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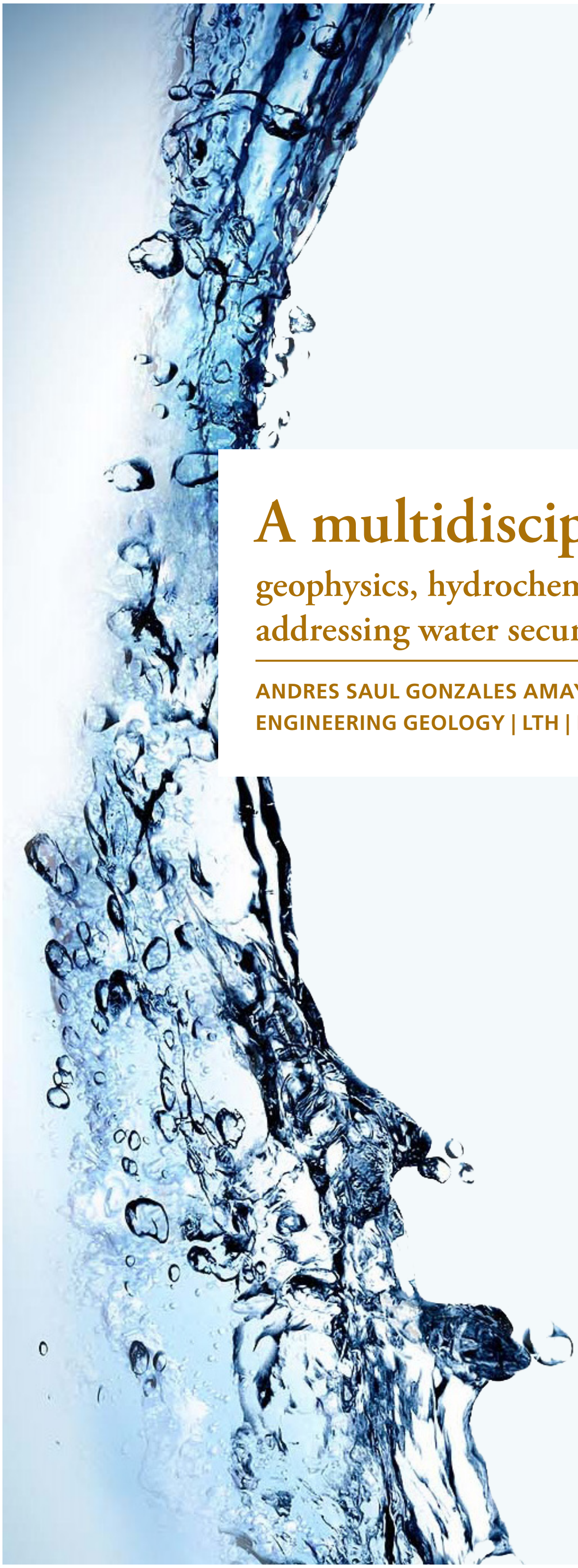

A multidisciplinary approach:

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LUND UNIVERSITY

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Abstract

Water security offers to the local population an adequate quality and quantity of water for health, economy, livelihoods and ecosystems. Hence, achieving basic levels of water security should be a priority in areas where access to fresh water is scarce. The Punata alluvial fan (Bolivia) is a semiarid zone and an important agricultural zone, where the main source of water is groundwater. Therefore, it is important to retrieve and broaden the knowledge about the main hydrogeological mechanisms, and the physical and chemical properties of the groundwater in the Punata fan. This research aims to apply and combine different disciplines such as hydrometeorology, geophysics and hydrochemistry to retrieve important hydrogeological information in the Punata fan. This information is of particular interest for achieving water security, so that freshwater (i.e. groundwater) can be provided to the local population, industry and environment.

The hydrometeorological results suggests that there is a cycling of El Niño events which are related to regional drought periods, hence the recharge of groundwater can be affected. Records from wells suggest that there is a lowering of the water table, which is more evident when an El Niño event take place in the same or in the previous years. Therefore stakeholders should take into consideration the occurrence of El Niño events in order to plan a more efficient usage of water. The geophysical results and interpretation are important for proposing and refining hydrogeological conceptual models, where a more accurate description of the layering, depth and thicknesses of the different aquifers units are displayed. One main finding is the delimitation of a saline layer at the bottom of the aquifer system. The delimitation of this saline layer is important in order to prevent the pollution of fresh water when drilling and pumping take place. Another application of the geophysical results is for elaboration of groundwater vulnerability maps, which are important for preventing groundwater contamination. The hydrochemical results highlight that groundwater in the Punata fan is mainly recharged by the Pucara River, while recharge from precipitation and irrigation are of less importance. The analysis of groundwater salinization suggests that saline deposits lying in the lacustrine layer are the main cause of salinization, which is also supported with the geophysical results where a saline layer was detected.

A multidisciplinary approach can produce more complete, accurate and reliable hydrogeological information in alluvial fans, where groundwater is the main source of water supply. The results and findings of this research are important for the local actors, due to the fact that a better understanding of the major hydrogeological processes is provided. Therefore, with this knowledge, further plans for sustainable groundwater management and protection can be proposed. Thereafter, if access to fresh water (i.e. groundwater) is guaranteed in the study area, basic levels of water security can be reached and with this an improvement of the local wellness.

Key words: Geophysics, Hydrochemistry, Hydrogeology, Climate variability, Water security, Bolivia

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Thank you to all my colleagues at Engineering Geology for their friendship. Eternal gratitude and love to my wife, parents and brothers.

Abstract

Water security offers to the local population an adequate quality and quantity of water for health, economy, livelihoods and ecosystems. Thus, achieving basic levels of water security should be a priority in areas where access to fresh water is scarce. The Punata alluvial fan (Bolivia) is a semiarid zone and an important agricultural zone, where the main source of water is groundwater. Therefore, it is important to retrieve and broaden the knowledge about the main hydrogeological mechanisms, and the physical and chemical properties of the groundwater in the Punata fan. This research aims to apply and combine different disciplines such as hydrometeorology, geophysics and hydrochemistry to retrieve important hydrogeological information. This information is of particular interest for achieving water security, so that freshwater (i.e. groundwater) can be provided to the local population, industry and environment.

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A multidisciplinary approach can produce more complete, accurate and reliable hydrogeological information in alluvial fans, where groundwater is the main source of water supply. The results and findings of this research are important for the local actors, due to the fact that a better understanding of the major hydrogeological processes is provided. Therefore, with this knowledge, further plans for sustainable groundwater management and protection can be proposed. Thereafter, if access to fresh water (i.e. groundwater) is guaranteed in the study area, basic levels of water security can be reached and with this an improvement of the local wellness.

Resumen

La seguridad hídrica ofrece a una población una adecuada cantidad y calidad de agua para la salud, economía, bienestar humano y ecosistemas. Por tanto, alcanzar niveles básicos de seguridad hídrica debería ser prioridad en áreas donde el acceso a agua fresca es un problema. El abanico aluvial de Punata (Bolivia) es una zona semiárida, sin embargo, es una importante región de producción agrícola, donde el agua subterránea es la principal fuente de agua. Consecuentemente, es importante ampliar y generar un conocimiento completo de los principales mecanismos hidrogeológicos de las aguas subterráneas locales. La presente investigación tiene como objetivo aplicar diferentes disciplinas como hidrometeorología, geofísica, e hidroquímica para generar información hidrogeológica en el abanico aluvial de Punata. Los resultados hidrometeorológicos sugieren que existe una ciclidad de eventos de El Niño, los cuales están relacionados a periodos de sequía locales y regionales, por lo tanto, la recarga de las aguas subterráneas puede llegar a ser afectada. Consiguientemente, las partes interesadas (por ejemplo, agricultores) pueden tomar en cuenta la ocurrencia de los eventos del El Niño y planificar un uso más eficiente del agua.

Los resultados geofísicos fueron importantes para poder proponer y refinar modelos hidrogeológicos, donde la descripción es más precisa en cuanto la estratificación, profundidad, y espesor de las diferentes unidades de acuíferos. Un importante descubrimiento fue la de una zona salina en fondo del sistema de acuíferos. La delimitación de esta zona salina es importante para evitar la contaminación de agua dulce durante la perforación de nuevos pozos. Por otro lado, otra aplicación que se dio a los resultados geofísicos fue para la elaboración de una nueva metodología para el mapeo de vulnerabilidad de aguas subterráneas.

Los resultados hidroquímicos fueron útiles para determinar que el agua subterránea en el abanico de Punata es principalmente recargada por el río Pucara, mientras que los aportes de agua de lluvia e irrigación son de menor importancia. El análisis del origen de la salinización de agua subterránea sugiere que los depósitos lacustres son la principal causa de salinización, esto también fue corroborado con los ensayos geofísicos. Los resultados y hallazgos de esta investigación son importantes para los actores locales, debido a que un mejor entendimiento de los principales procesos hidrogeológicos es alcanzado. Consecuentemente, este nuevo conocimiento puede ser utilizado para proponer planes de manejo sostenible y de protección de las aguas subterráneas. Posteriormente, si se garantiza en la zona de estudio el acceso a agua dulce (en este caso aguas subterráneas), se podrá alcanzar niveles básicos de seguridad hídrica, y con esto una mejoría en la estabilidad económica y bienestar humano de la población local.

Popular summary

Water is one of the most important constituents, if not the most important, for human beings. Therefore, it is important to preserve and protect all kinds of freshwater sources. In Bolivia there are several regions were access to water in good quantity and quality is a critical issue. In the central and western areas of Bolivia there are large populated areas where groundwater is the main supply source. The objective of this research is to highlight the significance of applying a combination of different methods for obtaining and complementing the information about groundwater. By having a wide and complete knowledge of the different hydrogeological properties in a selected region, the possibility of achieving sustainable usage of water increases. Sustainability is very important in areas that depend almost entirely on groundwater for their economic and social activities, such as the Punata alluvial fan.

This work applied several techniques to obtain a better description of aquifers in Punata and its main hydrogeological processes. Results suggest that El Niño events may affect the recharge of groundwater in Punata, and therefore can have repercussions on the daily activities of the region. Geophysics proved to be practical and useful tool for delimiting the geometry of the aquifer system, where the extent of the different layers was delimited. A main finding is the mapping of a saline layer at the bottom of the aquifer system. On the other hand, the hydro-chemical analyzes were important in determining that the main source of groundwater recharge is the Pucara river.

When there is enough information about the main hydrological and hydrogeological processes, water security can be addressed through a more sustainable usage of water and preventing the contamination of water supply sources. Therefore, all the information generated in this research should be directed to local actors and decision makers. This information can be the basis for elaborating laws and policies for sustainable management of groundwater in Punata, and thus safeguard the human, economic and environmental needs of the area, which would lead to a water secure status.

Appended papers

This thesis is based on the following papers, which will be referred to in the main text. The papers are appended at the end of the thesis.

I. **Gonzales Amaya, A.**, M. Villazon, and P. Willems (2018), Assessment of Rainfall Variability and Its Relationship to ENSO in a Sub-Andean Watershed in Central Bolivia, Water, 10(6), 701, doi:10.3390/w10060701.

II. **Gonzales Amaya, A.**, T. Dahlin, G. Barmen, and J.-E. Rosberg (2016), Electrical Resistivity Tomography and Induced Polarization for Mapping the Subsurface of Alluvial Fans: A Case Study in Punata (Bolivia), Geosciences, 6(4), 51, doi:10.3390/geosciences6040051.

III. **Gonzales Amaya, A.**, J. Mårdh, and T. Dahlin (2018), Delimiting a saline water zone in Quaternary fluvial–alluvial deposits using transient electromagnetic: a case study in Punata, Bolivia, Environmental Earth Sciences, 77(2), 46, doi:10.1007/s12665-017-7213-5.

IV. **Gonzales Amaya, A.**, G. Barmen, and G. Muñoz (2018). A Multidisciplinary Approach for Clarifying the Recharge Processes and Origin of Saline Water in the Semi-Arid Punata Alluvial fan in Bolivia. Water, 10, 946, doi:10.3390/w10070946.

V. **Gonzales Amaya, A.**, T. Dahlin, G. Barmen, and J.-E. Rosberg (2018), A geoelectrical and geomorphological based method for groundwater vulnerability assessment in alluvial fans: a case study in the Punata fan (Submitted to Environmental Earth Sciences).

Author's contribution

I. The author planned the study, carried out the literature review and collected the hydrometeorological information. The co-authors made the statistical modeling. The results from the statistical methods were analyzed by the author and he was the main contributor to the writing of the paper.

II. The author planned and performed the field work. The author was the main contributor during the writing and review process.

III. The author together with the co-authors designed the field work and collected the information. The author analyzed the results and wrote the paper.

IV. The author together with the co-authors designed the field work. The author performed the field work, analyzed the results and wrote the paper.

