this thesis.

This thesis also describes a software program called WEAP: **W**ater **E**valuation **A**nd **P**lanning system. The possibilities of the software are presented by applying the model WEAP to the area of Milluni. After defining the current situation, a reference scenario can be developed which can represent what will happen in the future if the current conditions (like population growth, precipitation level…) stays the same. Next, a scenario can be made based on the reference scenario, to observe what will happen if certain parameters change in the future. Concerning the Milluni-valley, scenarios where developed, researching what will happen in the future if the population growth rate increases and if the precipitation level alters.

Acknowledgements

To complete the "Professional Bachelor of Chemistry – Environmental Technology" at the University College of Ghent, Belgium, I accomplished an internship of eleven weeks at the University Mayor de San Andres of La Paz, Bolivia. I was accompanied by Andres Calizaya Terceros, professor at the University Mayor de San Andres. My Belgian promoter was Karla Berckmoes and my co-promoter was Christine Van der Heyden.

Before I start describing the situation, I would like to express my gratitude to people who helped me to complete this thesis.

First, I would like to thank my mother and her friend, for supporting me psychologically and financially at all times when I spent 4 months in La Paz, Bolivia. Also I would like to thank them for rereading this thesis for errors.

I thank Prof. Andres Calizaya Terceros for giving me this opportunity to work at the Milluni-project, for getting me into contact with a lot of interesting people to help me understand the WEAP-software and to support me during my stay in La Paz.

Also I would like to thank my good friend Eva Horemans for correcting errors in this thesis.

I would like to thank the University College of Ghent to give me the opportunity of doing my internship abroad and to enlarge my knowledge about environmental problems in the world. I also thank my promoter and co-promoter to help me find an internship and to support me during the my time in La Paz.

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1 Contents

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Introduction

To complete the 'professional bachelor of chemistry – environmental studies' at the University College of Ghent, I accomplished an internship of eleven weeks at the University Mayor de San Andres of La Paz, Bolivia. During the internship I examined a certain water basin which was contaminated by heavy metals due to waste water of the mine Milluni. I took samples at 9 effluents of the lakes located in the Milluni-valley. Except for the In-Situ-measurements, all analyses were done at the laboratory of the "Instituto de Investigaciones Quimica" of the University Mayor de San Andres (IIQ-UMSA) in La Paz.

In this thesis, I have described the current situation and I have tried to give a view of the conditions the inhabitants suffer from. Afterwards I have made a map with a Water, Evaluation And Planning model (WEAP). With this map, I try to indicate the problem and to estimate what can happen if the current situation stays the same. Hopefully, this map can be used to present the problem to certain organizations, f.e. the Inter-American Development Bank, to ask for support to eliminate the contamination in the Milluni-valley.

This thesis is divided into four chapters. The first chapter contains the description of the WEAP, which is used to develop scenarios about the study area. In the second chapter, a full description of all aspects of the area is displayed. The third chapter is dedicated to present the current water quality of the basin. In this chapter I discuss the results of the analyses. Finally, scenarios concerning the Milluni-basin are calculated in the fourth chapter. These scenarios give an estimation of what will happen in the future when certain conditions change (f.e. precipitation, population…).

While writing this thesis I experienced some difficulties finding the right information. Most information about the Milluni-valley is only known from theses. However not every thesis contains the same information and some theses were old and don't correspond with the results I have witnessed during the sampling.

1 Theoretical description of WEAP

1.1 Introduction

For a well integrated management of water resources, the development of a system for water planning is required.

WEAP is a software program, developed by the Stockholm Environment Institute, which makes an integral approach of the planning of water resources. The abbreviation WEAP stands for "Water Evaluation And Planning". The institute gives free licenses for the software to non-governmental organizations, government agencies, and academic institutions in developing countries. About 50 projects around the world are using the software for mapping water systems. The university Mayor de San Andres from La Paz in Bolivia meets the requirements to obtain a free license. (Universidad Ángela Salinas Villafañe, 2009)

Many regions all over the world experience challenges to preserve a well-working freshwater management. These challenges can occur as limited water resources, environmental quality goals and policies for sustainable water use. Global warming is thought to be an important underlying cause of many of those issues. As a forecasting tool, the software simulates water demand, supply, flows, storage, pollution, treatment and discharge. For political analysis, WEAP can take multiple and competing uses of water systems into account. The main purpose of the software is to give a realistic view of the distribution of the available water resources. (Stockholm Environment Institute, 2012)

To represent this image, the software is required to take different hydrological systems like superficial, subterranean, saturated zones and non-saturated zones into account.

WEAP is a mathematical model of which the representation is based on mathematical symbols, containing variables, parameters and relations like equations or inequalities. Its aim is to incorporate water demand and water supply into a practical tool for water resources planning. As a demand side water use patterns, re-use, prices, hydropower energy demand… can be observed. Supply sides can describe the stream flow, groundwater, reservoirs and water transfers. WEAP places those two sides on an equal footing in the equation. (Universidad Ángela Salinas Villafañe, 2009)

A model of a certain area is no more than just a formal representation of the reality that is tried to be described, analyzed and understood. The model is used to study, plan, design or verify a prototype by using certain data that predict what will happen at another place or time. In most cases, a WEAP-model can reduce costs, risks and time.

The software is applied to the Milluni-area to verify the compatibility of the software, the projects and the plans in the area for the development of the water sources. The application can verify if a realistic image of the distribution of the available water resources in the Milluni-area can be represented and if future scenarios can be predicted concerning the quality and quantity of water.

1.2 Description

The use of WEAP includes usually several steps (Universidad Ángela Salinas Villafañe, 2009):

- Determination of the study: this includes defining the time frame, special limits and the structure of the problem.

- Current Accounts: the Current Accounts represent the basic definition of the water system as it currently exists and forms the foundation of all scenarios analysis. It represents the actual water demand, load of pollutants and the sources and resources for the system. This can be perceived as the calibration step in the development of the application.
- Scenarios: Scenarios are story-lines of how a system might evolve in time in particular conditions. These conditions can be set by changing the socio-economic setting or the policy or technology conditions. The scenarios represent an image of the system of what will happen in the future with the water demand and the water supply after changing conditions like costs, future politics, climate… These alternative scenarios can be compared to each other. The comparison can be a very useful guideline to develop policies for water systems from local to regional scales.
- Evaluation: The scenarios will be evaluated taking certain aspects into account like the availability of water, the costs and the profit, the environmental aspect and the sensitivity to uncertainty in the key variables.

The scenarios can cause a range of "what if" questions. For instance: What will happen if population growth and economic development patterns change? What if reservoir operating rules are changed? What if the permissible limits for surface water are tightened? What if new sources of water pollution are added? What if a more efficient irrigation technique is added? What if the precipitation level increases or the temperature rises due to global warming? These scenarios can be viewed simultaneously in the results to compare their effects on the water system or to present a realistic image of what may happen in the future.

The software works according to priorities. Therefore three forms of water consumption can be distinguished (Universidad Ángela Salinas Villafañe, 2009):

I. Consumed water: the water disappears. For example irrigation. An important part of the irrigated water disappears due to evapotranspiration from the vegetation. Another large part of the water is getting stored in the vegetation. Only a small part returns in his original shape. This discharged water is usually highly contaminated by nutrients and agro toxics. Also human consumption is an example. The efficiency is about 80%.
II. The use of water without change of the available amount. For example in an hydroelectric power. The water can be diverted in a section of the river and be returned in the same conditions several kilometers downstream.
III. The use of water without the change of quantity but with change of quality. For example: refrigerant cooling water or diluents.

In general WEAP uses the following scale of priorities (Stockholm Environment Institute, 2012):

1. Human consumption: f.e. drinking water
2. Irrigation
3. Hydroelectric power
4. Industrial and mining use
5. Dilution for pollutants

2 Description of the study area Milluni

2.1 Physical description of the study area

2.1.1 Geographical situation

Bolivia is a country located in the middle of South America, divided into 9 departments including the department of La Paz. In the department of La Paz, the city La Paz and the city El Alto are situated next to each other. La Paz is located on the slopes of the Andes, while El Alto is located at the flat area on top of the Altiplano Highlands. La Paz is considered to be the administrative capital city and also the largest city of Bolivia. With the altitude of 3650 meters, La Paz also contains the title of highest located capital city all over the world. (Encyclopedia Bolivia, 2012)

El Alto is considered to be the suburb of La Paz. Today, it is one of Bolivia's largest and fastest-growing urban centers. With a population of 649 958 in 2001, the city's population increased to nearly 900 000 in 2010, and this increase is not downsizing yet as the average age is only about 20 years old. Part of the increase of population derives from migration of people from the countryside, who claim that farming becomes too hard due to the effects of global warming. (Instituto Nacional de Estadística, 2012)

The Cordillera Real is a mountain range in the Andes in the South American Altiplano of Bolivia with a lot of lakes at a high altitude. Most lakes are located in four glacial valleys in the provinces Omasuyos, los Andes and Murillo, in the department of La Paz. The names of the valleys arrive from the names of the biggest lake present in the area: Hichu Khota, Ovejuyo, Tunicondoriri and Milluni. (Chavez Apaza, 1991)

The Milluni-area is situated at an altitude of 4600 meters above sea level in the North of the province of Murillo, canton Achocalla, about 20 kilometers North of the capital city La Paz. It has the typical geomorphologic U-shape, characteristic of glacier regression, and exists of several small lakes and their effluents elongated over 30 km. The area is situated on the Southern latitude 16°08 – 16°10 and the Western longitude 68°17 – 68°21. The surface of the biggest lake, Milluni Grande, is 237 hectares and the profundity is about 4 meters. (Rios, 1985)

Figure 1: Google maps print screen: The contamination of the Milluni-lake (Google Maps, 2012, https://maps.google.be/)

According to the contamination, four different types of lakes can be observed which all four are connected (Rios, 1985):

- Pata Khota at 4670 meters (not contaminated)
- Jankho Khota at 4575 meters (slightly contaminated)
- Milluni Chico at 4540 meters (heavily contaminated)
- Milluni Grande at 4530 meters above sea level (heavily contaminated)

The principal head flow of the Milluni-basin consists of water coming from the glaciers of Huayna Potosí (6088 m), one of the most important mountains of the Cordillera Real, and the affluent of the lake that is located more above.

The highest located lake is Pata Khota. This lake has a chemical composition that characterizes a natural lake on a high altitude in the mountains. The water of the Pata Khota-lake flows to the Jankho Khota-lake. This lake experiences an acidification in the North-Southern direction due to ancient water discharges of the mine-activity of the company COMSUR at the Southern side of the lake. Until 1990 COMSUR used water from the Milluni-flow to cool down machinery and to transport and segregate ores to the outside (Rios, 1985). The remainder of the waste water was discharged back into the Milluni-flow. Nowadays the waste water of the mines is getting discharged by a canal that flows into a separate lake; Milluni Chico. This lake exists of highly concentrated contaminated water coming straight from the mines. A dam was built, but due to large leaks, the heavily contaminated water deriving from the mines flows straight into the water basin Milluni Grande. Over here the water mixes with the pure and clean water that comes via a by-pass canal from the glaciers. The mixed water still has a high conductivity, is extremely acid, has a high concentration on metallic ions and contains a large presence of heavy metals. Because of the contamination, Milluni Chico and consequently also Milluni Grande are colored red.

Figure 2: Milluni Chico

Figure 3: Leak of the dam at Milluni Chico – Llamas walking through and drinking the water

2.1.2 Geology

Northerly of the area the mountain Huayna Potosi is situated. The peaks consist of a rocky structure and reach an altitude of 6000 meters and more. In the South the depression of the Altiplano is filled with sediments. The Milluni-area is located between those two regions. The area is dominated by wide U-shaped valleys with a glacial character and with relatively small slopes (Salvarredy-Aranguren, 2008).

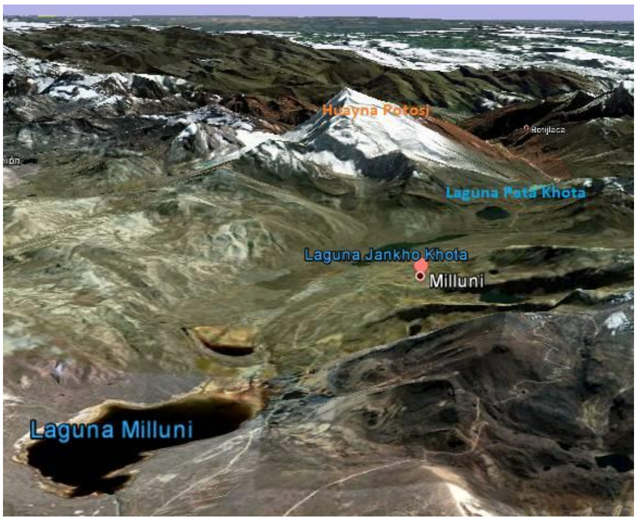

Figure 4: Google maps 3D print screen (Google maps 3D, 2012, https://maps.google.be/)

The Milluni Valley is part of the Bolivian Tin Belt. Because of this natural resource Bolivia became the biggest tin-producer in the world for almost all of the 20st century. The Milluni Mine, also known as "La Mina Fabulosa", operated between 1940 and 1990 by the company COMSUR. The most important extracted minerals where Sn and Zn. Since the beginning of the mining activities, a variety of potentially harmful elements (PHEs) have been drained into the Milluni reservoir. A large volume of sulphate-rich mine waste has been deposited in the area of Milluni until the nineties. (Rios, 1985)

This reservoir used to be one of the principal reservoirs of drinking water for the population of the city La Paz. Between 1940 and 1987 the reservoir provided water for the central and the north part of the city (Rios, 1985). The contamination with PHEs consists of a high content of Fe, Mn, Zn, As, Cd, Cu and Sn in the reservoir.

In the North, a granitic terrain partially covered by glaciers can be observed. Going further down to the South, the Milluni Valley consists of fine-grained sandstone. The main ore minerals in the region are pyrite, marcasite, sphalerite, arsenopyrite and cassiterite (Salvarredy-Aranguren, 2008).

However the mining happened underground, a large amount of mining waste was discharged in the Milluni Chico-lake.

2.1.3 Climatology

The Andes Mountains are a strong climatic barrier. The Northern-orientated slope is moister than the Southern-orientated one because it receives the moisture winds from the Amazonian basin. On the Northern side the clouds experience the phenomena of "the Rising Clouds" or "Relief Rainfall". When the wind blows the clouds up against the high mountains of the Cordillera Real, they cool down and can cause a heavy snow or rainfall. Another possibility is the rise of humid air at areas with high temperatures. Again heavy clouds can be formed which can cause snow or rainfall. This can be observed like the clouds are climbing over the mountains.

Figure 5: The rising clouds

The study Area Milluni experiences a tropical climate of high mountains which most part of the year are covered with snow or ice. The hydrological and climatic characteristics of the Milluni basin can be considered as similar to those of the nearby Zongo valley. At this area, the annual average precipitation level amounts to 800 mm and the annual average temperature amounts to 5,4°C at 4310 meters above sea level (Rios, 1985).

2.1.4 Hydrology

The hydrological characteristics of the Milluni basin *(Appendices I)* can be considered to be similar to those of the nearby Zongo valley: a dry season and a wet season. The dry season occurs from April to September, while the wet season covers October to March. (Calizaya, 2010)

There is an increase of precipitation during the wet season with a maximum in March. This causes an increase in head flow during the wet season.