V. The author conceived the method, performed the analysis of results and wrote the paper.

Other related work

i. **Gonzales Amaya A.** and Dahlin T. (2016) Characterization of an alluvial fan aquifer system in Bolivia by electrical resistivity tomography and induced polarization parameters, in Procs. 43rd IAH Congress, 25-29th September 2016, Montpellier, France, no 1515.

ii. Dahlin T., **Gonzales Amaya A.** and Gomez E. (2017) Geophysical mapping of aquifers in Bolivia, in Procs. SAGEEP 2017 – Symposium on the Application of Geophysics to Engineering and Environmental Problems, 19-23 March 2017, Denver, CO, USA, 1p.

iii. **Gonzales Amaya, A.** (2017) The application of geoelectrical methods for understanding the Punata aquifer (Bolivia), in Procs. NOVCARE – 5th International Conference Novel Methods for Subsurface Characterization and Monitoring: From Theory to Practice, 06-08 June 2017, Dresden, Germany, 1p.

iv. **Gonzales Amaya, A.** (2017) Flow patterns and recharge process in alluvial fans: a case study of the semi-arid Punata fan in Bolivia, in Procs. FLOWPATH, 3rd National Meeting on Hydrogeology, 14-16 June 2017, Cagliari, Italy, 1p.

v. **Gonzales Amaya, A.** (2017) Groundwater characterization in the semi-arid Punata alluvial fan (Bolivia), in Procs. 44th IAH Congress, 25-29 September, Dubrovnik, Croatia, 1p.

vi. **Gonzales Amaya, A.** (2018) EDIT: a novel geoelectrical and geomorphological based method for groundwater vulnerability in alluvial fans, in Procs. International Conference on New Approaches to Groundwater Vulnerability, 4-8 June, Ustron, Poland, 1p.

vii. **Gonzales Amaya, A.** (2018) Geophysical surveys for improving the hydrogeological conceptual models in the semi-arid region of Valle Alto (Bolivia), in Procs. Near Surface Geoscience Conference & Exhibition, 9-12 September, Porto, Portugal, 4p.

Table of Contents

1. INTRODUCTION

1.1. Background information

Water is one of the most important substances on earth for all kind of life, and it is essential for sustaining human life and welfare. However, around 1.1 billion people worldwide lack of access to water, and a total of 2.7 billion experience water scarcity for at least one month of the year (Grey et al., 2013). In order to mitigate and reduce water-related issues the water security framework can be addressed (refer to Figure 1). This framework can assist in solving issues that can have major ecological, social, economic and health implications. UN-Water (2013) defined water security as "the ability of a population to safeguard sustainable access to sufficient quantities of good quality water for supporting livelihoods, human welfare, and socioeconomic development, for protection against water borne pollution and water related disaster, and for preserving ecosystems in a climate of peace and political stability".

Figure 1 shows the three dimensions, defined by Grey and Sadoff (2007), that can affect water security: 1) the hydrogeological environment, 2) the socioeconomic environment, and 3) the future environment. If these three dimensions are accomplished, the region will have better conditions for a growth and enhancement in terms of health, lifestyle, economy and environment. The following paragraphs give a more detailed explanation about these three dimensions:

- Within the hydrogeological environment the main terms to be considered are the rainfall variability, river regime (i.e. perennial or non-perennial rivers), and groundwater accessibility. In general low variations in inter-annual and intra-annual rainfall, the presence of perennial river flows, and easy access to groundwater can guarantee a basic level of water security. A basic level implies comparatively low levels of effort and investment, and in this way growth can proceed without water being a constraint.
- Regarding to the socioeconomic environment, the main terms to be considered are the water infrastructure, local/national water-related institutions, and the macro-economy. Robust institutions are needed for an adequate water administration, and for the investment in and management of a water infrastructure. The latter is indispensable to access, store, regulate, distribute, and conserve the water resources. Adequate irrigation infrastructure is quite important especially in agriculture-based countries. The economic structure is important for achieving satisfactory investment in the water sector. Also a gradual shift into a more diversified economy, which is less water dependent, can ensure gains which in turn are invested in and reinforce water security.

- The future environment can be understood as the upcoming uncertain scenarios regarding water issues. The most likely scenario to occur is climate change and variability, which increases the complexity of ensuring water security. Thus, the main challenge is to incorporate climate change and variability as one of the key issues for enhancing water-secure levels.

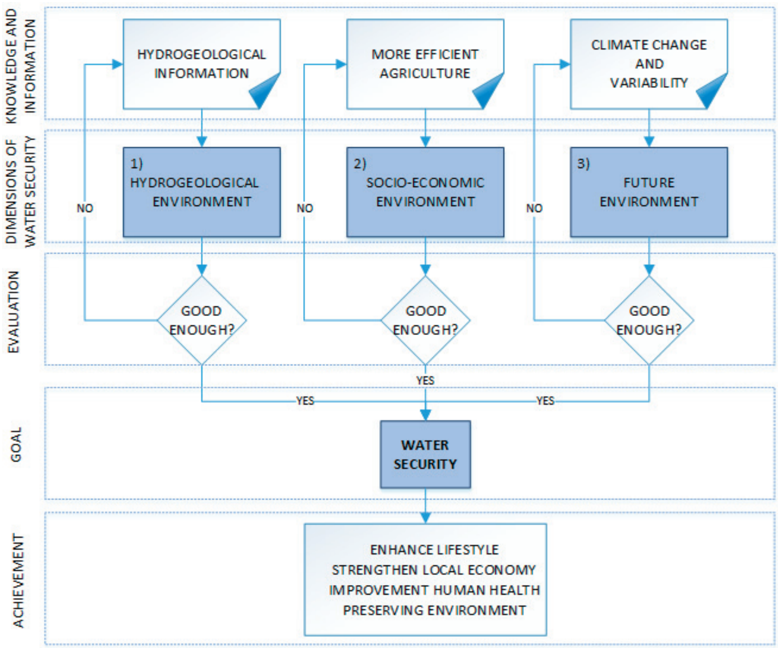

Figure 1 Framework of water security based on the dimensions proposed by Grey and Sadoff (2007).

When water security is accomplished several opportunities for development can be considered, for example investments in water for agriculture, hydropower and industry. These opportunities are key factors for the growth and development of countries, and Grey and Sadoff (2007) observed that most of the world's richest countries have accomplished water security. Consequently, water security should be an issue of concern in many regions, particularly in developing countries such as Bolivia. Although Bolivia has large sources of water they are not equally distributed in time and space, and hence there are several water-related problems across the country. For instance, the western part of Bolivia is considered as an arid zone with high rates of water deficit, while the eastern region of Bolivia is humid and dominated by the Amazon river system, with frequent flooding of riverine villages and settlements. In terms of water institutions and policies (e.g. laws, regulations or guidelines) there has been only slow improvements for many decades. The lack of investment in scientific research has also contributed to a general absence of knowledge in many topics such as hydrology and geology. All these circumstances have led to a situation where Bolivia is weak regarding water security.

This research has focused on some approaches that can contribute towards water security in dimensions 1) and 3), and the Punata alluvial fan region was selected as a case study. The study area is a semiarid region located in the central part of Bolivia, within a sub-Andean zone. This area is important not only in terms of economy, but also with regard to social and environmental issues. The main social and economic activity is the agriculture, and therefore water is an essential driver for welfare of the zone. The agriculture in this zone evolved from crops that were cultivated only during the rainy season to a variety of different crops, and hence water is needed the whole year. Consequently, the extensive agriculture has led farmers and villagers to find alternative sources of water, thereby making groundwater the main water source for the area. The recent years have showed an evident lowering of groundwater levels and this might be due to the fact that there is an uncontrolled increase of drilled wells and over-exploitation of the groundwater. Some reports, e.g. Centro-Agua (2012), suggest that there is an ongoing groundwater depletion, where groundwater abstraction exceeds the rate of groundwater recharge. Other water issues in the Punata region are, for instance, a weak investment in water institutions and infrastructure, and inappropriate irrigation practices, i.e. flooding, where water is lost through evaporation. Climate change and variability are also affecting the local agriculture since there are small shifts in the start of the rainy seasons, affecting mainly rain-feed crops which are planted too late or too early, and as a consequence crops do not get the right amount of water. Climate variability also poses a hazard to groundwater recharge due to the fact that extreme drought events are becoming more frequent and stronger (Holbrook et al., 2012, Villazon, 2015).

In order to create a better livelihood in the study area it is intended to achieve basic levels of water security. However, to achieve a basic level of water security, improved knowledge and information of several subjects such as hydrology, geology, climate change and adequate irrigation techniques is needed. In developing countries, such as Bolivia, national archive projects for storing and retrieving field information are very limited, which constrains the amount and quality of collected information. Therefore, low cost and efficient alternative methods are needed for retrieving these type of information.

1.2. Objectives

The overall goal of this research is to find and test a set of accessible methods which can provide new information and knowledge leading to basic levels of water security. The Punata alluvial fan is used as a case study. The new acquired information is expected to contribute towards a basic water security level. The specific objectives of this thesis can be outlined as follow:

- To evaluate the effects of climate variability on groundwater recharge in a sub-Andean region of Bolivia.
- To retrieve and refine the hydrogeological conceptual model in the Punata alluvial fan by applying geophysical methods such as Electrical Resistivity Tomography, Induced Polarization and Transient Electromagnetics.
- To investigate and determine the main groundwater recharge/discharge mechanisms in alluvial fans located in a sub-Andean region of Bolivia, by analyzing the composition of stable isotopes and hydrochemistry.
- To determine the saline water origin in the Quaternary fluvial-alluvial deposits of the Punata aquifer, and to delimitate its extension by combining geophysical and hydrochemical analysis.
- To propose an alternative method for assessing groundwater vulnerability in alluvial fans based in geoelectrical and hydrogeological information.

1.3. Limitations

The geophysical investigations in this study were limited to Electrical Resistivity Tomography, Induced Polarization and Transient Electromagnetics, mainly due to the accessibility of equipment. The local university in Bolivia, Universidad Mayor de San Simón (UMSS), provided access to equipment for performing Electrical Resistivity Tomography and Induced Polarization surveys. While the host university in Sweden, Lund University, managed to provide access to Transient Electromagnetic equipment.

The hydrochemical analyses of water samples were restricted to the capability of the local laboratory at UMSS which performs standard physicochemical analyses of water. However, through Lund University, it was possible to send about 45 water samples to the Geological Survey of Denmark and Greenland (GEUS) for stable isotopes analysis (i.e. concentrations of deuterium and oxygen-18).

1.4. Thesis outline

This thesis is divided into 6 main chapters. Chapter 1 and 2 summarize the background of this research and provide a description of the study area, respectively. Chapters 3 to 6 recapitulate the contribution of each published journal article and manuscript, the different methods and tools used in this research, and the main results and conclusions. In the following section a more detailed description of each chapter is given:

- The first chapter describes the background of this research, and how the framework of water security can assist in improving the welfare of a society. In Bolivia there are several shortcomings related to water, therefore in this chapter, it is suggested how water security can be addressed in Bolivia through the different specific objectives of this research.

- The second chapter describes the study area, and explains the lack of scientific and technical knowledge in terms of the local hydrogeology. This chapter also describes the socio-economic importance and significance of the study area.
- The third chapter deals with climate variability, and how it can have an impact on the local groundwater levels. Paper I provides an insight into the methods used for analyzing climate variability in the study area, and presents the main findings about the consequences of climate variability on the local groundwater levels. This chapter also describes how remote sensing techniques can assist in generating hydrological information (e.g. estimation of evapotranspiration).
- The fourth chapter summarizes the performed hydrogeophysical activities in the study area. The most important results obtained in this chapter are the refinement of the hydrogeological conceptual model, and the proposal of a groundwater vulnerability assessment method. The latter is based on the geoelectrical results and the geomorphological information of the study area. Paper II and Paper III provide a detailed description of the geophysical methods used for characterizing the aquifer geometry and refining the conceptual model of the study area. Paper V presents a new methodology for assessing groundwater vulnerability, which is based on the geophysical results from Paper II and Paper III, and from additional geomorphological information.
- The fifth chapter is focused on the hydrochemical analysis, and how the results can be used for assessing the regional water quality, groundwater flow and recharge/discharge processes. This chapter also deals with the determination of the origin of saline water in the Quaternary deposits of the study area. Paper IV contains a detailed description of the methods used, the findings, and a comprehensive analysis of the occurrence of saline water in the study area.
- Finally, the sixth chapter summarizes the general conclusions of this research and suggests possible further research options.

2. THE PUNATA ALLUVIAL FAN

2.1. Study area description

The Punata alluvial fan is located in the central valleys of Bolivia (Figure 2), in the department of Cochabamba. The study area is surrounded by a mountainous massif, with peaks that can reach 3500 meter above sea level (m.a.s.l.), and is gently sloping from northeast to southwest. The areal extension of the Punata fan is around 90 km^2. The main water source in the region is groundwater, and approximately 80% of drinking water comes from wells. The sanitation infrastructure is deficient and almost 50% of sewage water is drained to creeks or streams, or into the subsoil from pit latrines. The main urban center is the Punata city in the middle of the fan. The assessment of water issues in the Punata fan cannot be analyzed without taking into consideration the upper neighboring Pucara basin (Figure 2). This basin is the northeast upper neighboring catchment, which drains the runoff from this basin through the Pucara river. The lakes in the highlands of the Pucara basin also discharge water to the Pucara river. The discharge zone of the Pucara river is at the apex of the Punata fan, and this might be the main groundwater recharge zone of the fan (Paper IV).

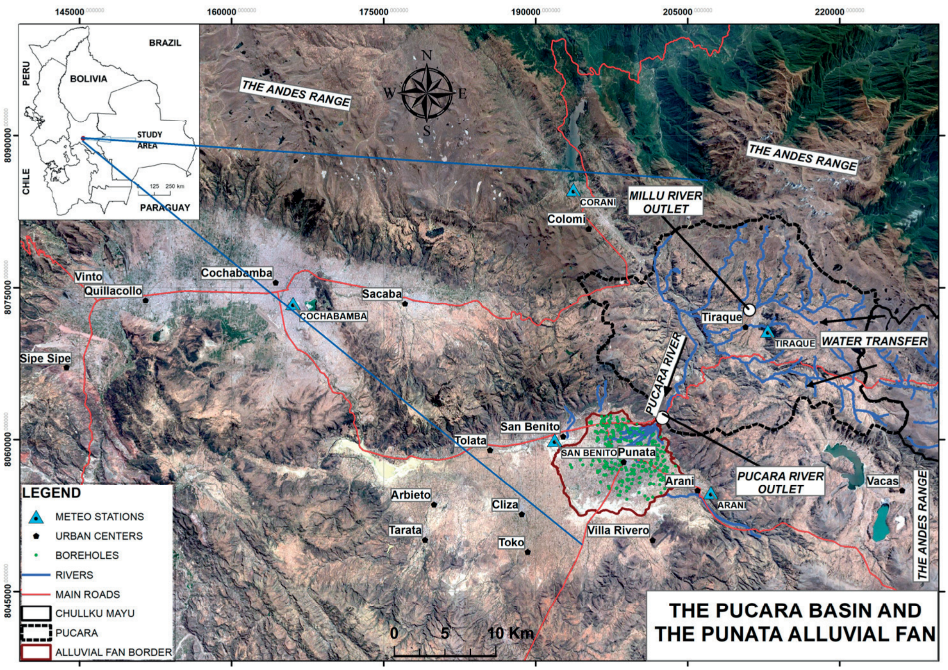

Figure 2 Location map of the Punata alluvial fan. The Pucara watershed, which is the northern neighboring basin, is also displayed together with the neighboring region of Cochabamba to the west, and Corani to the north.

2.2. Alluvial fans

Alluvial fans are geological units that can be of high importance for their regions due to the fact that they are often major groundwater reservoirs. The alluvial fan lands are also highly recommended for agricultural use (Bull, 1972). Alluvial fans are composed of mixed granular sediments formed by a mountain river or stream at the piedmont. Blissenbach (1954) suggested that the regions of alluvial fans are divided in four main zones (Figure 3):

- The apex of the fan develops at the point where the stream emerges from the mountain. It is the highest elevation point of alluvial fans.
- The head of the fan is the area closest to the apex.
- The mid part of the fan designates the area between the head of the fan and outer/lower margins of the fan.
- The distal part of the fan is the term applied to the outermost or lowest zone of the fan.

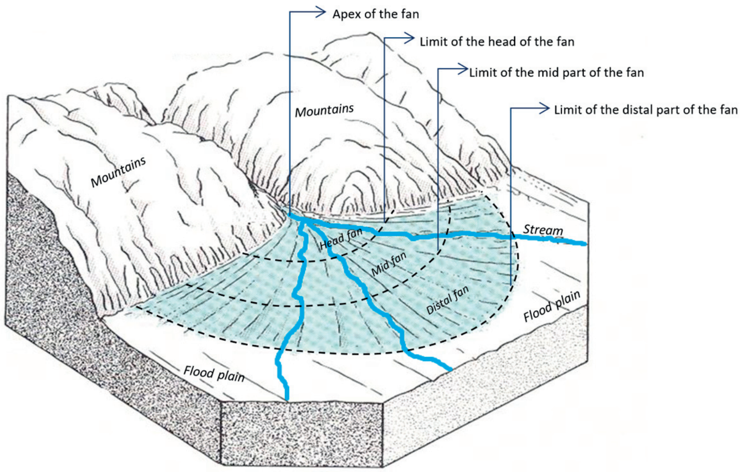

Figure 3 Parts of an alluvial fan. The colored part is the body of the alluvial fan mainly composed by detrital sediments. The highest point in the alluvial fan is the apex, while the lowest area is the distal part of the fan.

The sizes of the sediments in alluvial fan deposits might range from large diameters to very small diameters, i.e. from boulders to clay and silt (Blair and McPherson, 2009, Blissenbach, 1954, Bull, 1972). In the upper part (i.e. apex and fan head) material of larger diameter like boulders, cobbles and coarse gravels are most likely. In the mid fan, material of intermediate particle size is present, while in the distal part of the fan silt and clay are more likely. The sorting in an alluvial fan might vary widely, and in general the sorting may be a function of: the particle sizes of the detritus prepared for transport in a mountain area, the type of transporting and depositing agent, and the distance of transport.

2.3. Local geology

The regional geology is described by UNDP-GEOBOL (1978b), GEOBOL (1983) and May et al. (2011), refer to Figure 4. The basement of the study area is formed of Ordovician and Silurian rocks. The valleys are filled with unconsolidated sediments from the Quaternary; the main units are: fluvial, lacustrine, fluvio-lacustrine and colluvial-alluvial sediments. These units form terraces on riverbanks, beds and alluvial fans at the mouths of creeks and rivers. During the lower Pliocene, due to the uplift of the mountain massif, tectonic valleys and enclosed lakes were created. The weather in this period was predominately dry, and saline material with high clay content were deposited (UNDP-GEOBOL, 1978b).

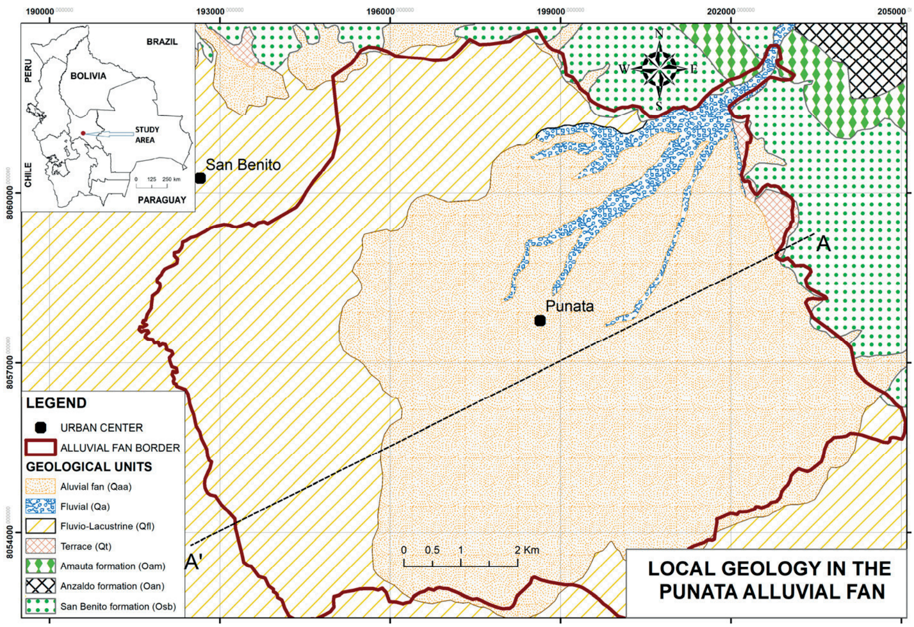

Figure 4 Regional geology map of the Punata alluvial fan.

The deposition of Quaternary sediments in the Punata alluvial fan is as follows: 1) In the apex and head of the fan, fluvial (Q_a) and terrace (Q_t) sediments were deposited. These deposits are mainly composed of coarse material, varying from boulders to sand. 2) The middle of the fan is a transitional zone from alluvial (Q_{aa}) to fluvio-lacustrine (Q_{fl}) deposits. The grain size of these deposits range from gravel to clay and silt. 3) The distal part of the fan is mainly composed of fluvio-lacustrine deposits (Q_{fl}). These deposits are mainly formed from clay and silt.

2.4. Socioeconomic value of the Punata alluvial fan

According to the National Institute of Statistics of Bolivia (INE, 2012) in 2012 the population in the Punata alluvial fan region was approximately 50000 inhabitants. Around 65% of the total population is dedicated to agriculture or related activities.

Natural hazards such as flooding and droughts, with the latter as the most likely to occur, affect drastically the welfare of the local population. In 2016 within the department of Cochabamba, 30 out of 47 municipalities were affected by droughts. In the Punata region around 700 families were affected and more than 2400 ha of crops were lost.

The losses in agricultural production affects dramatically not only local actors, but also have repercussions in important urban centers like Cochabamba and Santa Cruz cities. For instance, before 2016 a kilogram of potatoes had a price of approximately 0.4 USD, but after the drought the price was around 0.7 USD. The rise in the cost of living affects many low income families whit a monthly salary less than 300 USD (the minimum national salary in 2017 was around 285 USD).

2.5. Water law and regulations

Bolivia does not have an updated national water legislation, and the current Water Law was enacted in 1906, and it is outdated in terms of groundwater exploration, management and protection. The lack of water law leads to inefficient water management, with negative consequences such as over-exploitation of many aquifers. One clear example is the current situation in the Punata aquifers, where groundwater is over-exploited and drilling of new wells are done without any planning.

One aspect that must be pointed out, is that new laws and regulations should take into account the involvement of different stakeholders. This becomes more important in rural areas where villagers have ancient traditions for water use. For instance, in the Pucara system there are old agreements about who and how water can be used, and non-compliance might end in social conflicts. On the other hand, it is also important to include an adequate training of human and technical resources, which can guide the development of sustainable water management and protection plans.

3. HYDROMETEOROLOGY

3.1. Introduction

Bolivia has plenty of water, i.e. 303.5 km^3/year of internal renewable water (FAO, 2016); however it is not well distributed in time and space. The intra-annual and inter-annual variability in the hydrologic cycle makes it difficult to obtain an equal and sufficient water supply. In general, during the rainy season (December to March) around 80% of the annual precipitation takes place, while during the dry season (April to November) the precipitation rates are quite small. The eastern part of Bolivia has the highest annual precipitation rates, i.e. rates as high as 5000 mm. The western part of Bolivia is mainly arid with annual precipitation rates that can be as low as 100 mm. In addition to the unequal water distribution in Bolivia, climate change has caused severe problems during recent years. During 2015-2016 the second largest lake in Bolivia, Poopo lake, has dried up (Satgé et al., 2017, Allen, 2016). During these years the main cities of Bolivia suffered water supply shortages affecting more than 3 millions of inhabitants. In rural and urban areas conflicts between farmers and private water supply companies have increased (Wutich and Ragsdale, 2008, Olivera and Lewis, 2004). Consequently, it is important to monitor and measure hydrological variables, and to have a knowledge about climate variability in order to assess and evaluate possible water supply shortages. This consideration becomes more important in arid and semiarid zones, where water supply is scarce such as the Punata alluvial fan.

3.2. Methodology

The impacts of climate on the water resources of the Punata region was assessed through two different approaches. The first approach deals with the applicability of remote sensing for estimating daily values of actual evapotranspiration. The estimation of evapotranspiration is useful for assessing the crop water demand and therefore optimize the use of water for irrigation. The second approach for assessing the climate in the Punata region was performed by applying statistical methods for identifying patterns of climate variability in terms of precipitation. Changes in the precipitation rates are then compared to groundwater levels to evaluate possible correlations.

3.3. Remote sensing

In areas where meteorological data is scarce, information from remote sensing can play an important role. Thus this study used both remote sensing and gauged information to assess the climatic conditions in the Punata alluvial fan. Mapping of the actual evapotranspiration (AET) was performed with the Surface Energy Balance System (SEBS) algorithm developed by Su (2002). For this approach, satellite earth observation data were used in combination with meteorological information. Level 1B MODIS radiance and reflectance satellite images were used, with cloud-free sky conditions. The final spatial resolution of all the images were resampled at 1x1 km. For further complete concepts and equations refer to Su (2002), Rwasoka et al. (2011) and Elhag et al. (2011). The evaluation for the AET by SEBS was done by the logical consistence against the reference evapotranspiration (ET_o) by the FAO Penman–Monteith equation (Allen et al., 1998). If ET_o is assumed as the potential evapotranspiration (PET) (Xu and Singh, 2005), it would be expected that ET_o would be greater or at least equal to AET. A similar procedure was performed by Rwasoka et al. (2011) and Gonzales Amaya and Parodi (2010). Additionally, AET by SEBS was compared to the AET from the advection-aridity (AA) method (Brutsaert and Stricker, 1979), which has shown good results in arid environments.

3.4. Climate variability

The Quantile Perturbation Method (QPM) was used to determine decadal anomalies in extreme precipitation events. This method analyses the quantile frequency of a time series and perturbation factors (PF). The PF is the quantile relative magnitude based on a reference series (Tabari et al., 2014). The QPM can be used for analyzing changes in time series values for a particular period, which can be understood as the calculation of anomalies in extreme value of quantiles between full time series. Figure 5 shows the steps for the estimation of the PF and has been well explained by many authors, e.g. Ntegeka and Willems (2008), Mora and Willems (2012), and Tabari et al. (2014). The steps are:

1. The first step is the generation of block periods with a length of 'L' years from the reference series.
2. The yearly values for each block period are ordered from the highest to the lowest value, where 'i' is the rank order.
3. Then the empirical return periods are estimated as the ratio of the block period length and the rank of each year.
4. The yearly values that correspond to each return period represent the quantiles. Steps 1 and 3 are repeated for the baseline series.
5. Finally, the PF is estimated as the ratio of a respective value in the block period to that in the baseline series with the same return period.

The empirical return periods of the baseline and block period series do not necessary coincide, therefore the values of '$X_N(T_L)$' can be estimated from a linear interpolation from the values with closest empirical return periods (Mora and Willems, 2012). Finally, from the PF of all the years an average value is calculated for all the quantiles.

These average PFs represents anomalies in the quantiles. In this study, the anomalies were estimated for each block period of 12 years moved with a time step of one year.

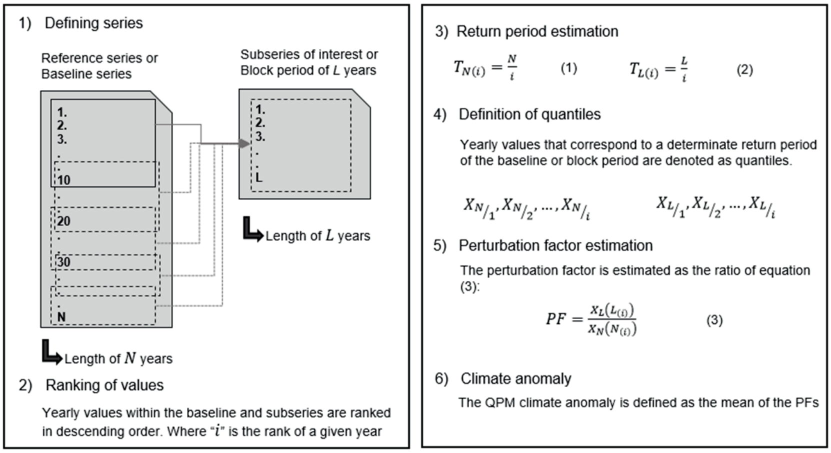

Figure 5 Main steps for estimating the perturbation factor in the Quantile perturbation Method. Modified from Gonzales Amaya et al. (2018d).