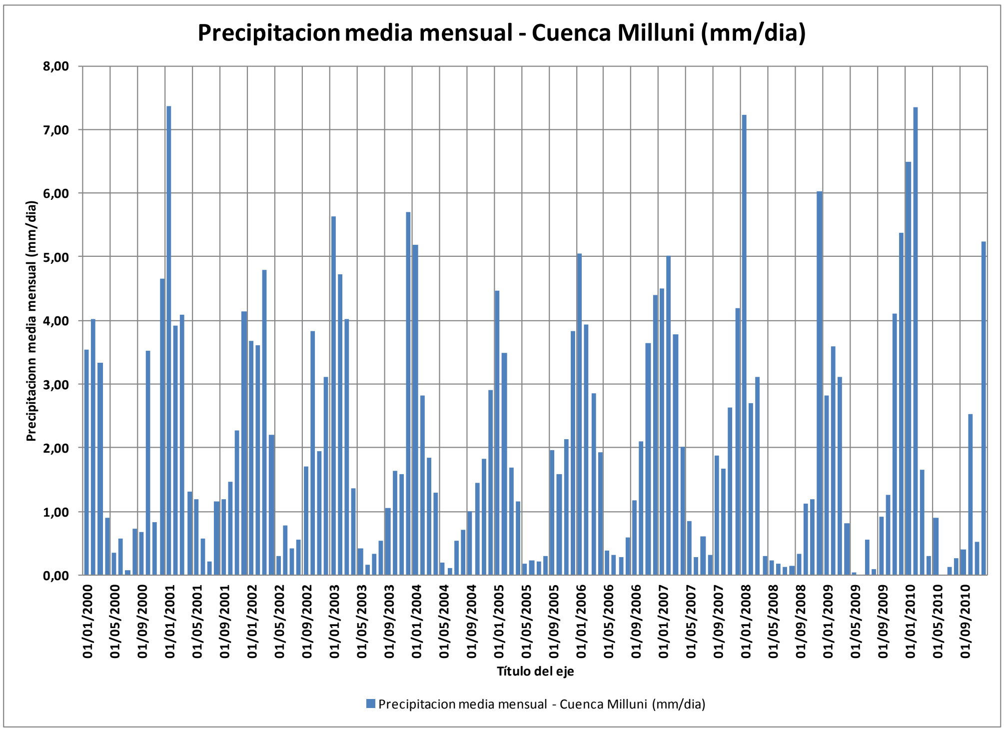

Figure 6: Monthly Average Precipitation Milluni basin (mm/day) (Calizaya, A., 2010, Hidrologia)

The Milluni reservoir has an average orientation of 192°, which indicates that the reservoir is predominantly facing south *(Appendices II).*

To calculate the travel time the water needs to drain through the dam, the slope of the basin first needs to be estimated *(Appendices III & IV).* This was estimated by use of the computer software ArcGIS. The software calculated an average slope of 27% in the reservoir.

The difference between wet and dry season can clearly be observed in the flow chart below.

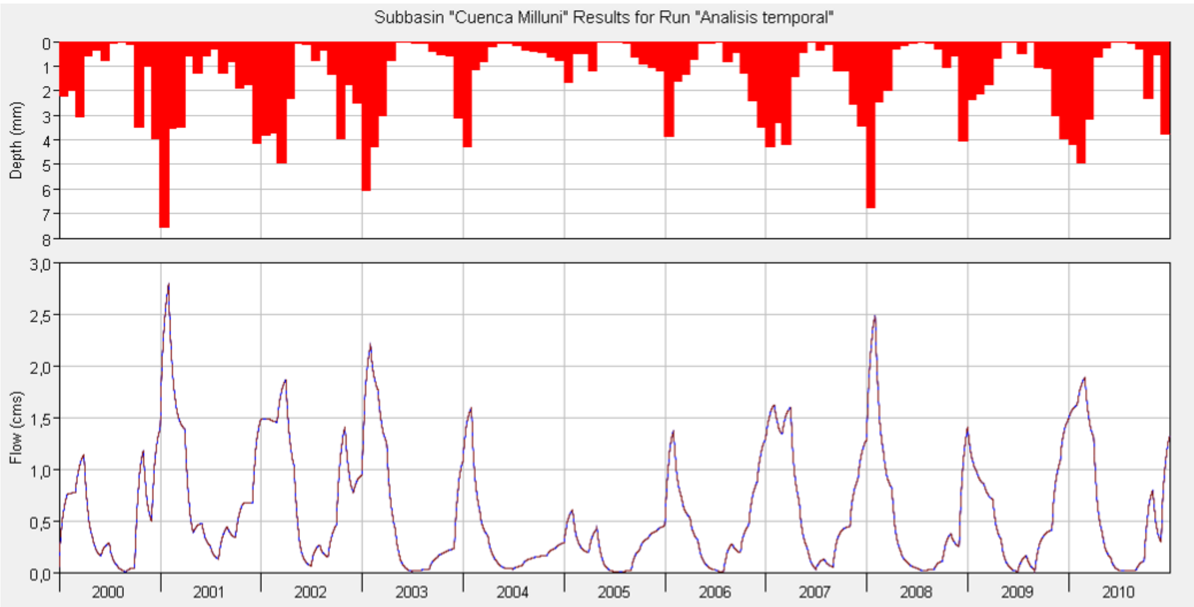

Figure 7: Flow (m³/s) and Depth (mm) chart of the Milluni basin (Calizaya, A., 2010, Hidrologia)

In 1989, a bypass canal was built to drain the waters of Jankho Khota down to the North of the Milluni-lake to improve the physical conditions of the lakes. This goal was not succeeded, because of presence of sediments that were still contaminated. Later on, the canal was extended to the South of the Milluni-lake, trying to avoid the contamination of the clear waters by the sediments in the Milluni-lake. However, the mixture of both waters still ended up highly contamined. (Chavez Apaza, 1991)

2.2 Socio-economical description

2.2.1 Population

The cities La Paz and El Alto are provided with drinking water by four water supply plants: El Alto, Pampahasi, Tilata and Achachicala. These supply plants don't have the capacity to deliver sufficient safe water to the entire population of the cities (ANESAPA, 2011). Specifically in El Alto and in the North-Eastern hillsides of La Paz, the water supply often reaches a shortage (ANESAPA, 2011). The municipal government and the water companies are struggling to provide enough drinking water. If the water problems remain unsolved, about 20% of the total population of La Paz city will see their access to safe water drop and poverty levels will further increase. To top this, the increased melting of the glaciers during the last decades presents a fundamental problem for the water supply in the future (Condóm & Escobar, 2011).

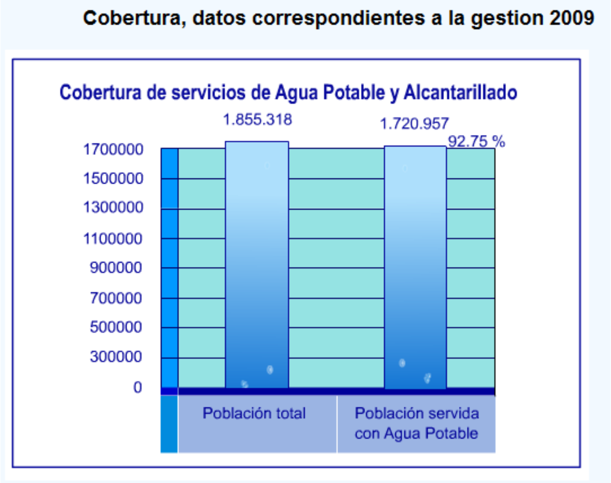

Figure 8: Coverage of demand – only 92,75 % of the population has availability to drinking water (ANESAPA, 2011, www.anesapa.org)

The most important water supply arrives from the treatment plant Achachicala. In 1970, the treatment plant already was extended from a production capacity of 400 l/s to 1000 l/s due to the increasing demand. (Erhard, 2012)

Since the nineties the municipal water and sewerage company of La Paz, SAMAPA, adds large quantities of calcium and sulphate to the water that enters the treatment plant of Achachicala to eliminate the high proportions of iron, manganese and zinc. These high doses have a significant impact on the treatment costs for the purification of the contaminated water.

If this problem can be solved, a lot of money will become available to invest in other improvements to increase the supply of safe water for the population of La Paz and El Alto.

Milluni used to be a thriving mining town with a population of 4000 people, until the mineral prices decreased in the eighties. The 4600 meters high located city became a ghost town, leaving nothing behind except for dilapidated buildings and heavily contaminated lakes. (Rios, 1985)

Figure 9: Minerals inside the mines of Potosi

Nowadays the Milluni mines are closed. But the problem continues to exist in other parts of South American countries. Even in Bolivia, where the government already witnesses the result of the water contamination by mining, there is still a very active mine contaminating the water supplies: El Cerro Rico. El Cerro Rico in Potosi gives the perfect example for the conditions in the mines, similar to what used to happen in the Milluni Mines.

Since the discovery of silver in 1546 in the mountain Cerro Rico, the city Potosi was settled at the more than 4000 meters high Altiplano. This height, and the cold arising from it, made the city unbearable to live in. However, the city grew and even reached a population of 200 000 in 1672, making it one of the largest and wealthiest cities all over the world. Today, there are still over 150 000 inhabitants in Potosi. Those people prefer a short life of exhausting work above the life of poverty. One once said: "With all the silver from the Cerro Rico, one can build a bridge from Potosí to Madrid. But one can build that same bridge, and a second one next to it, with the bones of all the people who died in the mines." (Rough Guide, 2010)

For the inhabitants, the money they earn by working in the mines is far more important than the damage that the working conditions do to their health or nature. It's not hard to imagine that the environmental aspect is not even considered. Even today, the chemicals and the mineral residues are still abundant present in the waste water. This waste water is being deposited somewhere where no tourist can see it and it keeps on contaminating the area, the wildlife and consequently also the people.

Figure 10: Mine workers inside the mines of Potosi

2.2.2 Economy

The Bolivian economy depends on the mining industry. Nowadays the production of minerals is decreased, but Bolivia still remains the biggest world producer of tin and still plays an important role in the production of other minerals like lead, copper, silver and others. Because of tin being the country's most important source of wealth, the mining industry was favored with very gentle laws for the exploitation of minerals (Rios, 1985). Consequently a lot of damage was done caused by the discharge of the mining waste water, which contained deposits in an inadequate form, straight into the surface water.

The area of the lakes Milluni Grande and Milluni Chico looks like they have been totally covered with a red-colored soil, consisting of a high concentration of iron. This is the result of a 40-year during accumulation of sediments discharged by the Milluni-mines.

Figure 11: Milluni Chico

The lakes in the area of Milluni are water reservoirs created for the storage of surface water that is meant to be used as drinking water supply for La Paz. Because of the large amount of water and the high acidity, the costs for treatment to become drinking water are very high.

The treatment plant of Achachicala is located in the upper part of the La Paz valley. The water is treated in the following manner: *(Appendices V)* (EPSAS, 2012)

1. Pre-sedimentation followed by decantation
2. Addition of chlorine to prevent the growth of algae
3. Addition of lime and aluminum sulphate for neutralization and flocculation
4. Sedimentation and removal of flocks
5. Filtering through sand beds
6. Disinfection by chlorine

The water deriving from Milluni, needs to be neutralized in order to achieve a pH above 7 and to precipitate metal ions. To achieve this, about 10 tons of lime per day is being consumed at a cost of 32,6 € per ton, equals to 119 000 € per year. (Chavez Apaza, 1991)

In Bolivia, the minimum price for one cubic meter is 0,2985 € (ANESAPA, 2012). In the Belgian water company Pidpa, the water price is 0,003 € per cubic liter (PIDPA, 2012). Belgium has a minimal salary of 1472 € (Armoedebestrijding, 2012). In Bolivia the minimal salary is only 107 € (EABolivia, 2010). If you look at the proportion between the minimal salary and the price for clear water, problems can be predicted for the people in Bolivia who earn the minimal salary.

Up until the nineties, the water passed a small hydro-electric plant before entering the water treatment plant Achachicala. This hydro-electric plant provided a power of 3-4 MW for the city of La Paz. Results showed that the acid composition of the raw water was causing problems in the turbines of the plant. Nowadays, the hydro-electric plant is out of use. (SAMAPA, 2012)

Figure 12: Water treatment plant Achachicala (2012, http://www.talis-group.com)

2.3 The contamination problem in the Milluni Valley

2.3.1 Water use for the treatment of minerals

One of the biggest causes of contamination of the water in the Milluni-valley is one of the procedures of the mining company COMSUR. It was a common practice to capture water deriving from precipitation and from the melting glaciers around this valley. Later on, this water was used in the concentration process of tin in the processing plant. This however lead to various environmental problems. (Chavez Apaza, 1991)

First, the minerals were reduced into little pieces of rocks. These parts were subjected to a breaking process by special rotating machines. Afterwards they were further reduced by a mill. Next the vibration table of concentrations separated for example cassiterite (SnO_2), based on specific gravity. For this separation, a large amount of water was used. (Chavez Apaza, 1991)

The second step in the process is based on the use of reagents. In the process, mainly 3 reagents were used (Chavez Apaza, 1991):

- Zantato (Na- or K- hydrocarbons) - 0,16 Kg/ton minerals bruto
- Dofroth 250 – 0,15 Kg/ton minerals gross: to enforce a foam based on alcohol
- Copper sulfate ($CuSO_4$)

Figure 13: Adding of chemical reagents to extract the minerals from the Potosi-mines

These reagents change the physical condition of the minerals. The minerals were coated mono-, bi- or polyvalent and separated by laws of gravity. In their turn, the reagents cause an extreme and inevitable contamination of the water. (Chavez Apaza, 1991)

The minerals can form sulfur compounds during extraction. These compounds on their turn can form sulfuric acid with water by the process of oxidation.

2.3.2 Types of contamination

The pollution by mining waste has a direct impact on the water quality of the lakes Jankho Khota and Milluni Chico. The impact can be seen first in the alteration of the aquatic ecosystems. Three different sources of contamination can be distinguished. Continuously, the impact can be witnessed in the lake of Milluni Grande. (Chavez Apaza, 1991)

2.3.2.1 Contamination by mineral extraction

COMSUR captured water derived from precipitation or from the melting of glaciers. This water was used to separate the minerals by specific gravity on the vibration table of concentration. Here the water gets largely contaminated with the minerals. Further during the process a solution of water and reagents is used to coat the minerals and separate them again on the basis of gravity. Afterwards this water was discharged into the Milluni Valley again by a bypass canal, without making any changes in the concentration of contaminants. (Chavez Apaza, 1991)

Most ores exploited in the Cordillera and the Altiplano regions of Bolivia contain sulfidic minerals, which oxidize and produce acidic waters with high heavy metal contents. This is the most serious pollution problem in the Bolivian mining industry. Research during the last few years regarding chemical and biological effects of mining in the area showed that the contamination has not only totally destroyed the natural ecosystem of the Milluni-lake, but also affected parts of the Jankho Khota lake. A large contrast can be observed with the abundant aquatic fauna and flora of the not contaminated Pata Khota-lake. (Chavez Apaza, 1991)

Figure 14: Canal Mina: the canal deriving from the Milluni-mine

2.3.2.2 Natural contamination

The geographical characteristics indicate a yellow colored soil (ferrous sulphate). This natural contamination is carried down in small amounts by rivers during the rainy season. This contamination can only be observed in a limited degree and will not cause problems if it occurs without the contamination of the mine. (Chavez Apaza, 1991)

2.3.2.3 Contamination by solid waste

Around the Jankho Khota-lake you can find a lot of old and decayed products that were used during the exploitation of the mines. For example: old machinery and a lot of light meters. These devices also have a small contribution to the contamination of the water of the Milluni Valley because they also contribute harmful toxic elements to the aquatic life.

Figure 15: Contamination by solid waste in the Milluni-valley

3 Physicochemical study of the Milluni Valley

3.1 Selection of the sampling points

The selection of sampling points is done based on results of earlier analyses. In total, 9 samples were analyzed. These sampling points are stretched out over the inflows and outflows of the most important lakes in the valley of Milluni.