The significance of the PF in the extreme quantiles were determined by using the bootstrapping method which uses the Monte Carlo confidence intervals (Moges et al., 2014, Tabari et al., 2014). This method randomly generates samples for each block period using the empirical data. The PF values between the upper and lower confidence interval limits, which is the area where the null hypothesis of no temporal dependency is true, are considered insignificant. The PF values outside the region of acceptance of the null hypothesis are defined as statistically significant. The calculation of the confidence intervals is made by randomly resampling the values of the full series generating a new sequence. Then anomalies from this new series are estimated with the QPM method. The calculation of these anomalies is repeated 1000 times generating for each block period a total of 1000 anomalies. Then these anomalies are ranked, and the 25th and 975th values define the 95% confidence interval for each period (Tabari et al., 2014, Moges et al., 2014, Taye and Willems, 2012).

3.5. Results and discussion

In the highlands of the study area (i.e. Pucara basin) the average annual precipitation is around 500 mm, while in the lowlands (Punata fan) the climate is semiarid with an average annual precipitation slightly higher than 300 mm. Therefore, more priority was given to the lowlands, where evaporation was monitored daily. This research has monitored the daily evaporation in two "class A" evaporation pans (Hargreaves and Samani, 1982) located in Punata and Arbieto (Figure 2). The measured evaporations were converted to ET_o, and the measurement period was from June to September 2017.

Figure 6.a and b shows the daily estimation of AET by SEBS and AA methods, and ET_o from class A pan and Penman-Monteith equation. Values of ET_o are consistently higher than the ones of AET, which is coherent since these were assumed as the PET.

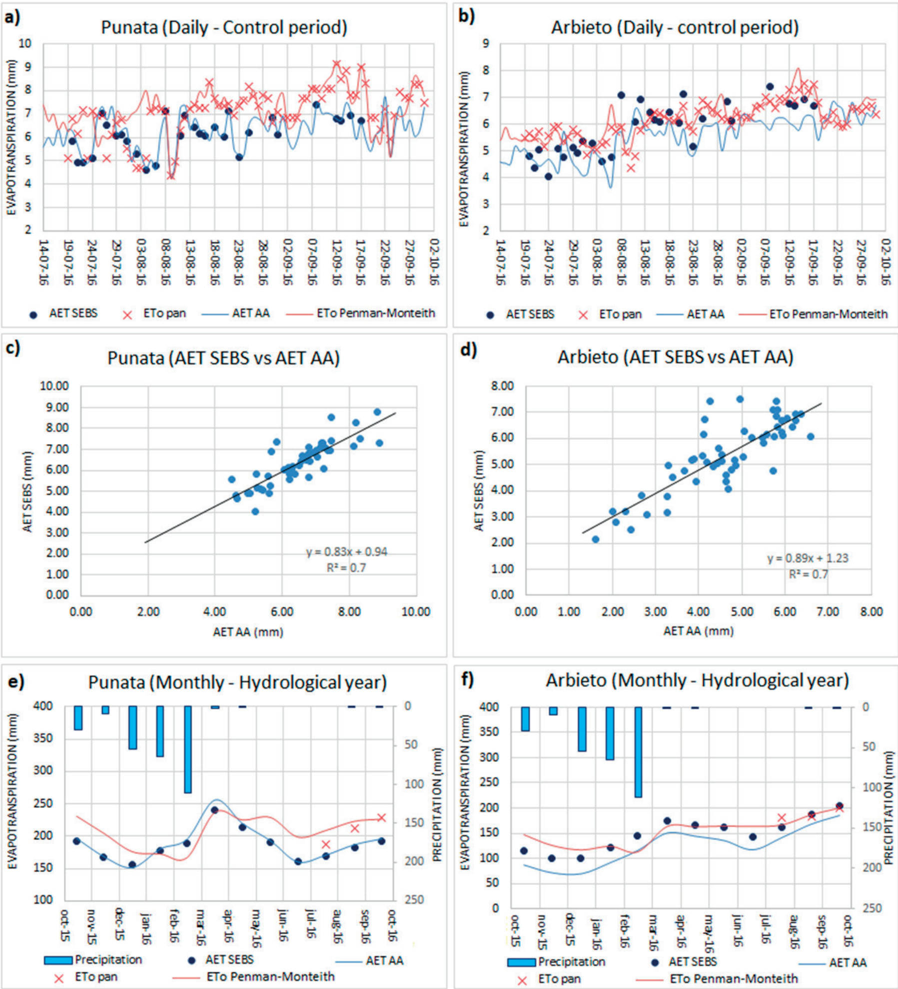

Figure 6 Estimation of evapotranspiration values, where a) and b) are the daily values of evapotranspiration, b) and c) display the linear correlation between the AET from SEBS and AA methods, and e) and f) are the monthly evapotranspirtaion values, for Punata and Arbieto locations, respectivly.

The estimations of AET values from both methods seem to be correlated (Figure 6.c and d), which might suggest that the real values are approximately those calculated in this research. Values of AET by SEBS are on average higher than the estimates from the AA method, and both of them have the same trend, always being smaller than ET_o values. When the results of AET are aggregated in monthly time steps (Figure 6.e and

f) the AET values from SEBS tend to be closer to the estimates of AET from the evaporation pan class A (ETpan), with differences ranging from 6.9 to 15.5 mm/month, which in a monthly time-step are small differences. Since ET_o from class A pan is derived from in-situ measurements it can be assumed that results of AET from SEBS are acceptable. The advantage of AET estimations from SEBS is that it is possible to have the spatial distribution of the values of AET, which together with other spatial information, such as precipitation, can be used for assessment of various water issues.

In Paper I the results of climate variability are well explained, and the influence of the Southern Oscillation Index (SOI) in the Pucara system is analyzed. The results suggested that there is an oscillation between each strong event of El Niño and La Niña approximately every 20 years (refer to Figure 7.a). La Niña events are odd numbered, while the El Niño events are even numbered. Based in this oscillation it might be suggested that stronger events of El Niño will take place in the coming years. As an example Figure 7.a shows that one event of El Niño took place on the years 2015-2016, and as a consequence, strong droughts occurred in the Andes and Sub-Andes of Bolivia (Satgé et al., 2017) during those years. The SOI might be used for planning future scenarios of climate variability, therefore the local precipitation in the study area was compared to the SOI oscillation (refer to Figure 7.b and c). Stations located at higher altitudes (i.e. the Andean region) and very close to the Amazon basin, where the weather is more humid, showed strongest influence to the positive phase of the SOI which is related to La Niña events (Figure 7.b). On the other hand, stations at lower altitudes (i.e. sub-Andean valleys), where the weather is warmer and dry, showed strongest influence from the negative phase of the SOI which is related to El Niño events (Figure 7.c). Some studies (Miranda, 1998, Villazon, 2015) reported that, in the region of the study area, events of El Niño and La Niña are related to dry and rainy years, respectively. Therefore, it can be suggested that rainfall in the study area is temporally and spatially correlated with SOI. These correlations might help in assessing possible drought scenarios which might affect the socioeconomic activities based on water usage (i.e. agriculture and drinking water access) in the Punata region.

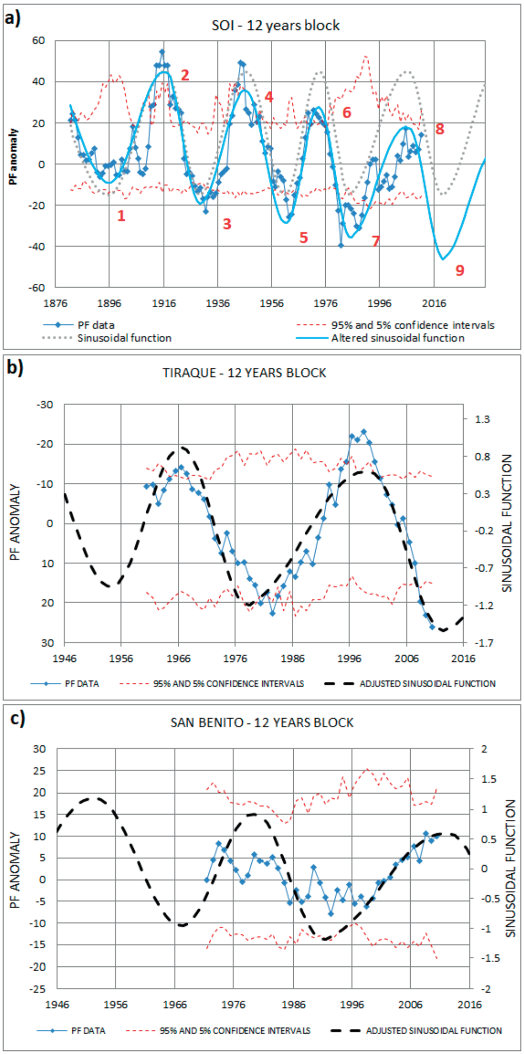

Figure 7 a) Variability of the SOI after applying the QPM approach. b) and c) Climate variability in terms of precipitation with an adjusted SOI sinusoidal function, for Tiraque and San Benito stations, respectively. Modified from Gonzales Amaya et al. (2018d).

Paper IV suggests that the main groundwater recharge source in the Punata region is the infiltration of flash floods from the Pucara river, and to a lesser extent, the Pocoata river. These flash floods occur when heavy precipitation events take place, therefore scenarios raised in Paper I, like El Niño events (i.e. drought years), can affect the rate of recharge in the Punata aquifer. Figure 8 shows two examples of water level oscillations, precipitation rates and the average water table during the year 1998.

Figure 8.a displays the water level records during the years 2011-2012 and it is observed that after the rainy season the water level increases and almost reached the water table of 1998. After the rainy season, the flows in Pucara and Pocoata rivers decrease and therefore the groundwater recharge also decreases, which, together with the extensive pumping from wells, decreases the water levels. Figure 8.b displays the water level records during the years 2015-2016, and it can be observed that after the rainy season the water levels did not increase as much as in the years 2011-2012, and also that the water table is situated at a lower level than in 1998. This might be explained by the fact that in these years an El Niño event took place and therefore the precipitation rates were lower and affected the river flow rates. Other reasons might be due to the fact that the number of wells increased dramatically during recent years, and this suggests that the groundwater extraction rates have now probably equalled or exceeded the groundwater recharge rate.

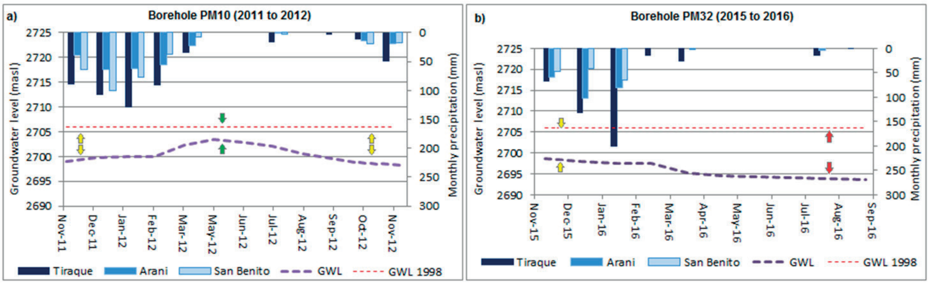

Figure 8 a) and b) Water table oscillation during years 2011-2012 and 2015-2016, respectively. It is also displayed the precipitation rates and the water level (GWL) from the year 1998. Modified from Gonzales Amaya et al. (2018d).

3.6. Conclusions

The results showed that remote sensing can be an important approach for estimating some hydrological variables within basins which are neither gauged nor monitored. The estimation of ET from remote sensing yielded good results when compared with other methods which use in-situ input variables. Hence, the estimation of actual evapotranspiration from remote sensing can be used for assessing the water crop requirements, and therefore it is useful for optimizing the groundwater extraction in the study area.

The assessment of climate variability in Paper I suggested that extreme SOI conditions might influence the precipitation regime of the study area. Positive SOI values are related to local events of La Niña, while negative values are related to El Niño events and also to dry periods. From this correlation possible future scenarios can be assessed, which is important for the study area since the Punata groundwater recharge relies on the infiltration from the local river flows, which are directly affected by the precipitation rates (i.e. dry and wet periods). For instance, the observation of groundwater levels highlight that in the recent years (i.e. 2015-2016) the levels tend to decrease and this might be due to two main reasons. The first one is that during those years an El Niño event took place (according to the SOI oscillation analysis), which has led to diminished groundwater recharge. A second reason might be due to the fact that several boreholes were drilled in recent years, which has led to increased groundwater extraction, maybe greater than the recharge rate.

Hence, analysis of trends in climate variability can be used for planning more efficient usage of groundwater and surface water in scenarios where water scarcity is a hazard (i.e. droughts). In addition, the estimation of hydrological variables is of high importance when water budgets and estimation of water irrigation volumes are needed. In conclusion, both assessment of climate variability trends and estimation of hydrological characteristics (e.g. actual evapotranspiration) are of interest when sustainable management plans are outlined. Such plans should result in a more efficient use of water, which can assist towards water security.

4. HYDROGEOPHYSICS

4.1. Introduction

A wide range of human activities are based on adequate access to soil and water. For instance, agricultural activities use about 80% of the world's fresh water (Vereecken et al., 2006). Hence, groundwater becomes extremely important because it sustains the irrigation for food production in many regions of the world. However nowadays the intensive irrigation in some regions is leading to problems, such as depletion of aquifers, soil salinization, percolation of nutrients and pesticides, and soil subsidence. Therefore it is important to improve the knowledge about the subsoil and aquifer systems. Direct methods such as drilling provide information about physical and hydrogeological properties; however these methods can be very time demanding and expensive. A combination of geophysical methods may be a suitable mean for retrieving underground information, since they are less time consuming and cheaper to perform than drilling.

Surface geophysical methods have the advantage of being non-invasive and able to map relatively large areas in comparison with direct methods. Geophysics may assist in mapping geological features such as fractures, bedrock, or gravel/sand/clay layers, which later can be used for the delineation of aquifer boundaries. Geophysical methods can be used in environmental problems for monitoring leaching of pollutants or plumes, water infiltration, or saline water delimitation.

In general, geophysical methods remotely retrieve information about physical properties of the subsurface of the Earth. For instance, passive methods measure changes and variations in gravity or magnetic fields, while active methods retrieve information on electrical conductivity/resistivity, density, elasticity, or permittivity. Then these physical properties might later be interpreted as different geological materials or features. The use of complementary ground truth information (e.g. geological maps or drilling reports) is necessary for an adequate interpretation of the geophysical measurements.

4.2. Methodology

One of the aims of this research is to improve the understanding of the geometry of the aquifer system in the Punata alluvial fan. The use of geophysics might offer spatially distributed models of physical properties with more details compared to models derived from direct methods such as pump tests or measuring of hydraulic heads (Vereecken et al., 2006). Geoelectrical methods are near surface geophysical techniques for engineering and environmental applications and have been used by many authors in a wide variety of applications (Guérin et al., 2001, Koch et al., 2012, Lesmes and Friedman, 2005, Lima and Niwas, 2000, Magnusson et al., 2010, Niwas et al., 2011, Revil et al., 2015).

This study applied different methods: Electrical Resistivity Tomography (ERT), Induced Polarization (IP), and Transient Electromagnetics (TEM). Paper II describes that ERT was primarily used for mapping the geometry of the Punata aquifer system, and IP was used during the ERT interpretation for solving ambiguities. Paper III recapitulates that in order to retrieve more information from deeper levels the TEM method was used, however due to lithological conditions the depth of penetration of this method was restricted to around 200 m. Nevertheless, TEM was useful for delimiting a previously non-detected saline water zone.

Figure 9 shows the locations of the performed surveys. More than 30 km of ERT were conducted together with IP. These surveys were performed close to boreholes with lithological information. A total of 128 TEM soundings were performed in two different areas: Area 1 (A1) which is close to the apex of the fan, and Area 2 (A2) which is located in the western distal part of the fan. Besides these surveys, archive information was gathered, and a total of 16 resistivity borehole loggings were included to assess the resistivity from ERT and TEM. Finally, information was collected from 60 drilling reports from boreholes with lithological descriptions.

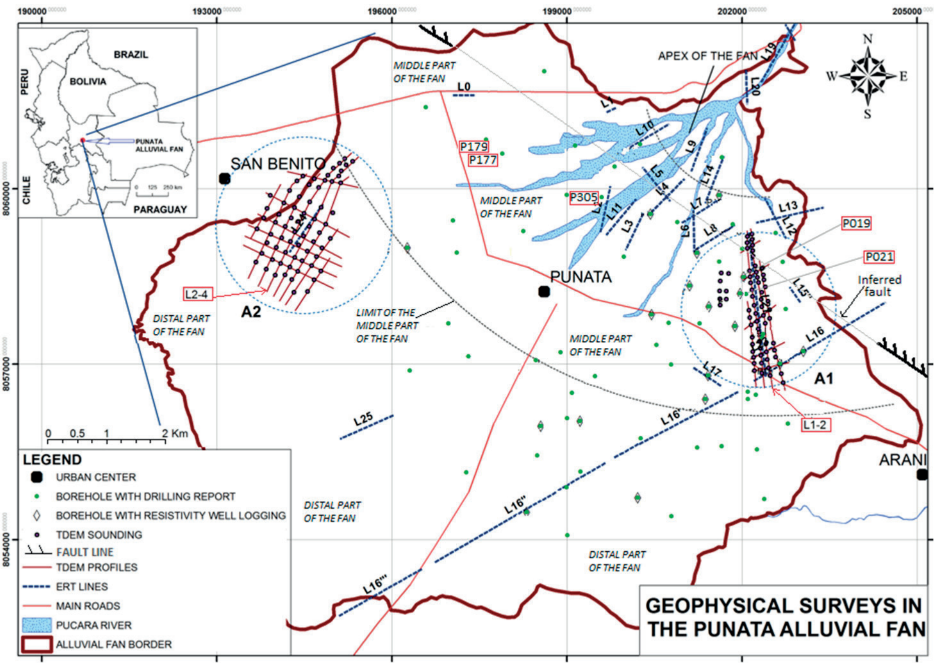

Figure 9 Locations of all the geophysical surveys performed, and archive information gathered in the Punata alluvial fan. Modified from Gonzales Amaya et al. (2018c).

4.2.1. Electrical Resistivity Tomography

The ERT is a geoelectrical method that is essentially several continuous 1D direct current (DC) surveys. The basic principle of this method (Figure 10.a) is that DC is injected to the ground through a pair of electrodes (A and B), where the current intensity (I) is known. Then the potential difference (ΔV) between a pair of electrodes (M and N) fixed at the ground surface is measured. The apparent electrical resistivity (i.e. bulk or effective resistivity) is calculated taken into consideration the geometry of the electrodes. This process is repeated several times with different electrode configurations, allowing the user to generate a spatial model of electrical resistivity distribution of the subsurface (Figure 10.b). The calculated resistivity is also known as apparent resistivity and is based on the assumption of a homogenous medium; however geological media are not generally homogeneous. Therefore, the estimation of the true resistivity distribution is done by an inverse numerical modeling process (inversion). The inversion process creates a model based on the apparent resistivity data. The inversion adjusts a finite difference or finite element model in an iterative process by comparing the measured apparent resistivity versus the calculated resistivity from the inverted model (Dahlin, 2001, Loke and Dahlin, 2002, Loke and Lane Jr, 2004, Reynolds, 2011).

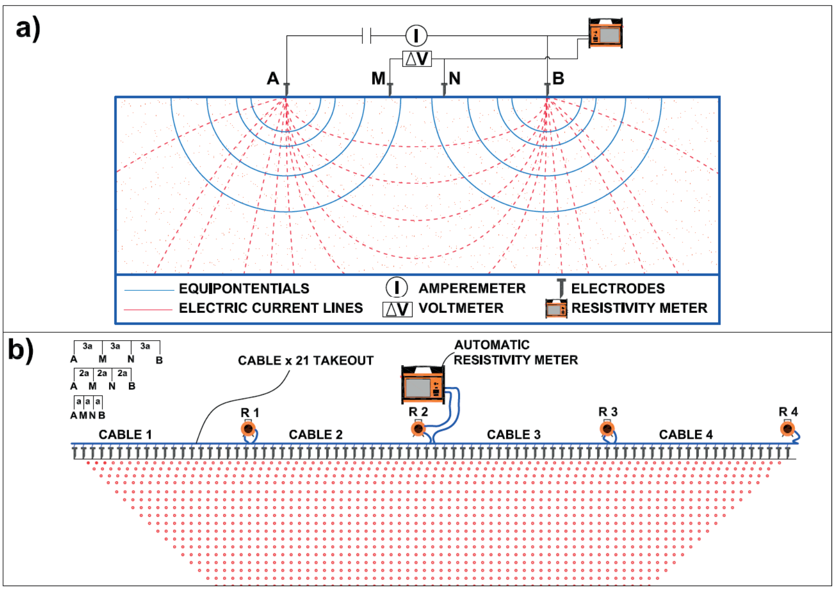

Figure 10 a) Principle of Geoelectrical resistivity surveying. b) Schematic positioning of Electrical Resistivity Tomography.

The surveys in the Punata alluvial fans were performed mainly with a maximum electrode separation of 10 m, using four reels of 200 m each. With this configuration a total spread length of 800 m between the outermost electrodes was reached. When conditions allowed, the roll-along technique was applied for getting longer continuous profiles. The Multiple Gradient array was used; this array has proved to be suitable for multi-channel data acquisition providing a significant increase in the velocity of data acquisition and giving a higher density of data points (Dahlin and Zhou, 2004, Dahlin and Zhou, 2006). The current transmitted in each survey depended on the ground conditions (electrode to ground contact resistance) and they varied from 5 to 200 mA. The selection of the ERT locations was predominately planned according to the availability of areas free of obstacles such as houses, fences, crops, and paved roads; another problem confronted was getting the permission of land owners to perform the surveys in their lands.

The collected field data were quality checked using visual tools such as pseudo-section plots and multi profile plots. Data were inverted using RES2DINV, version 4.02.02. The Robust Inversion (L1-norm) option was used as it is less sensitive to noisy data. For the model discretization, a setup of the model refinement with cell widths of half the unit spacing was used. For the damping parameter option, a vertical/horizontal flatness ratio of 0.25 was used, since the subsoil layers in the Punata alluvial fan tend to be predominantly horizontal, hence low values for this filter are advised. In addition to ERT surveys, data from drilling reports and geophysical borehole loggings were used in order to validate and interpret ERT results. This was done for ERT sections sufficiently close to (or at) the borehole logging points.

4.2.2. Induced Polarization

The IP effect is a measure of the soil's ability to be polarized when it is under the influence of an electric field; in other words, it means that during the polarization the energy is stored reversibly in the soil. For this research, the measurements of IP were carried out in the time domain approach. Time-Domain IP (TDIP) surveys are carried out by transmitting current into the ground (Figure 11.a) while potential difference is measured to determinate the resistivity. After the current is turned off, the potential decay in the ground is measured again in one or several intervals of time windows (Figure 11.b). The used software and inversion process for IP parameters were the same as for the ERT data.

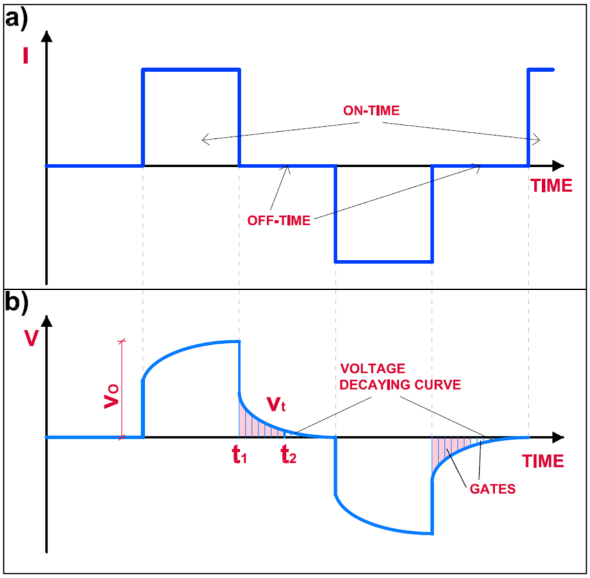

Figure 11 Time Domain Induced Polarization measurement. a) Current injection and alternation of time-on and time off. b) Gating of the voltage decaying curve.

A common parameter used to quantify TDIP measurements is the chargeability, which is expressed as the ratio of the measured voltage during the off-time over the measured voltage during the on-time. In other words, the measured parameter in the TDIP, is defined as the ratio of the secondary potential, i.e. 'V_t' area under the decay curve at different time intervals 't_1' and 't_2' (refer to Figure 11.b), divided by the primary potential of the transmitted current 'V_O' (Slater and Lesmes, 2002). The timing setup used for the ERT and IP surveys in this study applied a current-on of 1 s (with an acquisition delay time of 0.4 s and an acquisition time of 0.6 s) and a current-off of 1 s. The IP delay time was set on 10 ms. A total of eight time windows were measured, where each window time is a multiple period time of 20 ms in order to suppress any power line noise.

4.2.3. Transient Electromagnetics

The principle of the TEM method is that a controlled current is transmitted in a cable loop and alternately turned on and off (Figure 12.a). The induced current will produce a primary magnetic field. When changes occur in the magnitude of magnetic field an electromotive force (emf) is induced (Figure 12.b). The propagation of the emf into the ground will induce eddy currents (Figure 12.d), which at the same time produce a secondary magnetic field (Figure 12.c). The secondary magnetic field amplitude decreases with time and depends on the ground resistivity. Soils with high resistivity will yield magnetic fields with high initial amplitudes and quick decays; while soils with low resistivity will have an opposite behaviour (Christiansen et al., 2009, Guérin et al., 2001, Fitterman and Stewart, 1986).

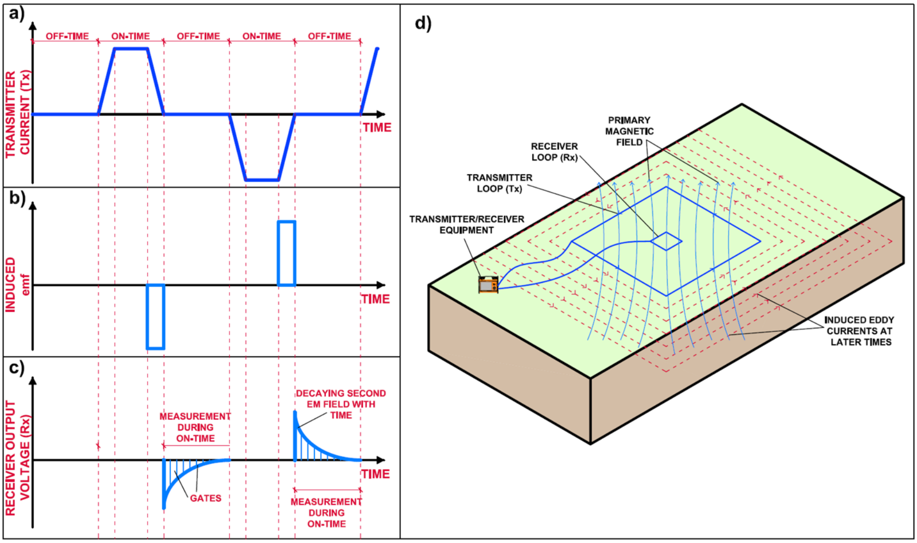

Figure 12 a) Transmitter wave form. b) Induced electromotive forces after the primary magnetic field. c) Receiver wave forms. d) Schematic TEM field setup.