During the sampling, geographical coordinates of the sample point were taken by GPS. These coordinates were integrated in the map with the software ArcGIS. The map of the Milluni-area is made based on the geographical coordinate system WGS1984 so that every length, curve and point is exactly into proportion with the reality.

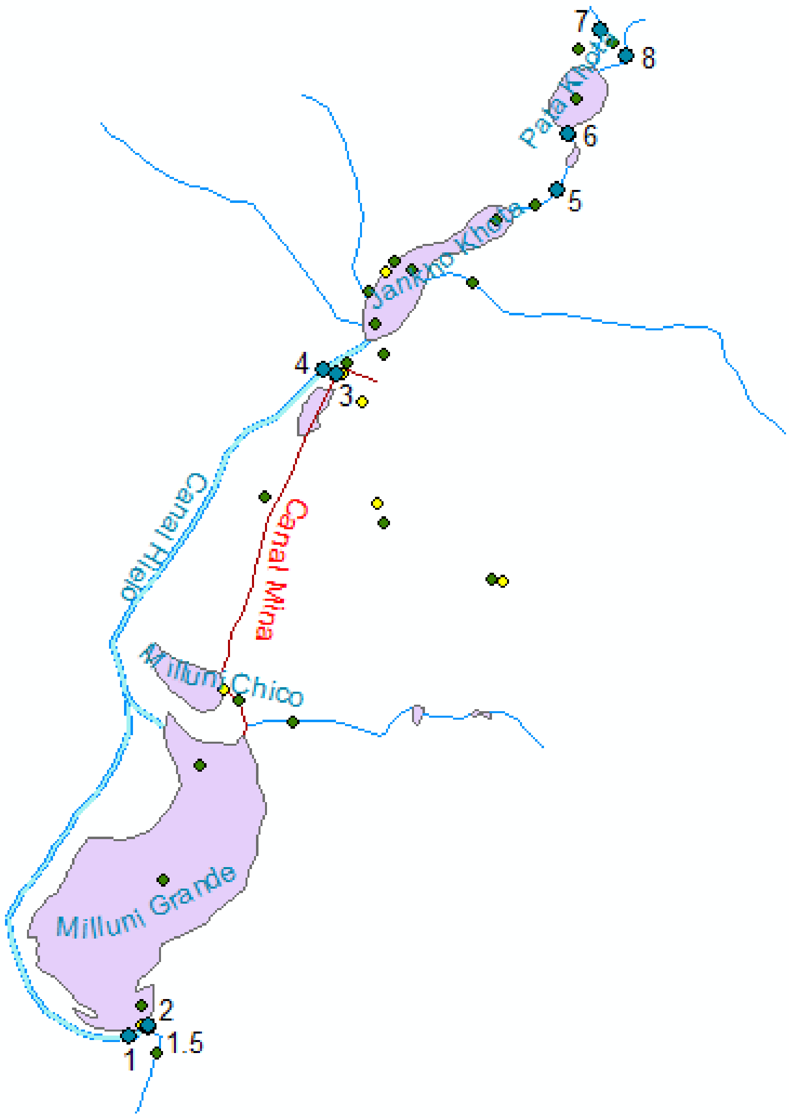

Figure 16: ArcGIS-map of the Milluni-valley
The blue dots are sample points of 2012.

Tabel 1: Sampling points in the Milluni-valley

Number of sample	Name of sample	Description
1	Hielo	Water ; not contaminated
1.5	Mezcla 1 x 2 Salida	Mixture of 1 and Outflow of the Milluni lake
2	Milluni Salida	Outflow of the Milluni lake
3	**Mina**	**Deriving from La Mina Fabulosa**
4	JK Out	Jankho Khota outflow
5	JK In	Jankho Khota inflow
6	Pk Out	Pata Khota Outflow
7	Pk In West	Pata Khota Inflow West
8	Pk in East	Pata Khota Inflow East

The 9 samples were taken in the end of March 2012. This month is still part of the rain season. The sampling took more or less 4 hours due to the large distance between every sampling point and the walking up and down the slopes. Another difficulty for foreign researchers is the height of 4600 meters above sea level. When not used to these heights, breathing is difficult and intensive activities are discouraged. An air temperature of 5,8 °C, the cold winds and the low water temperatures also complicated the sampling.

3.2 Physicochemical analyses

All analyses were done at the laboratory of the "Instituto de Investigaciones Quimica" of the University Mayor de San Andres (IIQ-UMSA) in La Paz, Bolivia. Except for the in situ measurements, the surface waters were all filtered over "Cellulose Nitrate Filters with a pore size of 0,45 µm".

One half of each sample was conserved in their original condition to analyze the anions. The other half was acidified with HNO_3 65% for cation and heavy metal analysis.

3.2.1 In Situ

The measuring of the water temperature, the conductivity, the oxygen content, the acidity, the concentration of salts, the total dissolved solids-content and the oxidation reduction potential all happened in situ. Therefore the Portable Multiparameter for Water Quality HI 9828 of Hanna Instruments was used.

Figure 17: Portable Multiparameter for Water Quality HI 9828 – Hanna Instruments

Tabel 2: In situ Measurements

Number of sample	Time	pH	T (°C)	C (µS/cm)	TDS (ppm)	DO%	DO (mg/l)	ORP (mV)	Sal %
1	16:14	8,66	8,65	76	38	22,6	1,7	218,9	0,04
1.5	16:39	**3,43**	8,63	426	213	21,5	1,47	535,6	0,21
2	16:29	**2,87**	8,56	950	475	18,7	1,28	536,6	0,47
3	14:10	**3,17**	8,84	2349	1175	4	0,27	397,4	1,22
4	14:00	8	8,48	64	32	16,3	1,12	83,5	0,03
5	12:50	8,05	7,79	32	16	14,1	0,98	50,4	0,01
6	12:34	7,89	8,81	34	17	18,7	1,3	91,1	0,01
7	12:05	7,65	11,91	28	14	16,7	1,08	74,5	0,01
8	12:20	7,92	4,85	64	32	19,2	1,39	84,5	0,03

3.2.2 Anions

The anions were analyzed by spectrofotometry, volumetry or argentometry.

Tabel 3: Anions results

Number of sample	Name of sample	CO_3^{2-} (ppm)	HCO_3^- (ppm)	NO_3^- (ppm)	SO_4^{2-} (ppm)	Cl^- (ppm)
1	Hielo	31,2	0	3,1	28	0,392
1.5	Mezcla 1 x 2 Salida	0	0	18,8	250	< 0,32
2	Milluni Salida	0	0	92,5	500	0,4752
3	Mina	0	0	217,5	**2150**	0,5968
4	JK Out	31,2	0	4,6	25	7,445
5	JK In	26,4	0	3,2	8	7,268
6	Pk Out	0	39,04	3,5	8	6,647
7	Pk In West	0	34,16	4,2	5	7,268
8	Pk in East	0	39,04	3,6	21	5,85

3.2.2.1 CO_3^{2-} and HCO_3^-

Carbonate and bicarbonate are both salts of carbonic acid. The carbonate and bicarbonate content were analyzed by volumetry with 0,012 N standardized HCl and an indicator that is a mixture of methyl orange and indigo carmine which has a color change from yellow to orange.

Carbonate only occurs in waters with a pH between 8 and 10.

$$2\ H^+ + CO_3^{2-} \rightarrow H_2CO_3$$

Bicarbonate only occurs in waters with a pH between 6 and 8.

$$H^+ + HCO_3^- \rightarrow H_2CO_3$$

Samples 1,5; 2 and 3 have an very acidic pH through which can be presumed that there is no carbonate or bicarbonate present in these samples.

Tabel 4: Carbonate and bicarbonate results

Number of sample	Name of sample	pH	CO_3^{2-} (ppm)	HCO_3^- (ppm)
1	Hielo	8,66	31,2	0
1.5	Mezcla 1 x 2 Salida	**3,43**	0	0
2	Milluni Salida	**2,87**	0	0
3	Mina	**3,17**	0	0
4	JK Out	8	31,2	0
5	JK In	8,05	26,4	0
6	Pk Out	7,89	0	39,04
7	Pk In West	7,65	0	34,16
8	Pk in East	7,92	0	39,04

3.2.2.2 NO_3^-

The nitrate content was analyzed by spectrofotometry "Cadmium Reduction Method" of HACH programs. Cadmium metal reduces nitrates in the sample to nitrite. The nitrite ion reacts in an acidic medium with sulfanilic acid to form diazonium salt. The salt forms with gentisic acid an amber colored solution. Test results are measured at 500 nm. The detection area is located between 0,3 and 30,0 mg/L NO_3^--N. For sample 1.5 and sample 2, a dilution had to be made.

3.2.2.3 SO_4^{2-}

The sulphate content was analyzed by spectrofotometry "Sulfaver 4 Method" of HACH programs. Sulfate ions in the sample react with barium in the SulfaVer 4 and form barium sulfate. The turbidity formed is proportional to the sulfate concentration. Test results are measured at 450 nm. The detection area is located between 2 and 70 mg SO_4^{2-}/L. For sample 1.5, sample 2 and sample 3, a dilution had to be made.

3.2.2.4 Cl^-

The chloride content was analyzed by argentometry. The Mohr's method uses 5 % K_2CrO_4 as an indicator in the titration of chloride ions with a silver nitrate standard solution. The color changed from yellow to red.

The color change though was not very visible for the samples with the highest concentration. These samples were analyzed again with spectrofotometry in the present of ammonium iron (II) sulfate, mercury (II) thiocyanate and nitric acid 10 %.

3.2.3 Cations

The cations where analyzed by atomic absorption spectrofotometry (AAnalyst 200, Perkin-Elmer).

Tabel 5: Cations results

Number of sample	Name of sample	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)
1	Hielo	2,15	0,58	11,74	2,03
1.5	Mezcla 1 x 2 Salida	3,55	0,62	14,26	6,1
2	Milluni Salida	1,775	0,685	16,45	11,75
3	Mina	2,175	0,714	59,1	61
4	JK Out	2,025	0,487	11,56	1,08
5	JK In	0,76	0,276	7,26	0,29
6	Pk Out	0,88	0,272	6,44	0,25
7	Pk In West	0,45	0,173	6,03	0,21
8	Pk in East	0,94	0,272	12,63	0,44

3.2.3.1 Na and K

Sodium en potassium are analyzed in the presence of lithium by AAS.

The coefficients of determination and the slopes concerning the calibration curves are:

Na:

- R^2 = 0,973948
- Slope = 0,38589

K:

- R^2 = 0,978255
- Slope = 0,28448

3.2.3.2 Ca and Mg

Calcium and magnesium are analyzed in the presence of strontium by AAS.

The coefficients of determination and the slopes concerning the calibration curves are:

Ca:

- R^2 = 0,997144
- Slope = 0,0,08469

Mg:

- R^2 = 0,9949
- Slope = 0,0435

3.2.4 Heavy Metals

The heavy metals where analyzed by atomic absorption spectrofotometry (AAnalyst 200, Perkin-Elmer).

Tabel 6: Heavy metals results

Number of sample	Name of sample	Cu (ppm)	Fe (ppm)	Pb (ppm)	Zn (ppm)	Mn (ppm)	Cd (ppm)	As (ppm)
1	Hielo	< 0,10	0,035	< 0,80	0,015	< 0,07	< 0,03	**3,762**
1.5	Mezcla 1 x 2 Salida	0,122	**11,1**	< 0,80	9,275	1,5	< 0,03	**3,851**
2	Milluni Salida	0,341	**58,95**	< 0,80	**22,575**	**4,5**	**0,034**	**4,045**
3	Mina	**2,75**	**446,4**	< 0,80	**182,2**	**30,05**	**0,698**	**4,619**
4	JK Out	< 0,10	< 0,10	< 0,80	0,047	< 0,07	< 0,03	**3,563**
5	JK In	< 0,10	< 0,10	< 0,80	< 0,02	< 0,07	< 0,03	< 0,007
6	Pk Out	< 0,10	< 0,10	< 0,80	< 0,02	< 0,07	< 0,03	< 0,007
7	Pk In West	< 0,10	0,179	< 0,80	< 0,02	< 0,07	< 0,03	< 0,007
8	Pk in East	< 0,10	< 0,10	< 0,80	< 0,02	< 0,07	< 0,03	< 0,007

The coefficients of determination and the slopes concerning the calibration curves are:

Tabel 7: Heavy metals R^2, slope and min. detection limit

	R^2	Slope	Min. Detection limit (in ppm)
Cu	0,99972	0,06926	0,100
Fe	0,99966	0,04221	0,100
Pb	0,99759	0,00815	0,800
Zn	0,99898	0,29261	0,020
Mn	0,99999	0,09677	0,070
Cd	0,99992	0,18052	0,030
As	0,97230	0,00580	0,007

3.3 Discussion of the water quality

When the concentration of certain elements is too high, they can induce physical, chemical and eventually ecological transformations, which can damage the aquatic ecosystems.

Rivers are less sensitive to the contamination because of their relatively high self-cleaning capacity. On the contrary, lakes assimilate the pollution.

3.3.1 Comparison of the permissible limits of Bolivia and Belgium

When Belgian and Bolivian permissible limits are compared *(appendices VI),* one can witness that the Bolivian permissible limits are less strict than the Belgian ones. In contrary with the Belgian law, the Bolivian law was once set in 1992 and has never become stricter (Ley del Medio Ambiente – Class B, 1992). In the previous tables, all values displayed in bold, are values that exceed the Bolivian permissible limits. Especially the canal arriving from the mine and the final mixture are more contaminated than allowed by Bolivian law.

3.3.2 Physical characteristics of the water

Temperature is an important ecological factor in most aquatic environments because it coordinates the physiological and biological activity and the behavior of the water organisms. During the sampling at the end of March 2012, the water temperature in the Milluni-valley takes an average of 8,54 °C and is lower during dry season and higher during wet season. The temperatures measured in the study area are typical temperatures for regions located high in the Andes, with periodical changes during dry and wet season (Chavez Apaza, 1991).

The clear water lakes have a low conductivity. In contrary, the water waste from the mine has a high conductivity of 2349 µS/cm during the sampling. The conductivity is related to the removal of minerals and it varies during dry and wet season because of the dilution that takes place during the wet season.

The pH is important because it indicates the acidity or the alkalinity of the water. The average values of the study area present different levels of acidity, varying between 2,87 and 3,43 for the contaminated effluents and between 7,65 and 8,66 for the natural effluents. The waters deriving from the mine are extremely acid. In the water treatment plant this is neutralized by adding lime to the water.

3.3.3 Chemical characteristics of the water

Many studies show a large and dangerous presence of high concentrations of metallic ions like iron, manganese and zinc, similar to this study of the Milluni-valley. Also because of the absence of bicarbonate and the extreme acidity, researchers have indicated that the damage done by the mining company COMSUR is irreversible (Chavez Apaza, 1991).

The amount of iron and other heavy metals founded in the Pata Khota-lake was very low. This is explained by the low natural contamination. The water deriving from the mine contains a large contamination by iron and by other metals. These values exceed the permissible limits of Bolivia. The iron causes the red color in the canal deriving from the mines, Milluni Chico-lake, Milluni Grande, and the canal from Milluni to the water treatment plant Achachicala. The present Cadmium concentrations are in general very low. However, Cadmium is highly toxic even at low concentrations so the waters deriving from the mine still exceed the permissible limits. Copper only exceeds the permissible limits in the canal deriving directly from the mine and in Milluni Chico. After the mixture with the clear water canal, the water is diluted and the copper-content decreases per cubic meter. Arsenic is a by-product of mining activities. It is present in extremely high concentrations in the waters deriving from the Milluni-mine. Also the Zinc- and Manganese-concentration is very high and exceed the permissible limits.