Figure 12.d displays the most common way for retrieving TEM data, which is by placing a square transmitter coil on the ground. After the electrical current is induced, the secondary magnetic field (b) is measured by a receiver coil. These measurements are conducted in discrete time intervals (db/dt) after transmitted current termination. With longer acquisition time (i.e. late gates) information from deeper formations is retrieved, while with the early times (i.e. early gates) information of layers close to the surface is retrieved (Christiansen et al., 2009, Mills et al., 1988). According to many authors, e.g. Christiansen et al. (2009), Vereecken et al. (2006), and Fitterman and Stewart (1986), the depth of penetration in the TEM method might be affected by three factors: the resistivity of the different geological formations, the intensity of the background noise, and the moment of the transmitter. Hence the only practical way for increasing the depth of penetration is often by increasing the moment of the transmitter.

A central loop layout was used in the Punata alluvial fan. The transmitter loop was 50x50 m, while the two central receiver coils were 0.5x0.5 m (RC-5), and 10x10 m (RC-200). Both receiver antennas measure the high moments (HM) and the low moments (LM). The HM allows one to retrieve information from deeper levels with poor resolution near to the surface, while the LM allows one to retrieve information with good resolution in shallower levels, but with a poor depth of penetration.

The data quality was assessed using visual tools such as plots of the stacked data of the time derivate of the magnetic flux magnetic field (db/dt) as a function of time, where it is easier to assess when data drowns in background noise. The inversion of the TEM soundings was done in the SPIA version 2.1.3, and the interpolation and creation of two dimensional profiles was performed in Workbench version 5.2.2. Each sounding was inverted by selecting the LM from RC-5 and the HM from RC-200.

4.2.4. Groundwater vulnerability

There are several methods for assessing the groundwater vulnerability to contaminants. However most of these methods rely on the input of several hydrogeological parameters. For instance, the DRASTIC method (Aller et al., 1987), which is one of the most used methods, uses seven parameters for describing the groundwater vulnerability. In some regions of the world, e.g. developing countries, gathering several hydrogeological parameters might result in a time demanding and consuming task due to the possible lack of available information. Therefore this research proposed an alternative method which uses fairly accessible techniques for acquiring hydrogeological input parameters, and then assess groundwater vulnerability in alluvial fan environments.

The proposed method was named EDIT, and it uses information from geoElectrical surveys (‘E’), Depth to water table (‘D’), description of the Infiltration conditions (‘I’), and the terrain slope derived from Topography (‘T’). Geoelectrical surveys are useful for mapping the subsurface electrical distribution, and the description of large areas can be covered in relative short time when compared to conventional methods such as drilling. Information about the water table depth can be obtained from hydrological maps, or by measuring it with a manual probe (if boreholes are available). The infiltration condition is assessed from a qualitative approach, where it is considered the description of the different parts of an alluvial fan and the local geology. Finally, for deriving the terrain slope information from Digital Elevation Models, which are available for free from online sources, e.g. Tachikawa et al. (2011) or Farr et al. (2007), can be used.

The EDIT index is defined by Equation 1, where the subscripts ‘w’ and ‘r’ are the weights and ranks, respectively, assigned to each parameter. For more information about the method refer to Paper V.

$$EDIT = E_w E_r + D_w D_r + I_w I_r + T_w T_r \qquad \text{Equation 1}$$

4.3. Results and discussion

Figure 13 shows how the ERT results (profiles of subsoil resistivity) were hydrogeologicaly interpreted with assistance of lithology logs. The maximum depth of investigation (DOI) with respect to ERT surveys was approximately 150 m depth, which depended on the layout of the surveys (i.e. a separation of 800 m between the outermost electrodes).

Figure 13.a displays the typical resistivity distribution in the ERT results, which is also discussed in Paper II. The top layers have high resistivity values ranging from 50 to 200 Ωm. These high values were correlated to coarse material such as boulders, gravel and sand. The coarse material is likely to have been deposited by flash floods from Pucara river and other smaller streams. The resistivity values decrease with depth, and a low resistivity layer of approximately 10 Ωm was delimited at the bottom of all the resistivity profiles. This bottom layer was interpreted as a high clay content unit, and becomes a no-flow boundary of the aquifer system. The high clay content might be explained by the deposition of sediments from former paleolakes during the Pliocene (GEOBOL, 1983, UNDP-GEOBOL, 1978a). The thickness of the coarse layer varies from 80 m in the head of the fan to 10 m in middle part of the fan, and due to the high primary porosity, it becomes the most important aquifer unit in terms of groundwater storage and extraction.

Figure 13.b shows the typical normalized chargeability results, which is also discussed in Paper II. Contrary to the resistivity distribution, high values were located at the bottom of profiles, while lower values were found on the top layers. Many authors (Revil et al., 2015, Revil and Florsch, 2010, Weller et al., 2013) suggest that the normalized chargeability can depend on clay properties (i.e. mineralogy and content), but the results may also vary according to the grain size distribution. Koch et al. (2012) suggest that normalized chargeability values are lower when uniform particle sizes of sand and gravel are present, whereas for fine grain size distribution, such as clay, the values are greater. This contrast in the values of normalized chargeability assisted during the interpretation process in clarifying the differences between areas with high clay content: i.e. high values of normalized chargeability at the bottom of profiles, and coarse material: i.e. low values of normalized chargeability at the top of profiles.

Figure 13.c displays the given hydrogeological interpretation. In general, in the Punata alluvial fan, unconfined aquifers are mainly composed of coarse material, which has a good primary porosity, and thus, groundwater storage capacity. Paper II concludes that semiconfined units are formed by gravel in a matrix of sand and clay, and generally are located in the middle to the distal part of the fan. Confined units are composed of sand, clay and silt, and generally boreholes at that depth have very low yield. Finally, aquiclude units are the confining bottom layer of the aquifer system, composed of high clay and silt content.

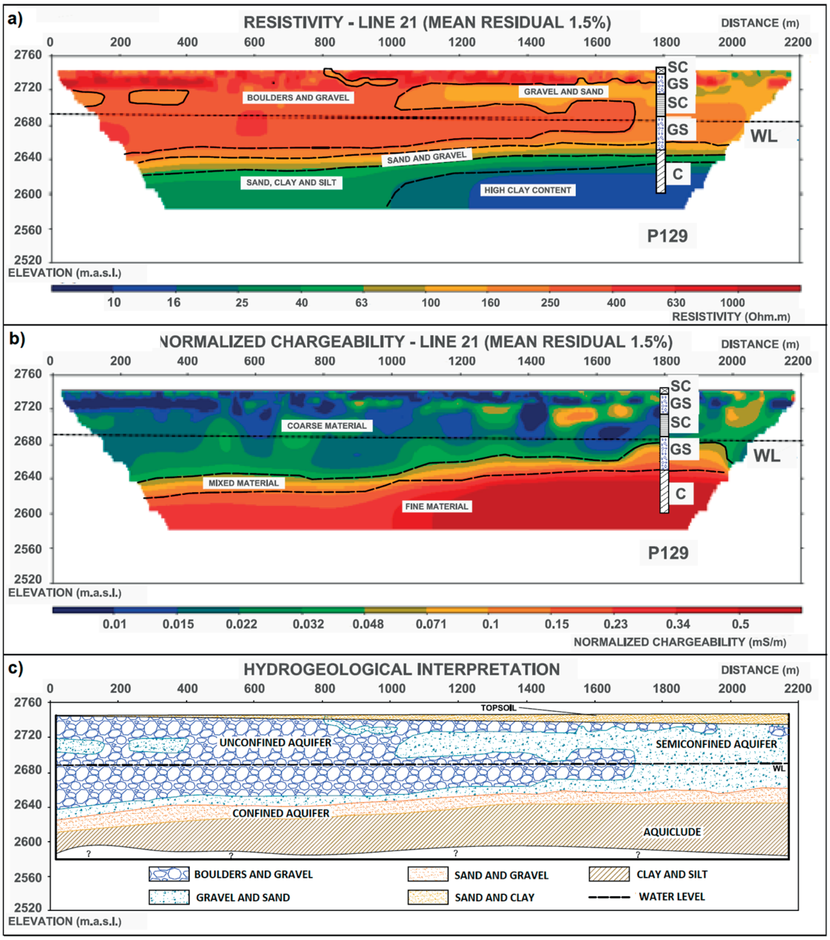

Figure 13 Example on how the ERT results (a) and normalized chargeability (b) were interpreted (c) with assistance of lithology logs.

Paper II demonstrated that the ERT results allowed refinement of previous hydrogeological conceptual models. Figure 14 shows the final refined conceptual model, however, even though this model shows more reliable information in terms of layering, lateral variation and thickness of layers, there are still some uncertainties to be answered. For instance, it is still needed to delimit the depth to bedrock and define the thickness of the bottom high clay content layer. In order to address this lack of information the TEM method was used due to the fact it might get more information from deeper levels.

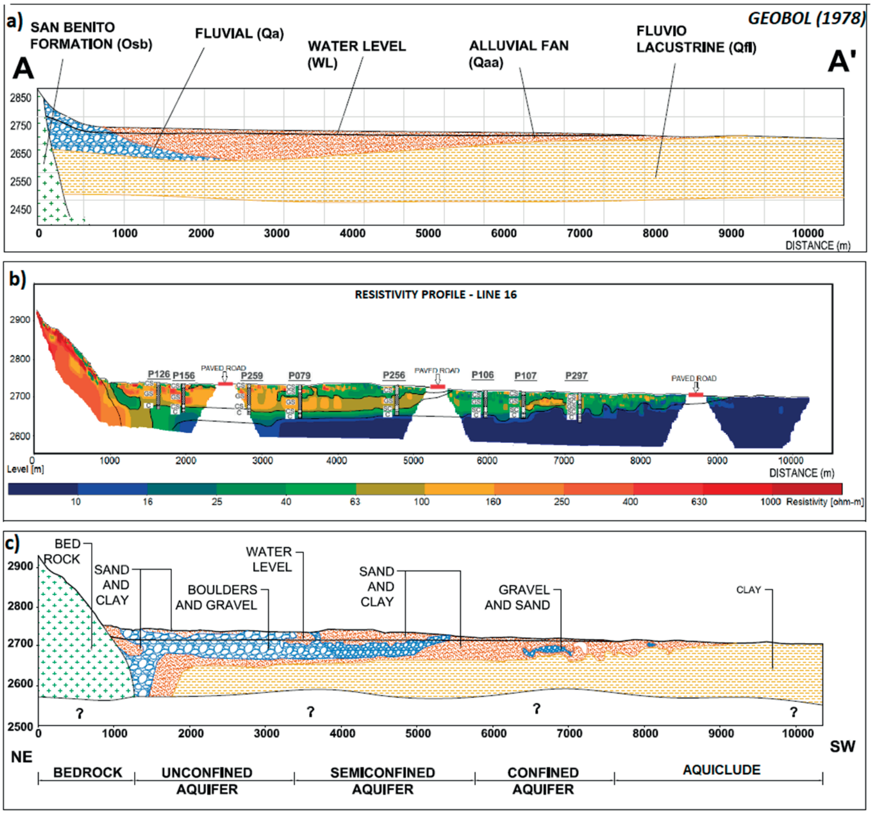

Figure 14 a) Refinement of the hydrogeological conceptual model from UNDP-GEOBOL (1978b). b) Resistivity distribution along the former conceptual model. c) Refinement of the hydrogeological conceptual model. From Gonzales Amaya et al. (2016).

In order to assess the performance of the geophysical results several comparisons between the results of each method were performed. Figure 15 displays two examples of how the resistivity values from TEM were compared against the resistivity values from ERT and resistivity from borehole loggings. The curves showed a good agreement between each other, showing higher resistivity values on top and decreasing values with depth. The normalized chargeability curve is also included, which as explained above, shows an inverse trend to the resistivity values: a trend of increasing values with depth. The DOI of TEM soundings was around 200 m, which was restricted by the bottom layer with high clay content which has dissipated the signals from TEM soundings. However, TEM sounding assisted in identifying an anomalous layer with very low resistivity values. In both soundings of Figure 15 it is displayed that approximately between 120 and 140 m depth the resistivity values ranged from 0.1 to 10 Ωm. Paper III describes that this zone with low resistivity values is interpreted as saline water and might be associated with the result of the mixing of fresh water with residual saline pore water in the high clay content bottom layer, and/or ion exchange within this layer (also discussed in Paper IV).