Calcium and magnesium are at all sampling points under the permissible limits of Bolivia. The concentration of chlorides is very low and has no importance for the discussion of the water quality.

In general, all the water deriving from the melting of glaciers and precipitation belongs to the bicarbonate type with a low concentration of iron and magnesium and salt. The water deriving from the mine and the mixture of clear water with the mine waste water belongs to a different type: the ferric sulphate. This type experiences the absence of bicarbonates due to the extreme acidity of these waters. The water contains a lot of sulphate (Chavez Apaza, 1991).

The lakes in the Milluni-valley experience a different type according to their contamination level. The Pata Khota-lake is from the carbonate type as well as other lakes situated in other glacial valleys in the Cordillera Real. Water from the mining sector is characterized by a low pH and alkalinity and an increase in $SO4^{2-}$ concentrations. Where the contaminated waste water from the mine mixes with the clear water deriving from Pata Khota, an increase of the concentration of sulphate and a decrease of the concentration of bicarbonate occur. (Chavez Apaza, 1991).

In the wet season, the concentration of ions is lower because of dilution with precipitation and snowmelt. The chemical characteristics of the lakes are tightly related to the rainfall patterns and the contribution of pollutants from the mine.

4 Application of the WEAP model in the study area

4.1 Discussion of the map

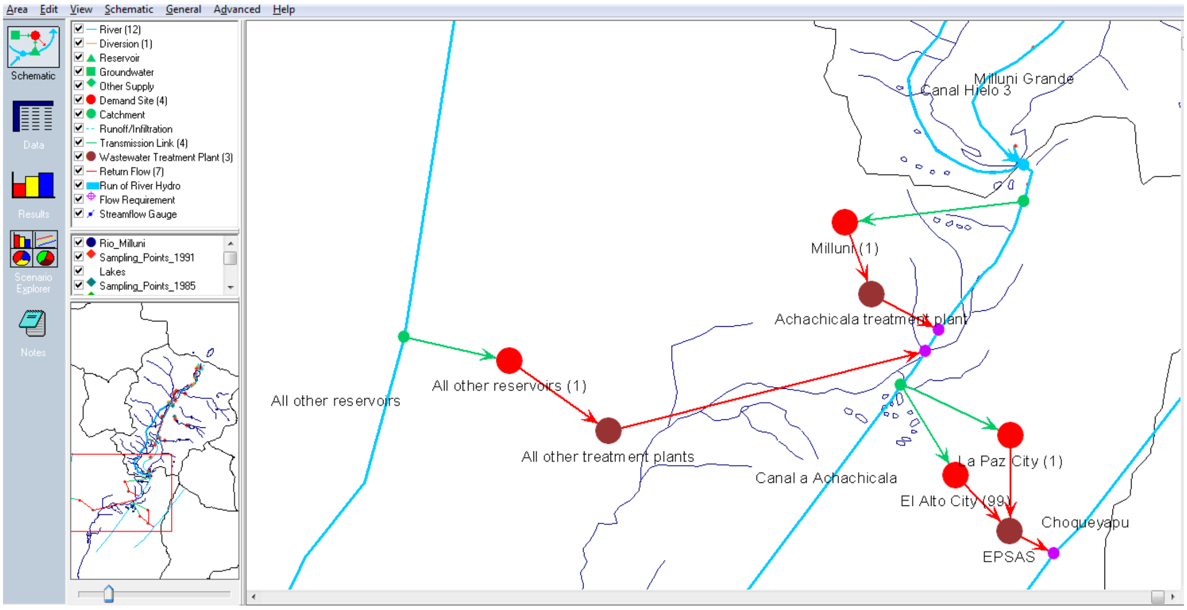

Figure 18: WEAP-model: Map water resources

(Appendices VII: enlarged map of the total Milluni-valley)

On the right top of the map the catchment "Milluni Valley" can be found with the largest lake Milluni Grande that mixes up at the end with the bypass canal Hielo 3. The first green arrow is a transmission link that takes 100% volume of the supply to the village of Milluni. Because there are no inhabitants left since the mining activity stopped, the population of the village was set to zero. The water continues flowing to the water treatment plant Achachicala. This treatment plant changes the water quality of the mining waste water to potable water.

On the left of the map the supply "All other reservoirs" can be observed. This is the water deriving from other water catchment areas in the Cordillera Real, which takes part in the supply for the cities La Paz and El Alto. The green arrow is the transmission link that brings the water from the catchments to the red dot: all other reservoirs (1). This dot represents the people who take use of the water before the water enters the treatment plant. This information is unknown, so the population of this demand site is also set to zero. Next, a red arrow, the return flow, takes the water to a treatment plant and thereafter the water merges with the cleared water deriving from the treatment plant Achachicala.

Further downstream a beginning of two green arrows can be observed. These transmission links take the water to the demand sites of La Paz and El Alto. La Paz, as the wealthiest part of the Metropolis, takes the priority to make their demand covered. Remaining supply is taken to El Alto. Finally, two return flows take the waste water to the treatment plant of EPSAS in La Paz.

4.2 Current Accounts

In WEAP the typical scenario modeling effort consists of three steps. First, there is the "Current Accounts" year. This year is chosen to serve as the base year of the model. Concerning the Milluni Valley, the base year was set on 2010 because it is the last year from which recent data is published by the INE[1].

Tabel 8: Import necessary data to simulate scenarios (INE, 2010)

	2010
Population Growth Factor	1,48
Life Expectancy	66
Children per woman	3,2
Population Bolivia	10 227 300
Population La Paz	835 361
Population El Alto	953 253

First, the data concerning population of the two big cities must be entered under Current Accounts in the "data-view" for the base year. Under the Water-Use tab, 4 sub taps can be found. Annual Activity Level can represent the population. Important is not to forget to set the unit to 'people'. For both demand sites, the population can be entered under the base year 2010. Also the "Priority" tab can be found under the demand sites.

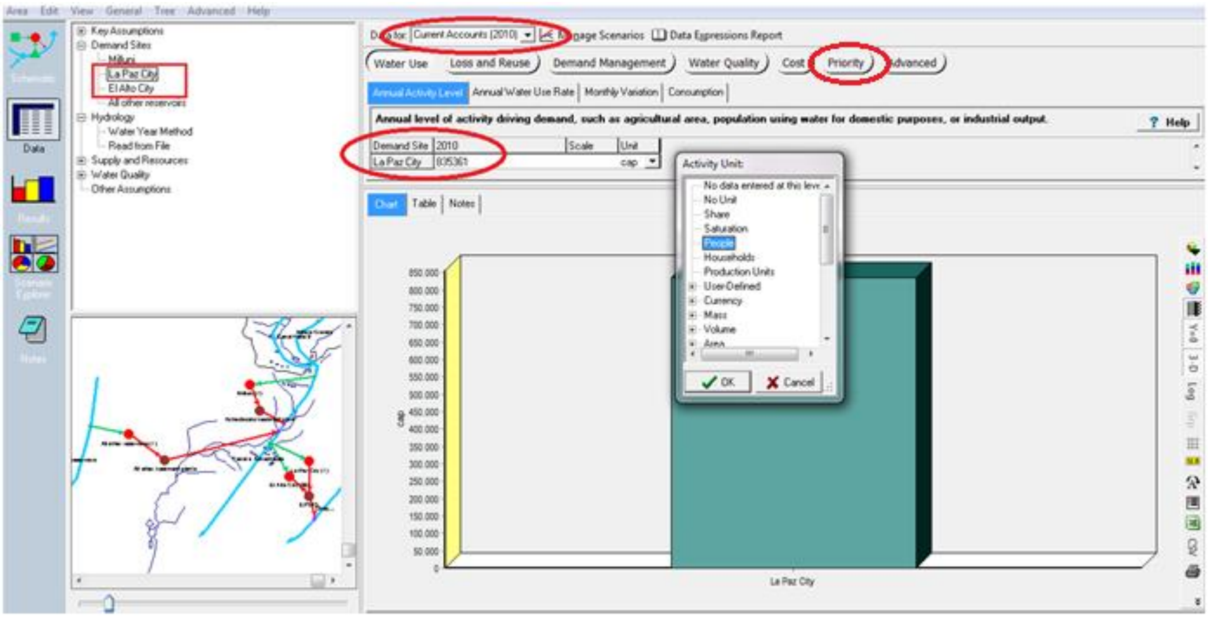

Figure 19: WEAP-model – data view – Current Accounts – annual activity level

Next, the second tap: the Annual Water Use Rate, must be set. This is the amount of water each person living in the cities uses. UNESCO[2] estimated that the average person in developed countries uses 300 m^3 per year. The average person in developing countries is estimated at 20 m^3 per year.

[1] INE: Instituto Nacional de Estadística de Bolivia (National Insitute of Statistics of Bolivia)
[2] UNESCO: United Nations Educational, Scientific and Cultural Organization

Last decades the water supply didn't cover all the demand in La Paz and El Alto. To represent this in the WEAP-model, the water use rate can be estimated by showing the results and adjusting the water use rate until a realistic representation of the coverage problem is displayed. This was obtained at a water use rate of 40 m³/person and 20 m³/person, respectively for La Paz and El Alto (Komives & Cowen, 1998). These data look realistic, compared to the situation in both cities, whereas La Paz has more wealth then the unbearable conditions in El Alto. In El Alto, where the inhabitants are mainly poor, 50 % of the water they receive is being consumed. In La Paz, only 30% of the received water is used for pure consumption, whereas the remaining water is used for the cleaning of houses, cars, watering plants…

Results of the data in the Current Accounts show the following water demand for the two cities:

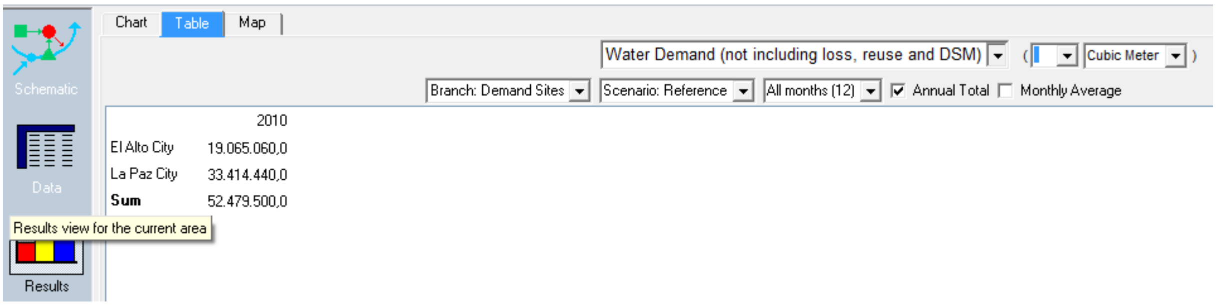

Figure 20: Results – Water demand La Paz and El Alto

Next, the head flow should be determined. Concerning the model about the Milluni Valley, two water supply resources can be distinguished:

- The inflow of the Pata Khota-lake: Pata Khota East and Pata Khota West
- All supply from other reservoirs for the cities

Tabel 9: Head flow Pata Khota

2010	Head flow Pata Khota (in m³/s)
January	1,5
February	1,6
March	1,9
April	1,4
May	0,4
June	0,1
July	0
August	0
September	0,1
October	0,8
November	0,4
December	1,4
Average	**0,8**

Starting from the head flow information of Milluni (Calizaya, 2012) which has an average of 0,8 m³/s, the total supply deriving from Milluni can be calculated*. (Appendices VIII)*

0,8 m³/s = 25 228 800 m³/year

Knowing that Milluni represents 18,72 % of the total supply for La Paz and El Alto, the total supply amounts to 134 783 630,76 m³/year (2010, www.epsas.com.bo).

This makes the supply coming from other sources than Milluni:

134 783 630,76 m³/year – 25 228 800 m³/year = 109 540 430,77 m³/year = **3,47 m³/s**

These data must be entered under 'Supply and Resources' – 'River' – Pata Khota inflow/all other reservoirs – 'Headflow' – '2010'.

Monthly supply observations were taken in the Milluni Valley. These data can set a more realistic image then the annual average. To enter the monthly variation, a specialized wizard can be used: Monthly Time Series Wizard.

The wizard gives the ability to enter monthly data. Consequently, the supply of the Milluni Valley alters every month and wet or dry seasons can be taken into account.

Concerning the supply of the other reservoirs, monthly variation is unknown, so the calculated value 3,47 m^3/s is entered as an annual average under "Supply and Resources – River – All other reservoirs". To indicate the unit m^3/s, the software uses the unit CMS, which stands for Cubic Meter per Second.

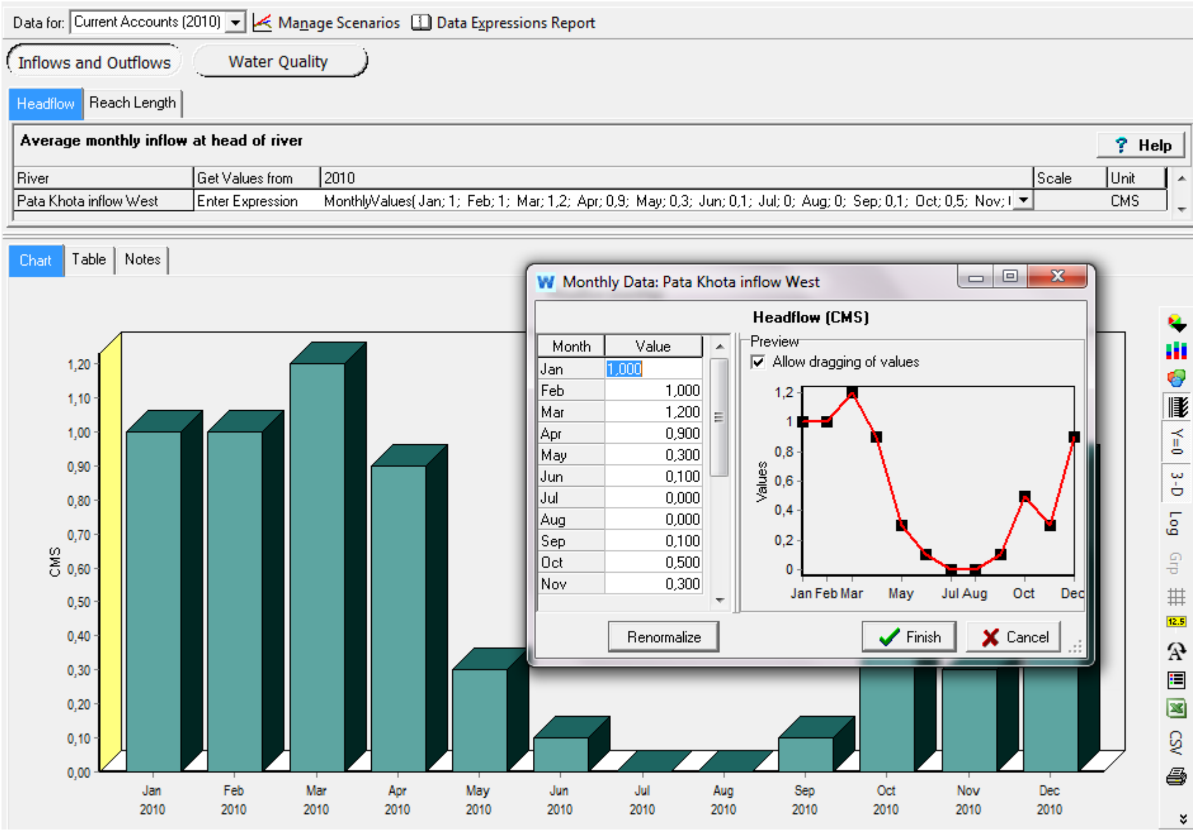

Figure 21: WEAP-model – Current Accounts – All other reservoirs – Headflow – Monthly data

At the moment the supply and the demand information are set. This is the first step to create a water planning model.