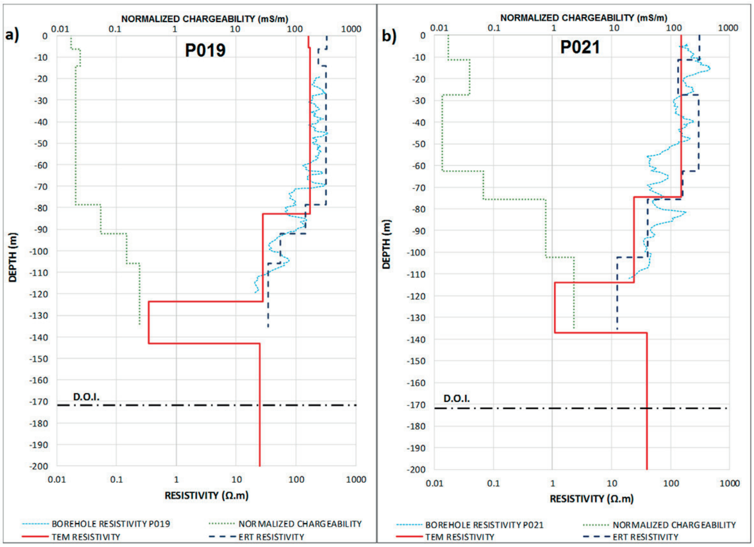

Figure 15 a) and b) Comparison of resistivity values from ERT, TEM, and resistivity borehole logging within the boreholes P019 and P021, respectively (refer to Figure 9 for locations). Also the values of normalized chargeability are plotted.

Although the TEM method did not retrieve information about the depth to bedrock nor the thickness of the high clay content layer, the TEM surveys yielded important complementary information. For instance, Figure 16 displays the geometrical distribution of the saline water in terms of depth, lateral variation and thickness. Figure 16 shows the resistivity distribution, and it can be seen that the saline water resistivity values are around 0.5 to 1 Ωm in A1, and values as low as 0.1 Ωm in A2 (refer to Figure 9 for locations). Paper III and IV discuss that the difference in values might be due to the fact that A2 is closer to the distal part of the fan, and longer groundwater residence time has led to more Na^+ and Cl^- enriched waters. An increase in the concentration of ions might decrease the resistivity values. Furthermore, in the bottom of the northern part of Figure 16.a there is an abnormally high resistivity zone. This zone is converse to what was expected: the bottom layer is dominated by clay, and therefore low values of resistivity. Hence, in order to explain these values, Paper III suggested that there is a fault which intersects and displaces the high clay content bottom layer. This hypothesis might be of interest, since if it is bedrock protruding with secondary porosity, there might be groundwater stored within the fractures. Figure 16 shows the interpretation of the results as 3D schemes of hydrogeological conceptual models, which might enhance the knowledge about the local aquifer system.

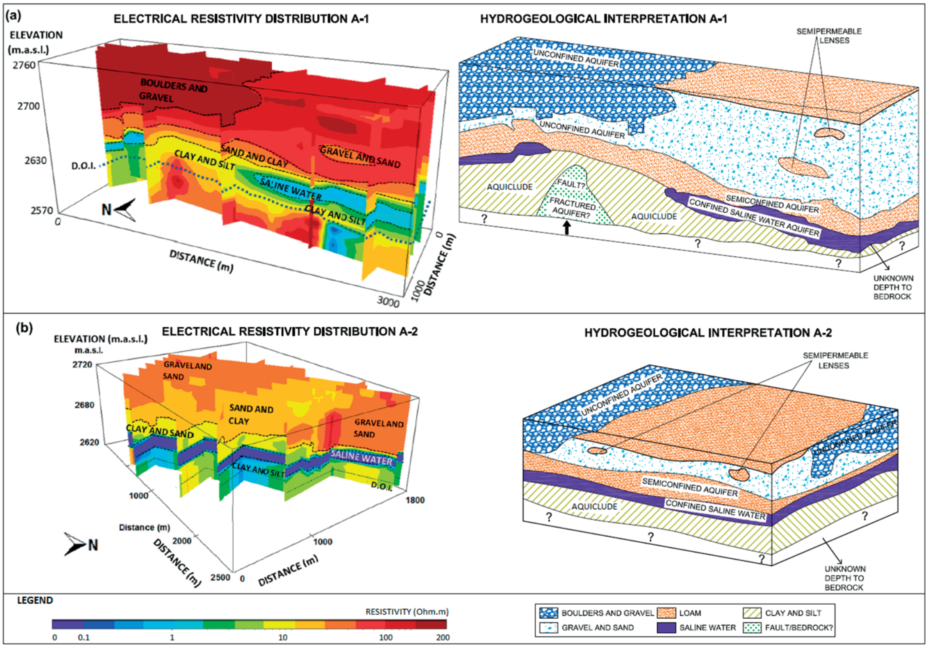

Figure 16 Electrical resistivity distribution in 3D schemes and their hydrogeological interpretation. a) and b) are located in areas A1 and A2 respectively (refer to Figure 9 for locations). From Gonzales Amaya et al. (2018a).

The geophysical surveys were key methods for acquiring the electrical resistivity distribution to use in the EDIT method (Paper V) for assessing groundwater vulnerability. Figure 17 shows the comparison between the EDIT method and the DRASTIC method. A good agreement between each method can be observed, where areas close to the rivers are marked with high values (i.e. potentially vulnerable areas). However, the EDIT method shows a smoother transition between different areas, which is more in line with what is expected. This smooth transition is due to the fact that geophysical surveys have the capability to map the subsurface with considerable high spatial relation (it depends on the survey layout). Moreover, EDIT yielded less vulnerable areas, and that might be due to the fact that the E parameter is taking into consideration the accumulated clay thickness above the aquifer.

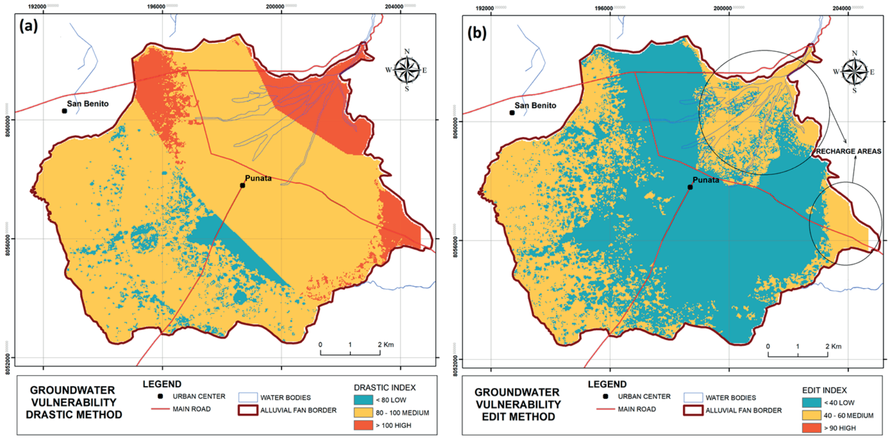

Figure 17 a) and b) DRASTIC and EDIT indexes for groundwater vulnerability classification, respectively, in the Punata alluvial fan. From Gonzales Amaya et al. (2018b).

4.4. Conclusions

Geophysical methods can play an important role when water security is addressed (refer to Figure 1: dimension of hydrogeological environment) since it can provide valuable information for refining or proposing hydrogeological conceptual models. For instance, Paper II and III showed that the use of geophysics was useful for improving the knowledge about the geometry of the local aquifer systems in terms of layering, thicknesses, depths, and lateral variation. The gathered information was used for refining the hydrogeological model, which later can be used for performing other measurements, tests, analyses and numerical modelling for estimating complementary hydrogeological properties such as the storage capacity and hydraulic conductivity.

The geoelectrical surveys measured the resistivity distribution within the Punata fan, which was of key interest for proposing a new method for assessing the vulnerability of groundwater. In Paper V, the EDIT method showed a good agreement when compared with the DRASTIC approach, however EDIT method has the ability to show gradual changes between the different vulnerable areas, which might be influenced by the electrical resistivity distribution input parameter. The strength of the EDIT method is based on the fact that it uses relatively easily accessible information, which might be less time consuming and demanding than other standard methods.

The third dimension of water security deals with the future environment, which can be partially addressed by protection policies. The incorporation of groundwater vulnerability maps is of high importance when protection policies are planned. Understanding the importance of the groundwater aquifer and its protection is of high interest for all the stakeholders, who must guarantee the preservation of aquifers for next generations.

5. HYDROCHEMISTRY

5.1. Introduction

One of the main aspects about water security is to guarantee the water quality and quantity for human needs. The water quality is highly sensitive to natural and anthropogenic factors. Natural processes include the weathering of different rocks or minerals, and evaporation cycles. It also includes hydrogeological processes such as velocity and direction of groundwater flow, and residence time. The anthropogenic factors include pollution from pesticides, and effluent from industrial and domestic activities. The knowledge of the water composition and processes affecting water quality is vital for integrated water resources management. Hydrochemical analysis of different ions and stable isotopes can provide information about water quality, groundwater recharge/discharge mechanisms, and flow patterns.

5.2. Methodology

5.2.1. Surface and groundwater quality assessment

Surface water and groundwater suitability for drinking and irrigation purposes were assessed with the standards from the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) (WHO, 2004, Ayers, 1985). The evaluation of water suitability for drinking and irrigation purposes was done by applying quality indexes: Drinking Water Quality (DWQ) and Irrigation Water Quality (IWQ) indexes. These indexes assign weights and rankings to the different physio-chemical parameters of water samples; for more details about these applied indexes refer to Simsek and Gunduz (2007) and Parmar and Parmar (2010). For the IWQ index it was necessary to estimate Magnesium Adsorption Ratio (MAR), Exchangeable Sodium Ratio (ESR), Sodium Adsorption Ration (SAR), and Residual Sodium Carbonate (RSC). Several studies worldwide are available with an extensive description of the theory and equations of these expressions (Alkinani and Merkel, 2017, Chakraborti et al., 2010, Alobaidy et al., 2010, Thapa et al., 2017).

5.2.2. Weathering process and ion chemistry

This research has used multiple approaches for analyzing and visualizing the hydrochemical processes occurring within the study area. Different graphical analyses (e.g. bivariate plots and Piper diagram) were used to help in the task of differentiating patterns and chemical evolution within the aquifer system. The methods used are described in Paper IV.

The ion concentration in water samples might be explained by several processes like weathering processes or ion exchange. For instance, by performing chemical analyses of groundwater samples, it is often possible to track the mineral weathering (e.g. halite or calcite dissolution) occurring along a groundwater path within an aquifer system (Freeze and Cherry, 1979, Drever, 1988, Datta and Tyagi, 1996). In general, ion exchange might occur between some ions in water with other ions in environments formed of clay and organic soil materials. Some authors, e.g. Chebotarev (1955) and Fetter (2001), proposed the following order of cation exchange: $Na^+ > K^+ > Mg^{2+} > Ca^{2+}$, where the divalent ions tend to replace the monovalent ions, but it is reversible and at high activities the monovalent ions can replace the divalent ions.

5.2.3. Stable isotopes

The use of stable isotopes can assist in providing a better insight about the origin of water samples and about some hydrogeological processes. This study has used environmental isotopes, i.e. oxygen-18 (^{18}O) and deuterium (^{2}H), which are considered as non-anthropogenic and natural. The study by Craig (1961) proposed a linear relationship where most of the water samples of meteoric origin must be plotted. This line is named as the Global Meteoric Water Line (GMWL) and is given by the following equation: $\delta^2H = 8\delta^{18}O+10$. Deviations from this linear relationship might suggest different hydrological processes such as evaporation, or precipitation events that occurred during warmer or colder climates than at present. The main effects that cause changes in the GMWL are temperature, evaporation and altitude (Mook and Rozanski, 2000).

5.2.4. Data collection

A total of 57 water samples were collected in both Pucara and Punata regions (Figure 18). The samples were collected from surface water and groundwater. The samples from groundwater are located within the Punata fan, while the surface water samples are distributed along water bodies in the neighboring basins. The samples were spatially distributed in order to take into consideration all the possible recharge sources.

The water sampling followed the protocol and standards methods of APHA (1995). In each sampling location, Electrical Conductivity (EC) and pH values were measured. The water samples were analyzed at the Center of Water and Environmental Sanitation (Centro de Aguas y Saneamiento Ambiental) at UMSS. The analyses (refer to Table 1) include Total Dissolved Solids (TDS), the major species calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), bicarbonate (HCO_3^-), chloride (Cl^-), sulfate (SO_4^{2-}); and the minor species potassium (K^+), nitrate (NO_3^-) and total iron (Fe_{total}). The concentrations of major and minor species are in milligram per liter (mg/L), while EC is in micro Siemens per centimeter (µS/cm). The stable isotope (^2H and ^{18}O) analyses were carried out at the laboratory of the Geological Survey of Denmark and Greenland. Only 45 water samples (refer to Table 2) were analyzed due to time restrictions of the sampling campaign. The isotopic compositions are reported as the deviation ('δ') of the ratio of the heavy isotopes (^{18}O and ^{2}H) to the light ones (^{16}O and ^{1}H) of a sample from that of the VSMOW (Vienna Standard Mean Ocean Water) in parts per thousand, ‰.