4.3 Reference Scenario

A Reference scenario is established from the Current Accounts to simulate likely evolution of the system without intervention.

In Current Accounts, the base year was set to 2010. Now the time zone for the scenarios must be set. Concerning the Milluni Valley was decided to work in a time zone of 20 years in the future. All the scenarios will be simulated from 2011 until 2030 to look at the estimates for the near future.

4.3.1 Population Growth

In the reference scenario, the population growth continues at the 2000-2010 rate: 1,48. The population growth rate is set as a key assumption, this is a variable where can be referenced to elsewhere in the model.

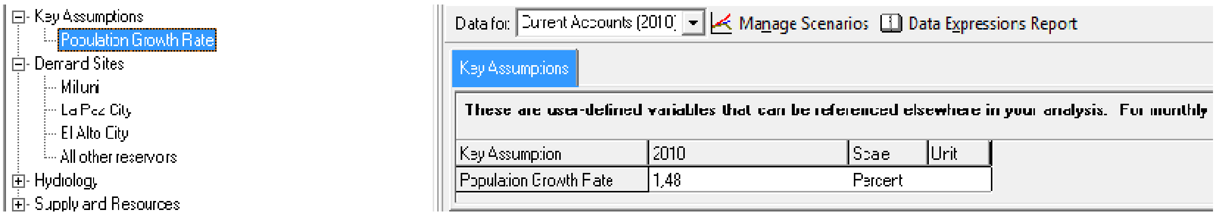

Figure 22: Key assumption – Population Growth Rate

Next the population of the cities in the reference scenario (2011-2030) must be set with the Expression Builder. This is a Wizard where you can form certain formulas. In case of the growth rate, the formula has to be:

Growth(Key\Population Growth Rate[%]/100)

This makes the population grow every year by the assumption key 'Population Growth Rate'.

By running the result, a chart is given where the growth of the cities can be observed.

The demand grows as the population increases over the years. However the supply stays the same. Consequently, over the years the supply always covers less of the demand.

Next the results are run for Water Demand and for Unmet Demand:

- Water Demand: The demand for water of all the inhabitants in the city, taken the annual water use rate and the consumption rate into account.
- Unmet Demand: The demand that is not fulfilled after the distribution of the water.

Running the result for Water Demand:

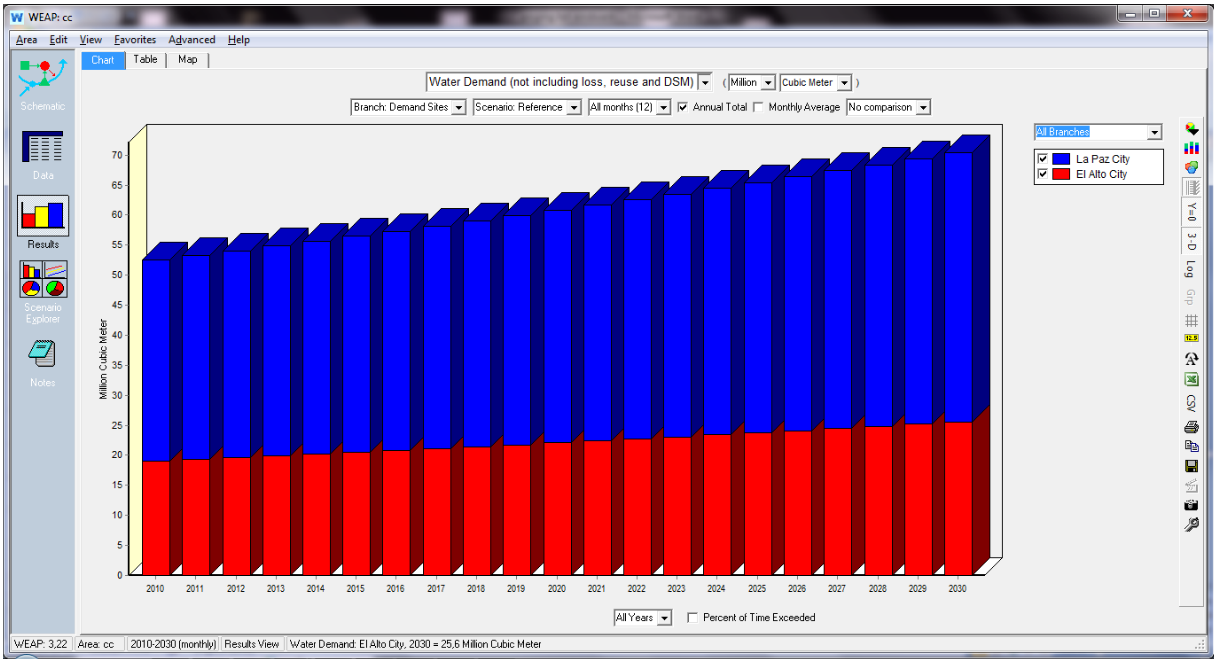

Figure 23: Population Growth: Result – Water Demand

Running the result for Unmet Demand:

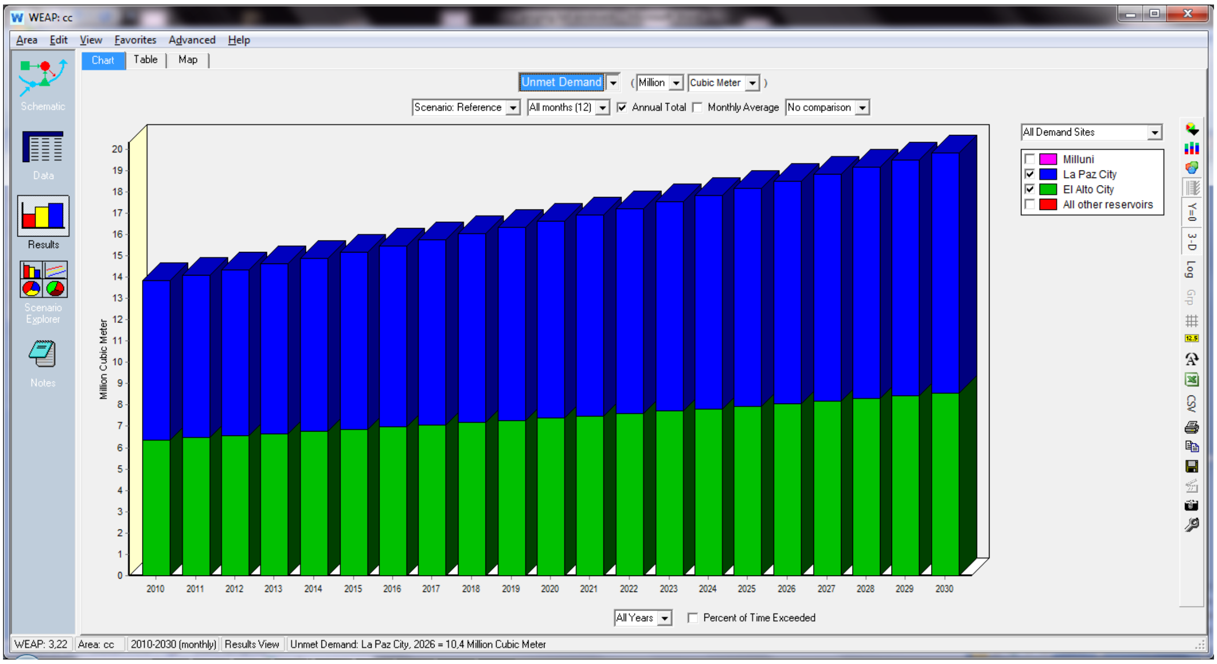

Figure 24: Population Growth: Result – Unmet Demand

4.3.2 Water Year Method

Population Growth only shows a variation in demand, not in supply. Water Year Method is a way to represent a variation of the supply. For example: natural variation in climate data (stream flow, rainfall etc.).

The method first involves defining how different climate regimes (e.g., very dry, dry, very wet) compare relative to a normal year, which is given a value of 1. Dry years have a value less than 1, very wet years have a value larger than 1.

First, the definitions of the wet and dry years have to be set in de reference scenarios under Hydrology – Water Year Method.

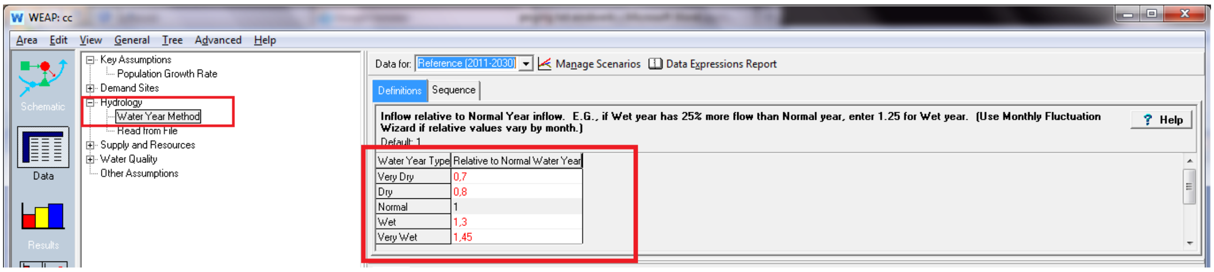

Figure 25: WEAP-model – Data – Hydrology - Water Year Method

Next, the sequence has to be defined.

In the Reference Scenario, the following is assumed:

Year	Water Year Type
2010	Normal
2011	Dry
2012	Wet
2013	Normal
2014	Normal
2015	Normal
2016	Dry
2017	Normal
2018	Normal
2019	Wet
2020	Wet
2021	Dry
2022	Normal
2023	Normal
2024	Normal
2025	Dry
2026	Normal
2027	Wet
2028	Normal
2029	Wet
2030	Dry

Figure 26: Water Year Type in the Reference Scenario

The head flow of the Milluni Valley has to be changed from Expression Builder to Water Year Method to take the variation of the years into account.

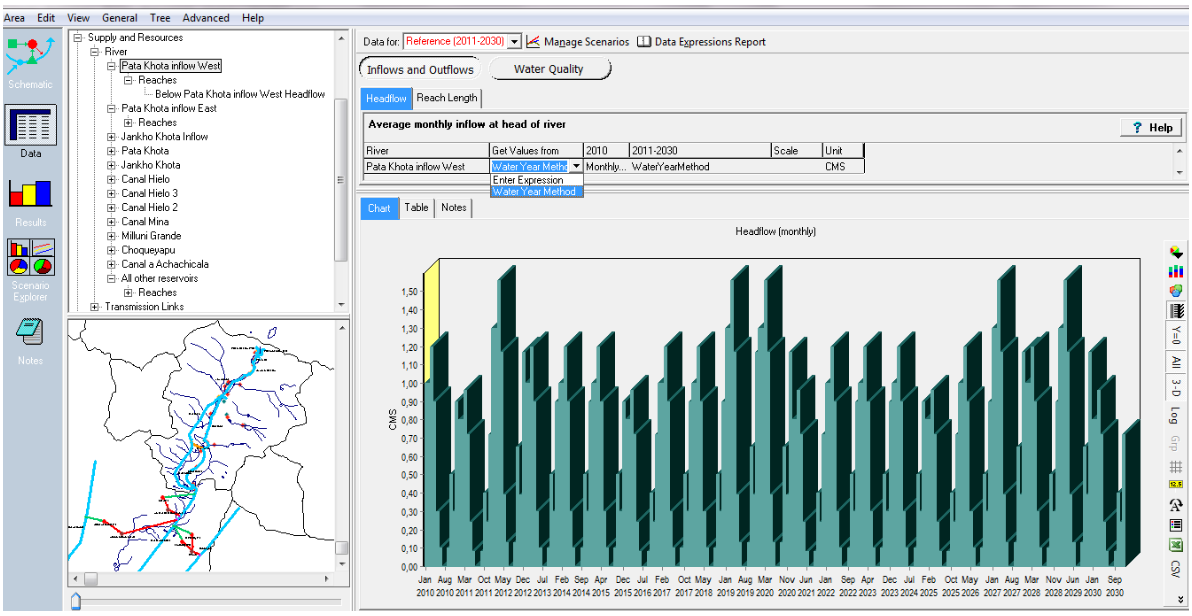

Figure 27: WEAP-model: Data - Water Year Method

4.4 What-if Scenarios

What-if scenarios can be created to alter the reference scenario and evaluate the effects of changes in policies and/or technologies.

In the "Manage Scenarios"-window all scenarios can be observed and new one's can be added.

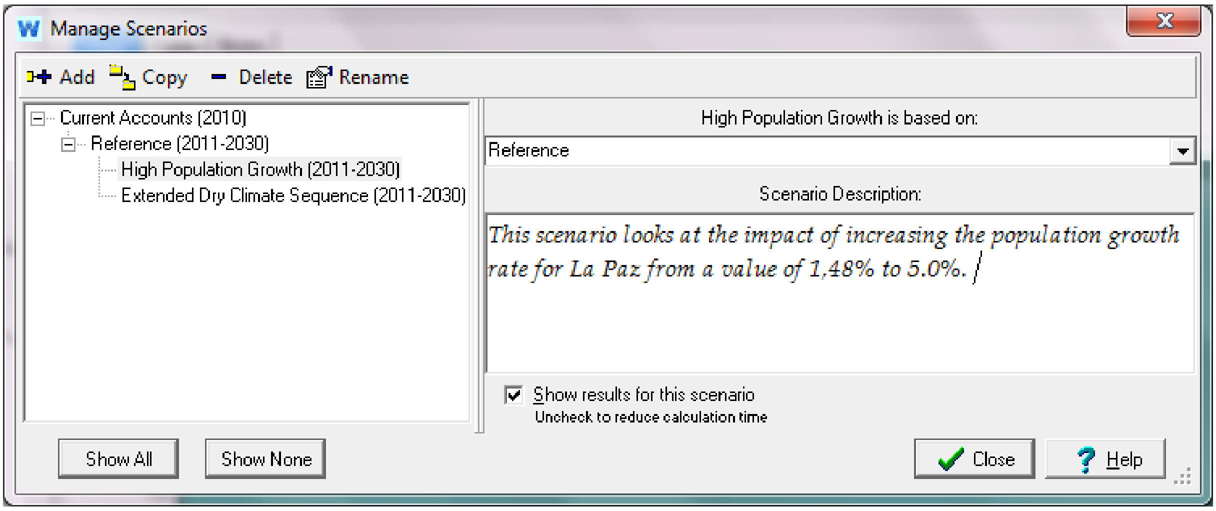

Figure 28: Manage Scenarios-window

4.4.1 Scenario: High Population Growth

This scenario is created to evaluate the impact of a population growth rate for La Paz and El Alto higher than 1,48% for the period 2011-2030.

First the new scenario is added in the "Manage Scenarios"-window. It is based on the Reference Scenario, so the changes can be compared to time zone with a normal growth rate of 1,48.

Working in the High Population Growth Scenario, the rate is changed to 5,0 %

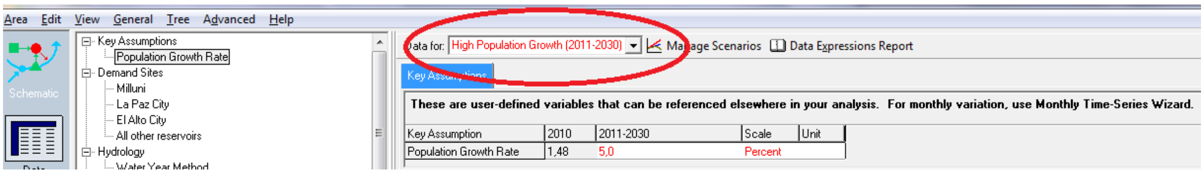

Figure 29: High Population Growth Scenario: 5,0%

Changes made compared to the Reference Scenario, will automatically be displayed in red.

When the population grows very fast, the demand increases even faster. Over the years the supply always covers less of the demand.

Running the result for Water Demand:

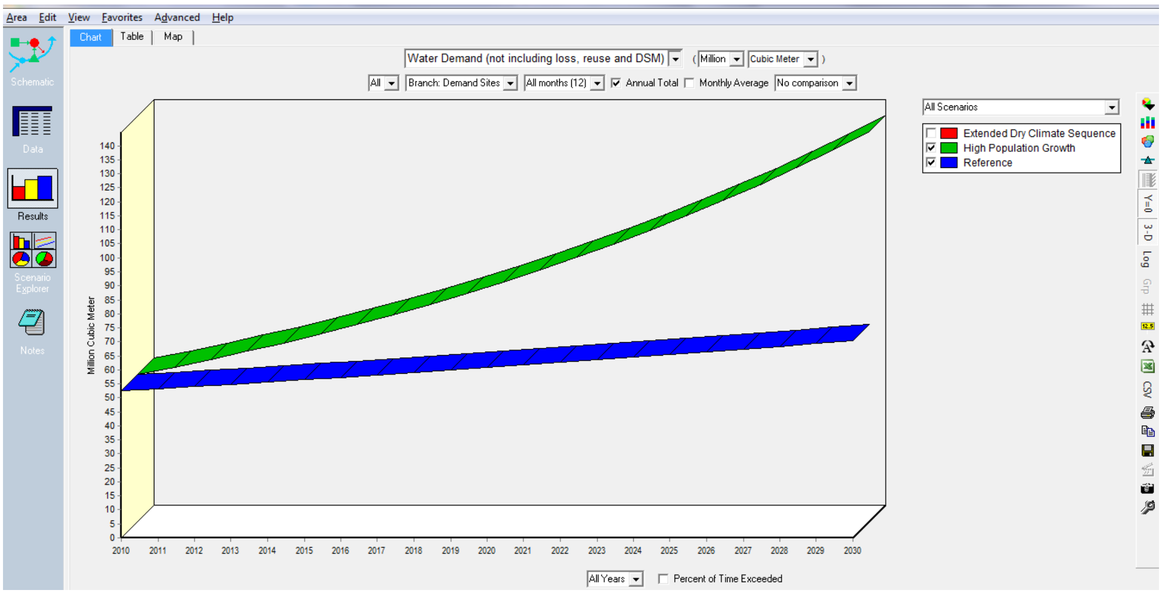

Figure 30: High Population Growth Scenario: Water Demand

Running the result for Unmet Demand:

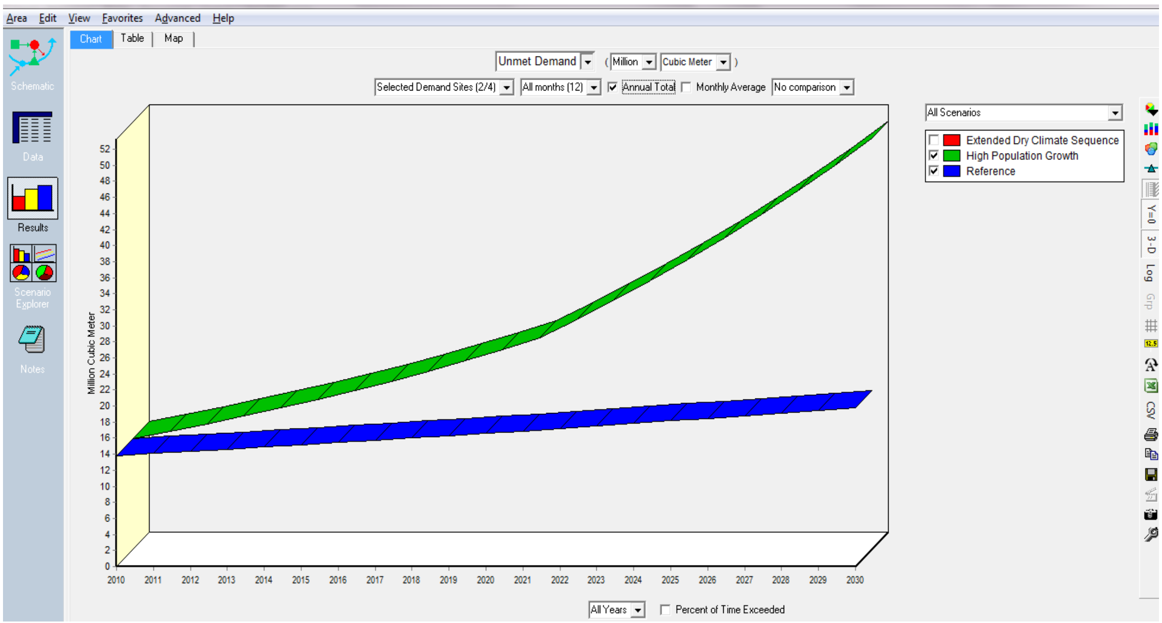

Figure 31: High Population Growth Scenario: Unmet Demand

4.4.2 Extended Dry Climate

In the "Manage Scenarios"-window a new scenario is added, called Extended Dry Climate.

This scenario represents the impact of several dry and very dry years between 2011 and 2030. There for, the Sequence of the Water Year Method was changed while the scenario was set to Extended Dry Climate.

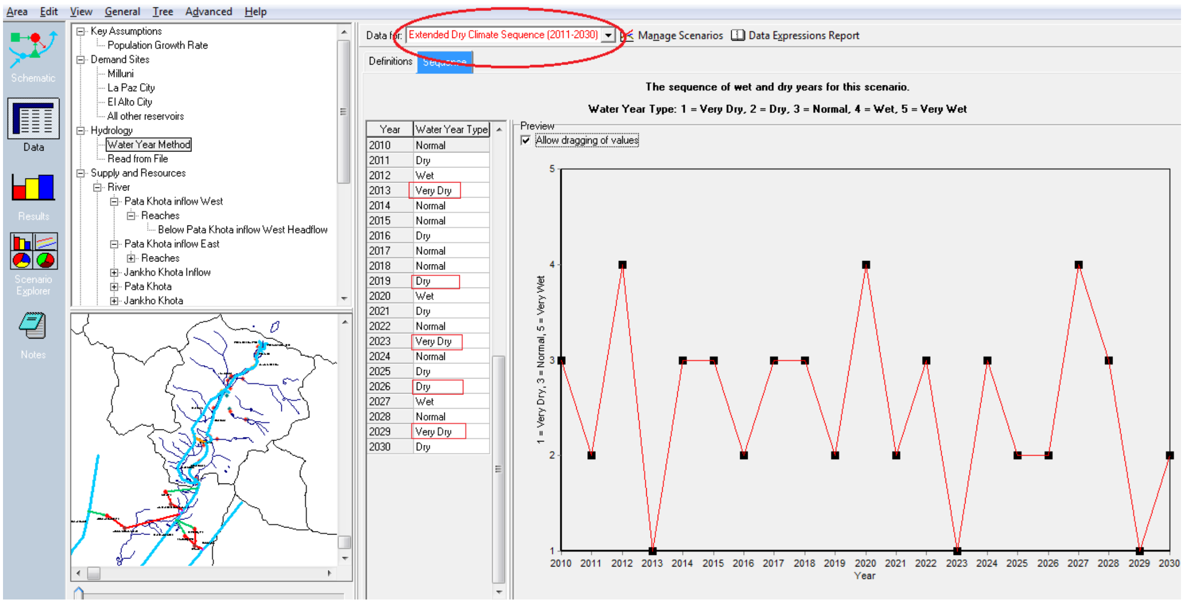

Figure 32: Extended Dry Climate Scenario – Water Year Method

The result shows the influence that the altering of the supply has on the Unmet Demand. The Unmet Demand is bigger in dry years and smaller in wet years. Of course, the Water Demand stays the same as the Reference period because the Population Growth Rate stays 1,48.

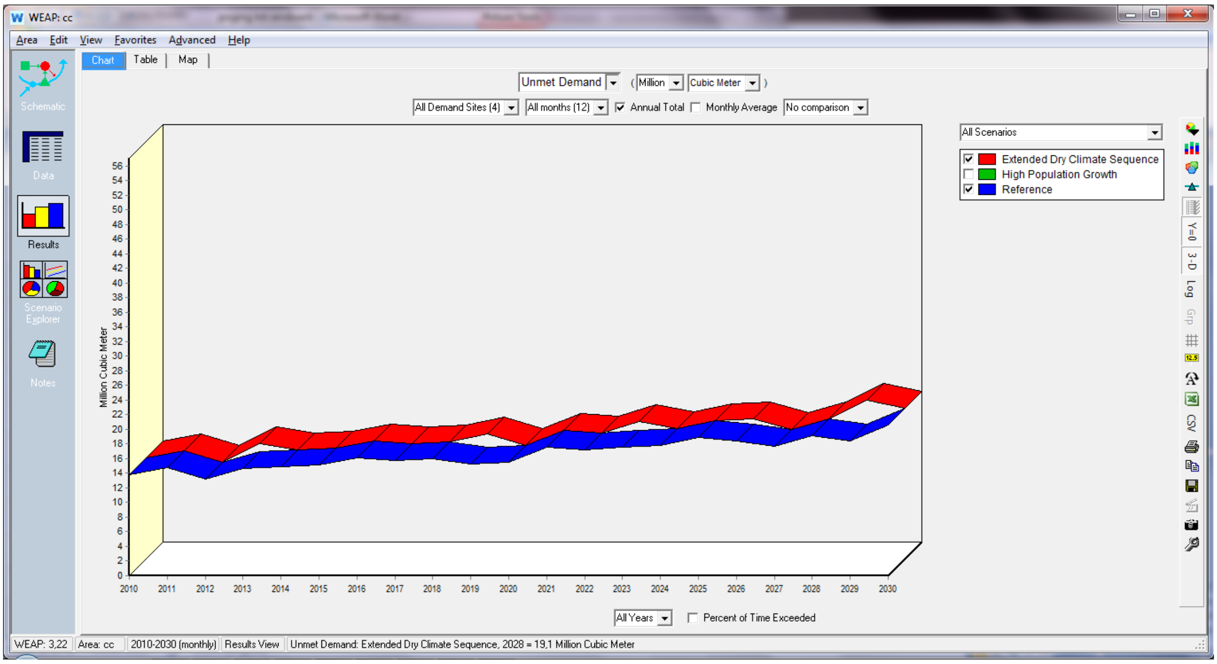

Figure 33: Extended Dry Climate Scenario – Unmet Demand

4.4.3 Influence of scenarios at each other.

By placing a new scenario underneath the Water Year Method scenario and by changing the Population Growth Rate of the new scenario to 5 %, a scenario can be created that takes the increase of growth rate and the variable climate into account. The results can be shown with changing demand and changing supply. This would be an example of a more advanced scenario because of the influence of one scenario at the other scenario.

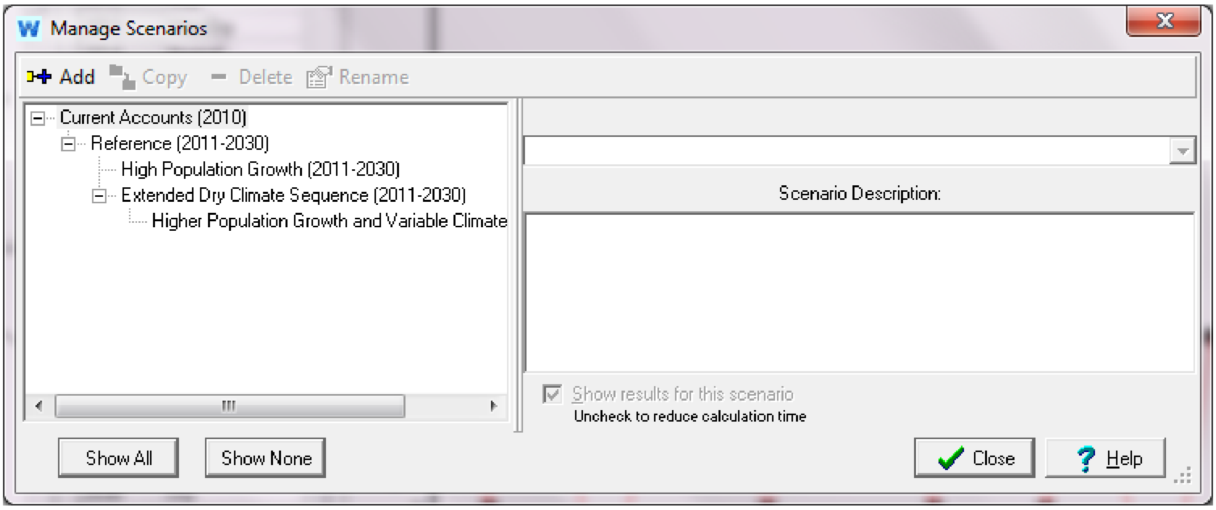

Figure 34: Manage Scenarios

The population of La Paz and El Alto increasing by 5,0 % and the altering of the water supply every year will give the following result for the Unmet Demand of the Milluni Valley:

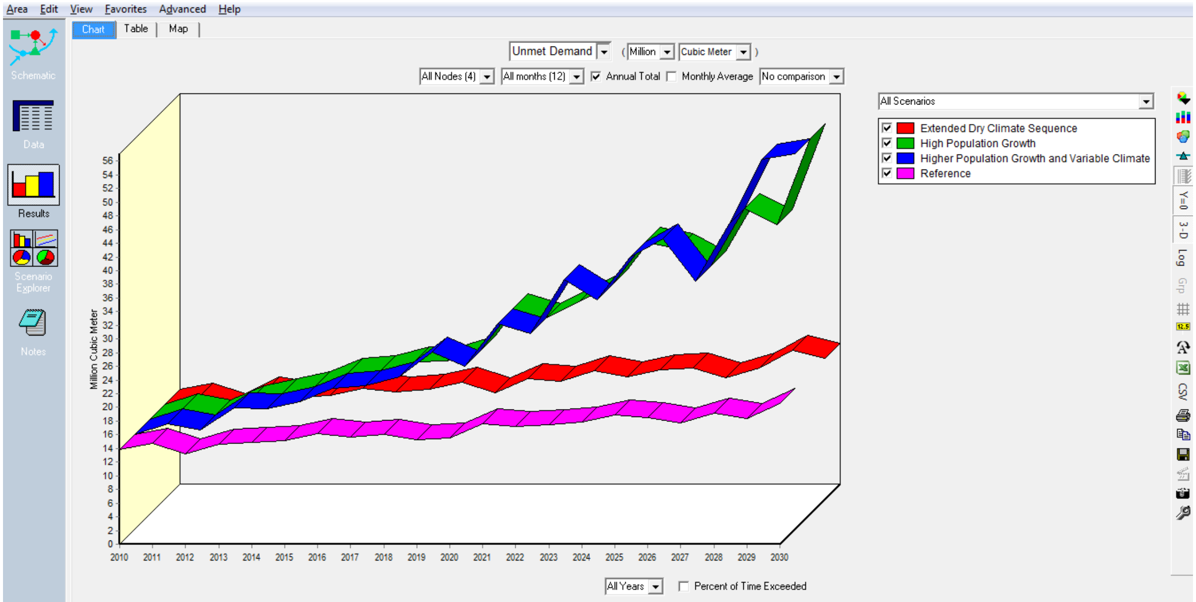

Figure 35: Results – Comparing Scenarios

4.4.4 Priority Changes

Scenarios can also be developed by changing the priorities of demand sites (Universidad Ángela Salinas Villafañe, 2009). The result can be displayed of what will happen with the water supply for La Paz, if El Alto takes the first priority because of the higher population rate.

Below, you can see a flow chart of the Unmet Demand from each demand site, compared to the Unmet Demand in the Reference Scenario.

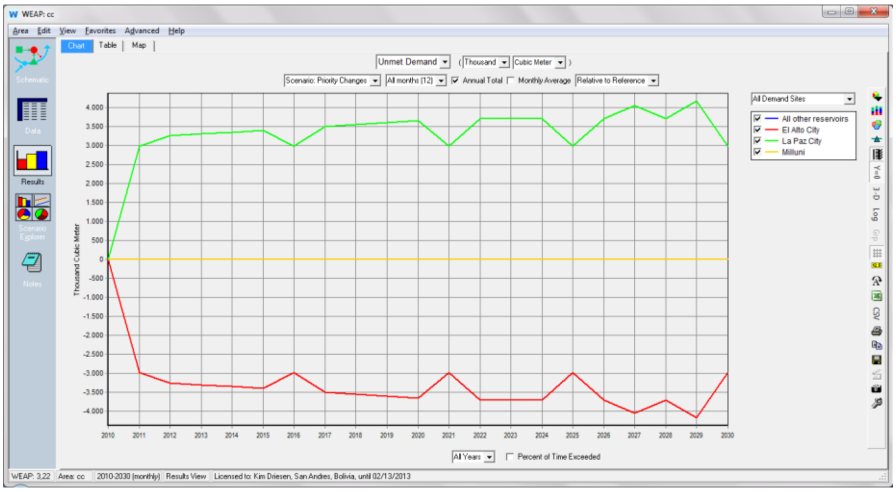

Figure 36: Results – Priority Changes compared to the Reference Scenario

The yellow line shows the Reference Scenario where La Paz takes the priority of the supply. The green line represents the Unmet Demand of the city La Paz in the Scenario of Changed Priorities. This graph shows that the unmet demand of the city La Paz is about 3 500 000 m³ bigger when El Alto takes the priority than the unmet demand in the Reference Scenario.

The red line represents the Unmet Demand of the city El Alto in the Scenario of Changed Priorities. Now that the city of El Alto takes the first priority for the water supply, a decrease of unmet demand can be observed compared to the Reference Scenario.

5 Results and discussion

5.1 Water Quality

The Pata Khota-lake represents an ecological intact environment. This lake has low constant temperatures during the dry season, with a neutral pH and a low conductivity. The lake belongs to the bicarbonate type and has low concentrations of ions. The Pata Khota-lake is similar to other lakes situated in other glacial valleys in the Cordillera Real. The quality of the water is very good.

The Milluni-lake represents a contaminated lake after mixture of the clear water of Pata Khota with the waste water of the mine Milluni. It characterizes itself with an extremely acid pH and high conductivity content because of the large presence of heavy metals. This lake belongs to the type ferric sulphate type. Consequently, the water of this lake has a poor quality.

5.2 WEAP

4 graphs can be observed: *(An enlarged image of the Unmet Demand in Appendices IX)*

- Purple: The Reference Scenario. This is a scenario with a Population Growth Rate of 1,48 % and takes variable climate into account thanks to the Water Year Method. Other scenarios are based on this reference.
- Red: The Extended Dry Climate Sequence Scenario. This is a scenario evaluates the Unmet Demand in a time zone with several dry or very dry years. Compared to the Reference Scenario, some changes can be observed. For example, the Unmet Demand is bigger in dry periods.
- Green: The High Population Growth Scenario. This is a scenario with a Population Growth Rate of 5,0 %. The Unmet Demand enlarges in the future.
- Blue: The Higher Population Growth and Variable Climate Scenario. This is a scenario with a Population Growth Rate of 5,0 % where the cities La Paz and El Alto experience several dry or very dry years between 2011 and 2030.

6 Conclusions and recommendations

6.1 Conclusions

The water shortage for cities located in the mountain range of the Andes depends of several parameters. If one of these parameters changes, it can have a major impact on the coverage of drinking water for all inhabitants.

The results of this study give an image of the consequences in the future. Nowadays, only 92,75 % of the population of La Paz and El Alto has access to clean drinking water. If the population will keep on growing or/and if the precipitation level decreases due to global warming, this shortage will only increase in the future. This problem does not only represent itself in La Paz, but also occurs in other South-American cities located in the mountain range of the Andes, f.e. Quito, Ecuador and Bogota, Colombia.

This thesis could be used to represent the problem to organizations that might have an impact on policy or may contribute with financial support to bring a water purification project into reality. Also, this thesis denounces the irresponsible behavior of the mining companies. Hopefully some changes will be made in their policies which will make them purify the waste water before discharging it in the water basins.

A proper operation of the purification of the mining waste waters deriving from the Milluni-mine will save money that in turn can be spend on the development of sustainable technologies to economically cope with water or to create a bigger supply.

6.2 Recommendations

Finally, I represent a few recommendations:

- The contamination in the Milluni-lake can be stopped spreading by eliminating the effluent of the mines. The canal deriving from the mines should be guided, separated from the clear water canal, to a water treatment plant that is able to purify a high contaminated water flow. Eventually also the sediments will stop contaminating the clear water deriving from the Pata Khota and the Jankho Khota-lake.

- All solid wastes and dump must be removed to prevent the contamination of the water.

- A solution must be found to prevent the contaminated sediments to mix with the water.
    - One way could be by planting certain macrophytes which have the ability of decontaminating water flows.
    - Another solution could be to remove all the sediments of the Milluni-lake and to recover some metals by a bacterial leaching method.

- Force the mining sector to develop a way to prevent contamination by waste water or to purify the waste water before discharging it in the valleys. Require them to build a water treatment plant.

- Make laws concerning solid waste more strict.

- Make the permissible limits stricter for surface water that is meant to be treated for drinking water.
- Make sure these laws are complied in all the country by regular inspections from the "Dirección Nacional de Saneamiento Ambiental".
- Make SAMAPA clear the water canal from Milluni to Achachicala to prevent further contamination.
- Represent the result of these thesis to the Inter-American Development Bank (IDB) in hope they can contribute with financial support to bring a water purification project into reality.

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Appendices

I. Basic characteristics from the basins

II. Map of orientations – Milluni basin

III. Map of slopes – Milluni basin

IV. Physiological characteristics – Milluni-basin

V. Drinkwater production in the treatment plant of Achachicala

VI. Comparison permissible limits Belgium and Bolivia

VII. Total map of the Milluni-valley displayed with WEAP

VIII. Monthly Flow 2000-2010: Milluni-basin

IX. Result of the scenarios in a flow chart

I. Basic characteristics from the basins

<u>**DESCRIPCION**</u>	<u>**MILLUNI**</u>	<u>**PATAKHOTA 1**</u>	<u>**PATAKHOTA 2**</u>
Información básica:			
COORDENADAS LATITUD	16.221°	16.3001°	16.3035°
COORDENADAS LONGITUD	68.095°	68.134°	68.1328°
COTA CRESTA REPRESA	4534	4660	4656
COTA ESPEJO DE AGUA	4530	4659	4655
Año de construcción presa:	1940		
Tipo de presa:	Gravedad	Tierra	Tierra
Tipo de material utilizado:	Mampostería Piedra	Mampostería Piedra	Mampostería Piedra
Cuenca de cada presa (Km2):	58.2	4.67	4.97
Superficie del embalse: (Km2)	2.44	0.193	0.016
Volúmen del embalse: (Hm3)	10.8		
Longitud de presa (coronamiento): (m)	132	80	25
Altura Máxima (desde pie a coronamiento)	9.1	7	5
Sistema de alivio:			
Vertedero, compuertas y descarga	Stoplogs operables sobre el vertedero	Vertedero libre	Vertedero libre
Caudal de diseño m3/h	38755		
Caudal máximo m3/hr (2000-2006)	4830		
Métodos de auscultación:			
Piezómetros	NO		
Medición de desplazamientos	SI		
Aforo de filtraciones bajo el dique	SI		
Análisis de aguas de las filtraciones	SI		
Otros	NO		
Distancias entre cuerpos de presa:			
Longitud en planta y en km	13.3 km a Incachaca	8.2 Km a represa Milluni	7.5 Km a represa Milluni

Tabel 10: Information of Milluni and Pata Khota (EPSAS, 2010)

II. Map of orientations – Milluni basin

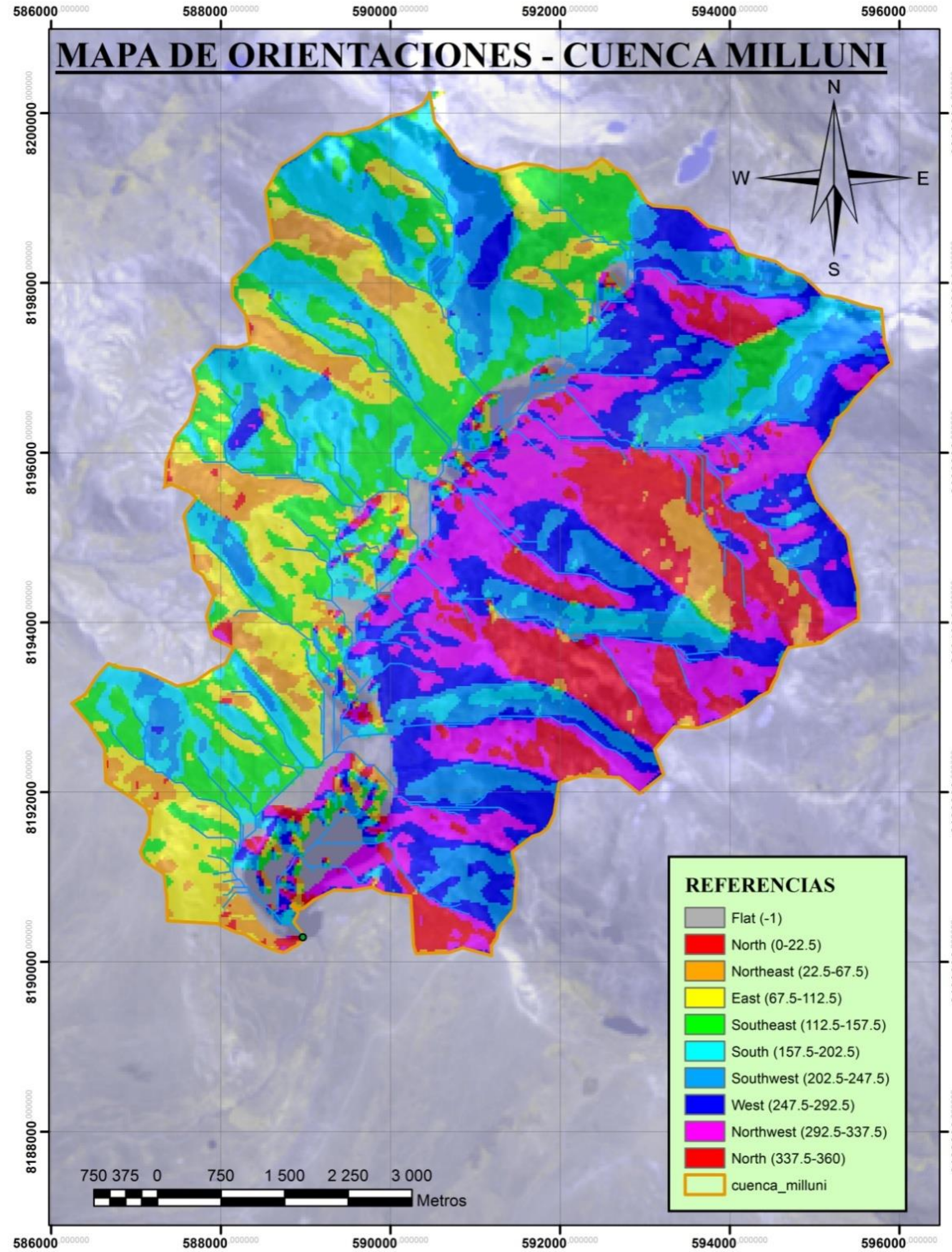

Figure 37: Map of Orientations – Milluni-basin

III. Map of slopes – Milluni basin

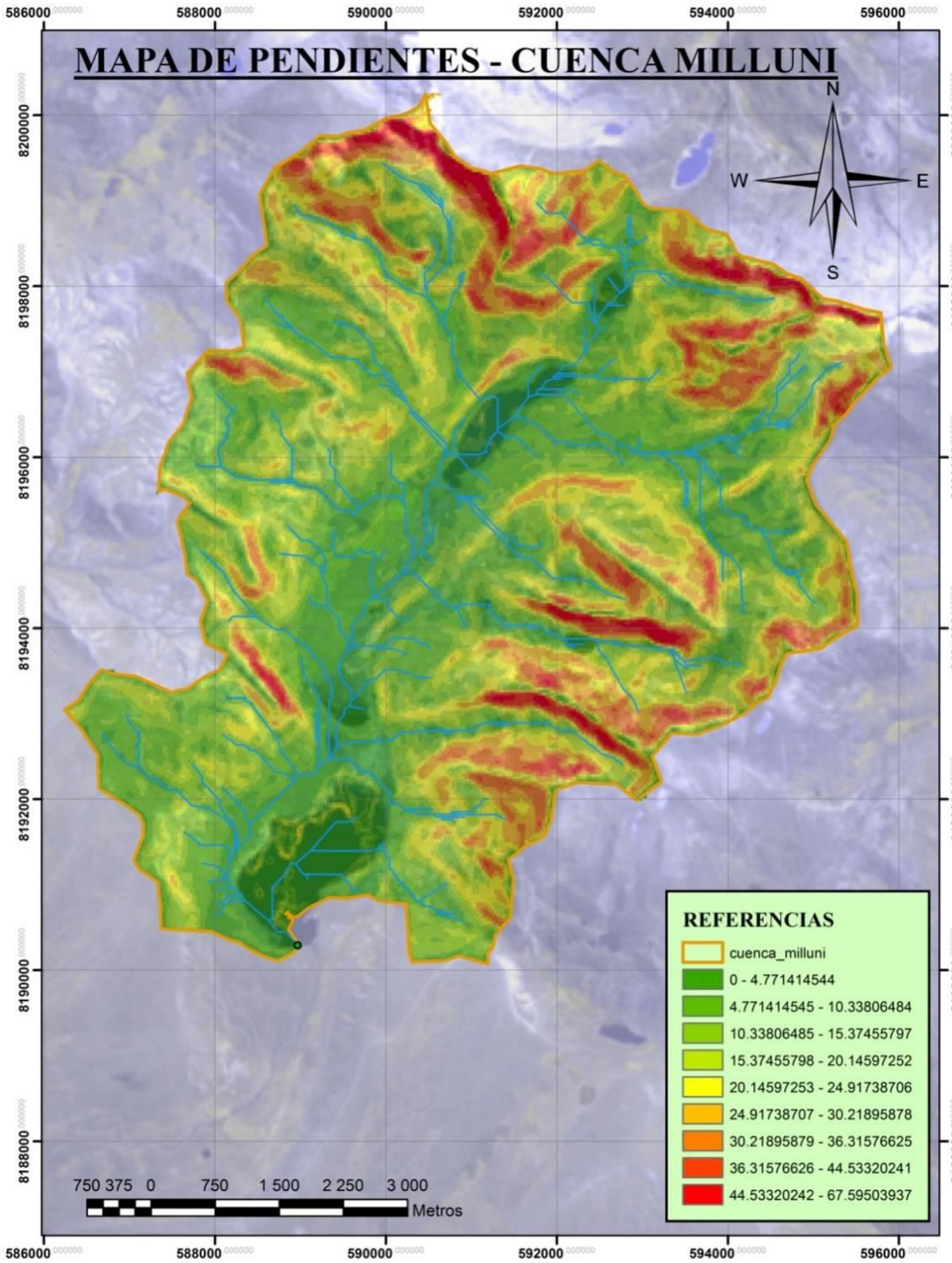

Figure 38: Map of Slopes – Milluni-basin

Tabel 11: Physiological characteristics – Milluni-basin (Calizaya, 2012)

IV. Physiological characteristics – Milluni-b
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Características Fisiográficas	**Cuenca - Milluni**
Estación Hidrométrica para control de caudal	Milluni (Presa de regulación Milluni)
Coordenadas de la cuenca (centro)	590997.202 , 8195102.13
Rango Altitudinal (msnm)	4451 - 5669
Elevación media (msnm)	4807,473071
Superficie (km2)	59,477
Perímetro (km)	38,037
Exposición general	Sur (193.84)
Pendiente media (%)	26,79%
Longitud del cauce principal (Km)	11,430
Longitud de la red de drenaje (km)	109,970
Coeficiente de compacidad	1,357
Factor de forma	0,457
Densidad de drenaje (km/km2)	1,842
Tiempo de concentración (h)	0,702
Tiempo de almacenamiento (h)	0,456

V. Drinkwater production in the treatment plant of Achachicala

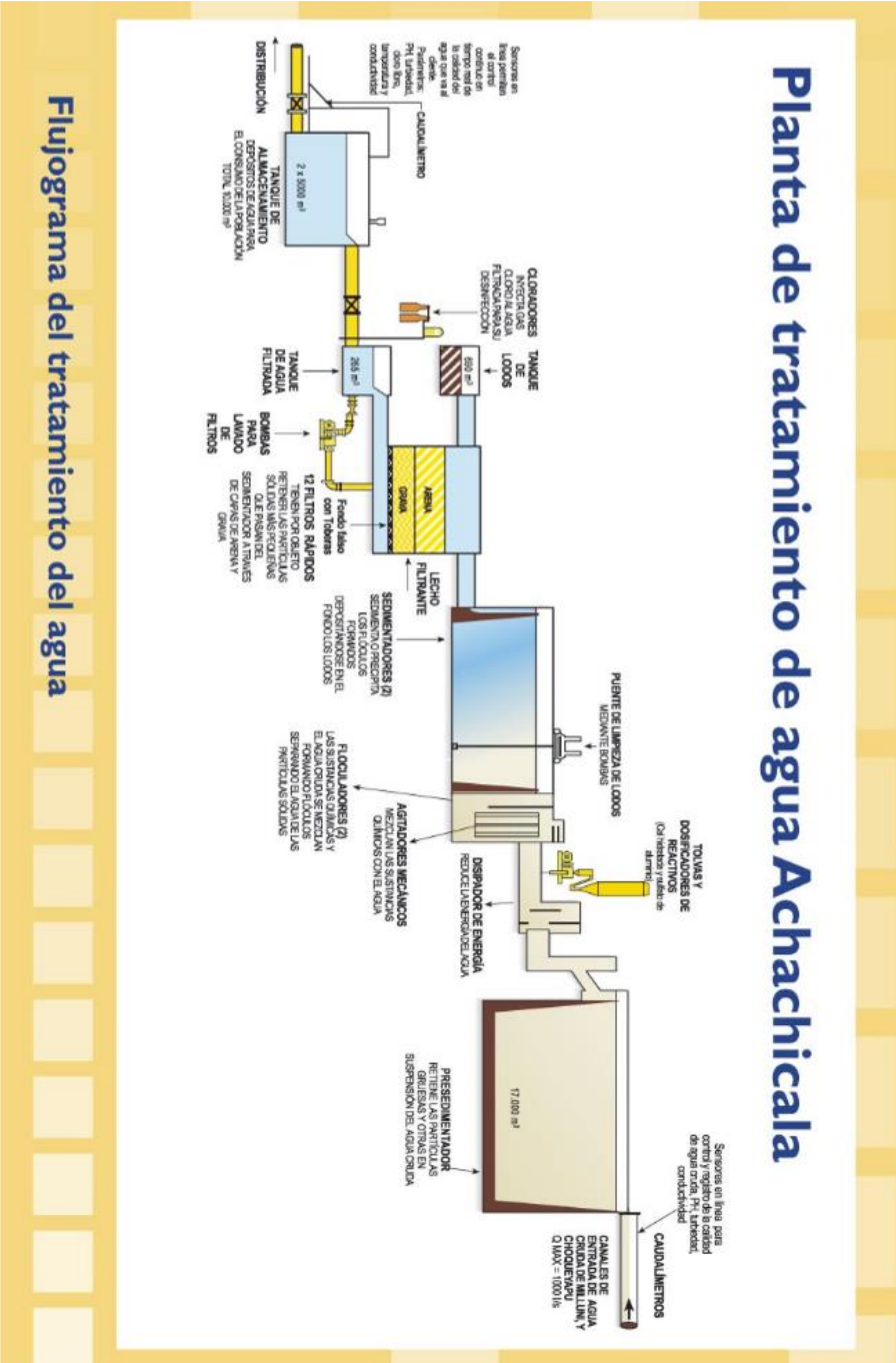


Figure 39: Treatment plant of Achachicala (EPSAS, 2012)

VI. Comparison permissible limits Belgium and Bolivia

Parameters	Eenheden	Permissible limits Belgium	Permissible limits Bolivia - Class B
pH		5,5-9	5,5-9,5
Zwevende stoffen	mg/l	G: 50	1500
Temperatuur	°C	25(0)	
Soortelijk geleidingsvermogen	µS/cm à 20°C	G: 1000	
Opgelost ijzer	mg/l Fe	G: 0,2	2
Mangaan	mg/l Mn	G: 1	2
Koper	mg/l Cu	G: 1	2
Zink	mg/l Zn	5	15
Arsenicum	mg/l As	0,1	0,05
Cadmium	mg/l Cd	0,005	0,2
Lood	mg/l Pb	0,05	0,1
Kwik	mg/l Hg	0,001	0,01
Cyanide	mg/l CN	0,05	
Sulfaten	mg/l SO4	250(0)	600
Chloriden	mg/l Cl	G: 200	700
Fosfaten	mg/l P2O5	G: 0,7	
Verzadigingspercentage O2	% O2	G: > 30	> 60%
NMP/100 ml. (Numéro Maís Provával)	NMP/100 ml.		< 10.000 < 2.000 en 80 %
Magnesium	mg/l		300
Calcium	mg/l		400

Tabel 12: Comparison Permissible Limits Belgium and Bolivia
“G:” stands for “Guideline”

VII. Total map of the Milluni-valley displayed with WEAP

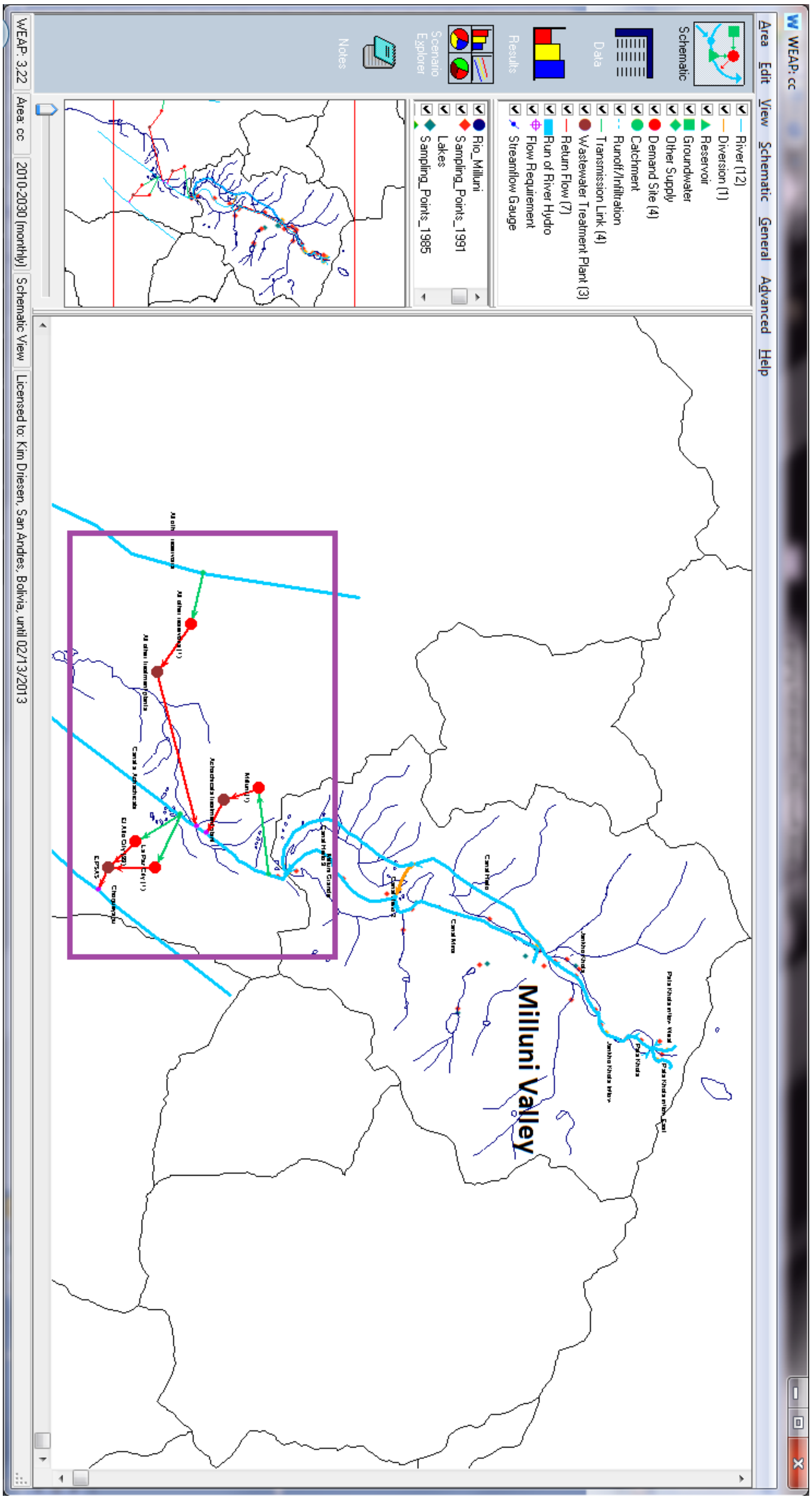


Figure 40: Total map of the Milluni-valley displayed with WEAP

Tabel 13: Monthly Flow 2000-2010 Milluni-basin (Calizaya, 2010)

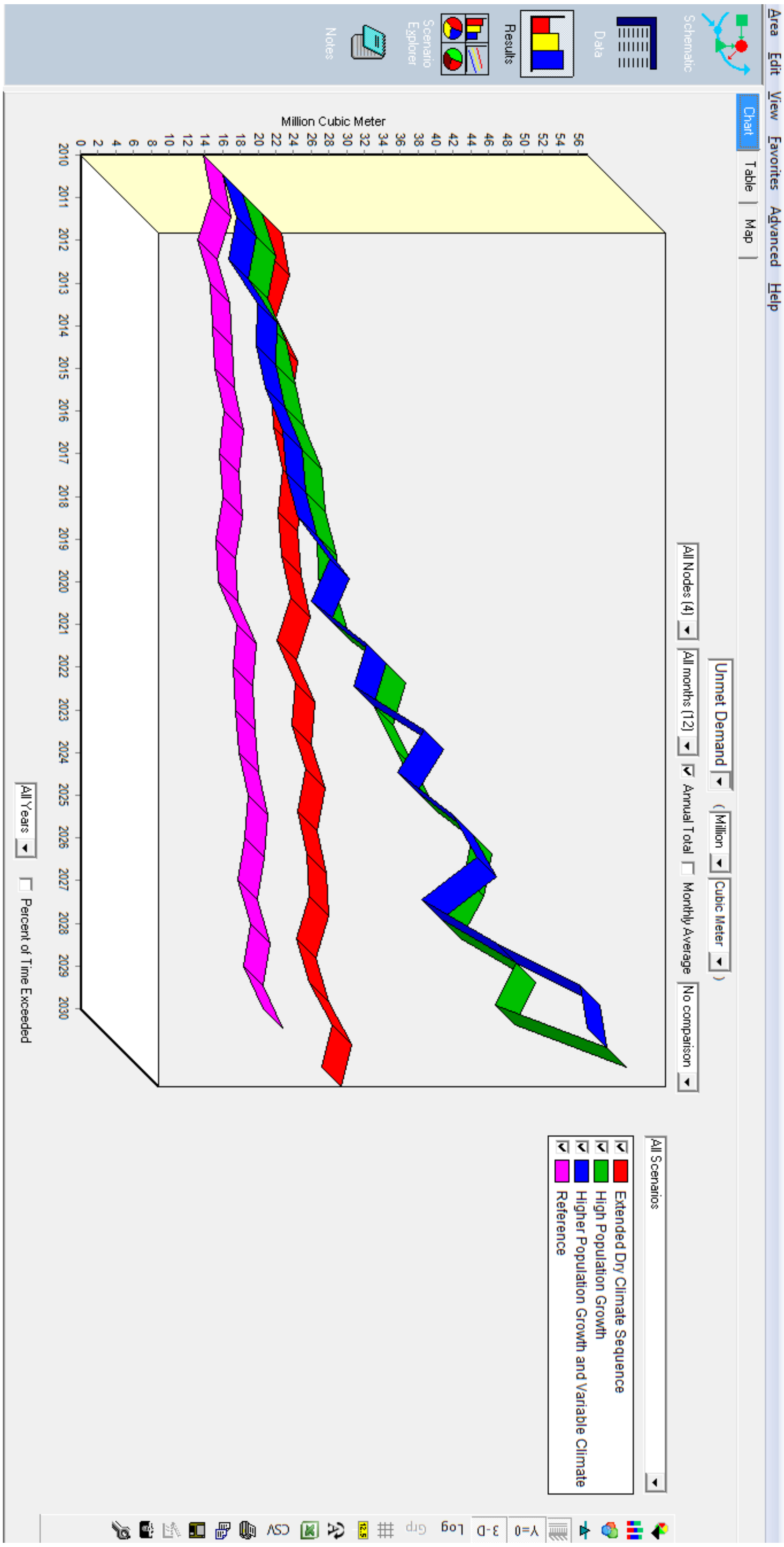
VIII. Monthly Flow 2000-2010:

Monthly Flow 2000-2010 Cuenca Milluni

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
januari	0,3	2	1,5	1,2	1,4	0,4	0,5	1,4	1,5	1,4	1,5
februari	0,7	2,8	1,45	2,2	1,6	0,6	1,4	1,6	2,5	0,9	1,6
maart	0,75	1,4	1,85	1,7	1,3	0,4	0,9	1,4	1,5	0,7	1,9
april	1,2	0,45	1,1	1,4	0,4	0,3	0,6	1,6	0,9	0,4	1,4
mei	0,5	0,5	0,4	0,1	0,3	0,25	0,4	0,7	0,2	0,1	0,4
juni	0,2	0,35	0,1	0,05	0,1	0,45	0,1	0,4	0,05	0	0,1
juli	0,3	0,2	0,3	0,05	0,1	0,3	0,05	0,05	0,05	0,2	0
augustus	0	0,4	0,2	0,1	0,2	0,05	0	0,1	0,1	0	0
september	0,05	0,35	0,5	0,2	0,25	0,05	0,25	0,05	0,4	0,4	0,1
oktober	1,2	0,7	1,4	0,3	0,3	0,2	0,2	0,4	0,3	0,5	0,8
november	0,5	0,7	0,8	0,6	0,35	0,35	0,5	0,9	0,9	1,2	0,4
december	1,4	1,5	0,9	1,1	0,4	0,5	1,4	1,3	1,4	1,5	1,4

Milluni-basin

IX. Result of the



scenarios in a flow chart

Figure 41: Result – Comparing Scenarios