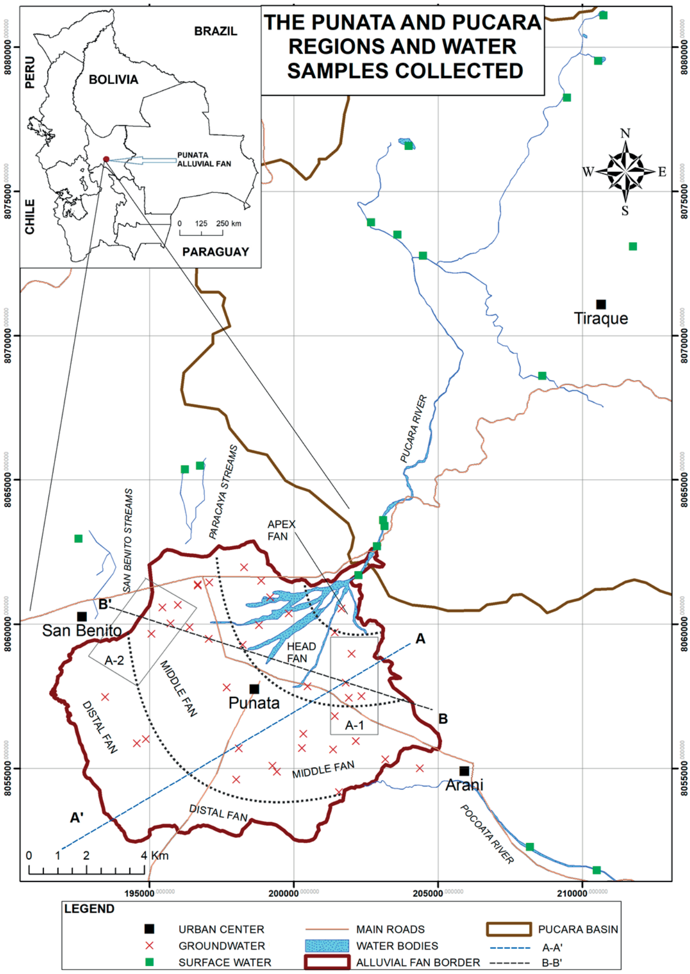

Figure 18 Map showing the location of the collected water samples. The samples were collected from surface water and groundwater. Modified from Gonzales Amaya et al. (2018a).

5.3. Results and discussion

Table 1 shows the values of each measured physiochemical parameter and the permitted range (according to the Bolivian Norm NB 5212 and FAO), for drinking and irrigation purposes. In general, it is very likely to have water samples with good quality for drinking purposes. High concentration of salts such as Cl^- and Na^+ are the main parameters which affects the quality of some samples, and consequently the electrical conductivity (EC) values increased outside of the permitted range.

Table 1 Physio-chemical parameters of water samples collected in the study area. Concentrations of ions are in mg/L, EC in µS/cm, and pH dimensionless. The T column describes the water type, where G and S stands for groundwater and surface water, respectively. Bold italic numbers are out of the permitted range.

ID	T	pH > 6.5 < 9.0	EC < 1500	HCO_3^- < 370	Ca^{2+} < 200	Cl^- < 250	Mg^{2+} < 150	NO_3^- < 45	K^+ --	Na^+ < 200	SO_4^{2-} < 400	SAR < 16	ESR < 1	MAR < 50	RSC < 1
P1	G	7.3	181	74	16	4	5	1	2	12	13	0.6	0.4	35.6	0.0
P2	G	7.6	***1619***	173	32	***350***	2	1	3	***253***	56	11.6	***6.1***	11.2	0.9
P3	G	7.9	191	81	20	5	3	1	2	12	13	0.7	0.4	19.4	0.1
P4	G	7.7	190	80	6	7	2	1	3	29	12	2.4	***2.4***	38.6	0.7
P5	G	7.6	367	93	14	45	2	2	3	47	18	3.1	***2.3***	18.2	0.6
P6	G	7.6	345	84	16	47	4	1	2	64	16	3.7	***2.5***	30.5	0.2
P7	G	7.7	446	95	11	74	3	1	2	94	12	6.5	***5.1***	30.1	0.7
P8	S	7.5	213	93	19	5	5	0	7	14	4	0.8	0.5	29.5	0.1
P9	S	8.4	192	90	20	5	3	0	3	13	10	0.7	0.4	21.0	0.0
P10	*S*	***9.0***	191	89	19	4	4	0	3	13	11	0.7	0.4	27.3	0.0
P11	G	7.6	198	99	15	7	4	1	2	22	12	1.3	0.9	29.7	0.5
P12	G	8.0	635	157	12	89	2	1	3	91	1	6.3	***5.0***	25.1	***1.7***
P13	G	8.4	599	158	6	77	2	0	3	93	29	8.1	***8.1***	40.1	***1.9***
P14	G	8.4	806	226	16	110	2	1	3	145	23	8.9	***6.3***	20.1	***2.3***
P15	G	7.6	184	78	12	8	4	1	2	20	12	1.3	0.9	35.5	0.3
P16	G	7.5	164	70	11	5	4	1	1	18	12	1.2	0.9	37.9	0.2
P17	G	7.8	190	78	16	5	5	1	3	16	16	0.9	0.5	35.6	0.0
P18	G	7.5	348	84	19	51	5	1	2	36	14	1.9	***1.2***	30.0	0.0
P19	G	7.7	508	100	22	87	13	1	2	49	18	2.0	***1.0***	49.2	0.0
P20	G	8.0	529	101	24	87	6	1	2	51	23	2.4	***1.3***	30.3	0.0
P21	G	7.1	452	106	21	68	6	1	2	50	19	2.5	***1.4***	33.4	0.0
P22	G	7.2	***1555***	207	44	***314***	10	1	3	***267***	58	9.5	***3.9***	26.7	0.0
P23	G	7.6	942	196	12	159	6	1	2	***235***	35	13.8	***9.3***	45.6	***2.0***
P24	G	7.4	157	83	9	4	4	1	1	21	12	1.5	***1.2***	42.2	0.5
P25	G	7.2	186	84	13	11	4	1	1	21	12	1.3	0.9	33.4	0.3
P26	G	7.4	551	140	14	86	7	1	2	85	17	4.6	***2.8***	46.2	0.8
P27	G	7.4	179	90	15	5	7	1	1	19	36	1.0	0.6	44.1	0.0
P28	G	7.6	***1945***	229	40	***437***	7	1	3	***418***	6	***16.0***	***7.0***	23.1	***1.0***
P29	G	6.9	570	106	30	100	10	1	2	63	39	2.6	***1.2***	34.9	0.0
P30	G	8.6	***2407***	199	24	***604***	12	0	5	***527***	12	***21.8***	***1.4***	45.5	***1.1***
P31	S	8.0	70	31	8	0	2	1	1	2	7	0.2	0.2	33.4	0.0
P32	S	8.2	114	46	7	<0.12	8	0	1	12	25	0.8	0.5	***64.8***	0.0
P33	S	7.7	92	56	12	<0.12	8	0	1	3	2	0.2	0.1	***50.1***	0.0
P34	S	8.0	115	56	6	4	7	0	5	6	1	0.4	0.3	***63.7***	0.0
P35	*S*	***9.0***	228	116	8	6	11	0	3	45	18	2.4	***1.5***	***71.3***	***1.6***
P36	S	8.1	273	139	8	16	12	<0.4	5	37	7	1.9	***1.1***	***71.5***	0.9
P37	S	***9.3***	240	132	20	5	8	0	3	29	21	1.4	0.7	39.9	0.7
P38	S	7.3	42	27	3	<0.12	1	0	1	5	1	0.6	0.8	0.4	0.1
P39	S	7.7	232	127	11	6	6	1	2	50	3	3.0	***2.1***	45.2	***1.0***
P40	S	6.9	323	88	14	43	6	1	2	36	19	2.0	***1.3***	41.8	0.0
P41	G	6.8	168	84	14	4	6	1	1	19	16	1.1	0.7	40.8	0.0
P42	G	6.9	281	99	18	29	3	1	1	35	19	2.0	***1.3***	22.8	0.1
P43	G	6.7	34	20	1	<0.12	1	1	1	6	2	0.9	***1.5***	***61.2***	0.1
P44	S	6.8	39	31	3	<0.12	1	1	1	7	2	0.9	***1.4***	39.7	0.2
P45	S	7.4	69	52	5	1	2	2	1	12	2	1.1	***1.2***	35.8	0.4
P46	G	7.6	***5765***	286	110	***1515***	34	1	3	***1370***	**336**	***29.2***	***7.2***	33.8	0.0
P47	G	7.3	856	82	17	205	6	10	2	189	73	10.0	***6.1***	37.1	0.0
P48	G	6.9	375	83	15	54	6	1	1	71	20	3.9	***2.5***	39.8	0.0
P49	S	6.8	144	65	7	3	3	0	2	23	6	1.9	***1.7***	43.9	0.2
P50	G	7.2	598	174	25	64	14	0	2	82	28	3.3	***1.5***	48.0	0.1
P51	G	7.5	393	109	22	38	6	0	1	157	35	7.6	***4.3***	30.1	0.1
P52	G	7.4	1087	214	64	139	17	<0.4	1	165	121	4.7	***1.6***	30.5	0.0
P53	G	7.6	294	75	6	43	3	0	1	157	7	12.9	***12.2***	46.5	0.6
P54	S	7.0	81	22	7	3	2	1	2	6	2	0.5	0.5	32.1	0.0
P55	S	6.8	95	32	6	7	4	1	8	9	<0.36	0.7	0.6	48.5	0.0
P56	S	6.9	61	20	6	3	2	1	1	4	1	0.4	0.4	35.0	0.0
P57	G	7.4	293	77	10	42	3	3	0	54	10	4.0	3.4	30.5	0.5

The estimation of the DWQ index applied a maximum weight of 5 to parameters like NO_3^-, TDS, Cl^-, and SO_4^{2-} due to their major importance in water quality assessment (Parmar and Parmar, 2010, WHO, 2004). Hardness (HA) and HCO_3^- were given the minimum weight of 1 as they have low impact in the water quality assessment. Other parameters like Ca^{2+} and Mg^{2+} were assigned a weight of 3, and Na^+ was assigned a weight of 1. Figure 19.a displays the spatial distribution of the DWQ indexes. Values lower than 22 mean a low risk to human health, while values between 22-37 mean that there might be some parameter(s) which is (are) above the minimum standards, and finally values greater than 37 mean that the water is not recommended for drinking purposes.

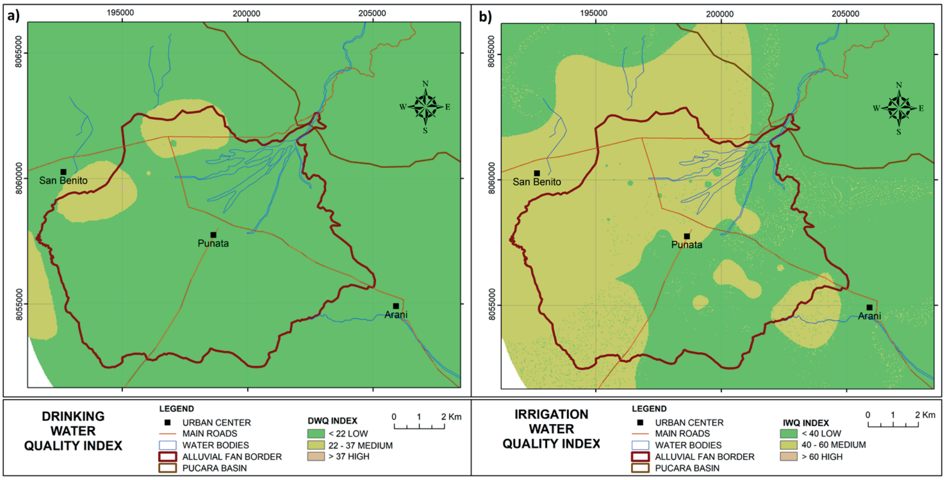

Figure 19 a) and b) Maps of the Drinking Water Quality, and Irrigation Water Quality indexes classification, respectively.

In general, the parameters for IWQ assessment showed more risk to ESR and MAR, while RSC and SAR yielded few points with non-permissible values (refer to Table 1). The weighting of the different parameters was done in line with the recommended standards of Ayers (1985) and weights from Simsek and Gunduz (2007). A weight of 5 was given to EC due to the fact that high values of EC is closely-related to high concentration of salts, which might be restricted, or used with caution during irrigation. Weights of 4 were given to SAR, ESR, MAR and RSC due to possible effects on the modification of soil properties such as salinization, infiltration and permeability. Weights of 3 were given to specific ions such as Na^+ and Cl^-, which, in high concentrations, can be toxic for several different crops. Finally, a weight of 2 was assigned to NO_3^-, and a weight of 1 was assigned to HCO_3^- and pH, which in some cases can have negative effects for some sensitive crops. Figure 19.b displays the spatial distribution of the IWQ indexes. Values lower than 40 mean a low risk, while values between 40-60 mean that there might be some parameter(s) which is (are) above the minimum standards, and finally values greater than 60 means that the water is not recommended for irrigation purposes.

The hydrochemical results have not shown heavy contamination. The DWQ indexes yielded values associated to good water quality in almost all the Punata fan region, and fulfilled the minimum standards. In some regions, i.e. north and northwest of the fan, the quality decreased mainly due to high concentrations of Cl^-, however the quality was good enough for drinking purposes. On the other hand, the IWQ indexes showed large areas with a moderate risk, which might be mainly due to further problems in soil salinization or plant toxicity by high concentrations of specific ions such as Cl^- or Na^+. The classification based on quality indexes for drinking and irrigation purposes can be used for planning the introduction of new crops and/or orchards with more tolerance to high concentration of specific ions, or to avoid groundwater extraction where the quality is harmful to human health.

The concentrations of the stable isotopes ranges from -106.5 to -77.9 ‰ and from -15.5 to -9.6 ‰, for δ^2H and $\delta^{18}O$ respectively (Table 2). The groundwater samples displayed less variation than surface water samples.

Table 2 Concentrations of $\delta^{18}O$ and δ^2H both in ‰ versus VSMOW. The letters G, R, and S in the field Type stands for groundwater, rainfall, and surface water, respectively. R type samples are from Stimson et al. (2001). Modified from Gonzales Amaya et al. (2018a).

ID	Type	Sampling date	$\delta^{18}O$	δ^2H	ID	Type	Sampling date	$\delta^{18}O$	δ^2H
P1	G	Nov-15	-11.9	-93.2	P26	G	Jul-16	-13.4	-100.5
P2	G	Nov-15	-13.1	-98.9	P27	G	Jul-16	-13.2	-99.2
P3	G	Nov-15	-12.4	-94.7	P28	G	Jul-16	-13.4	-101.3
P4	G	Nov-15	-13.7	-101.4	P29	G	Jul-16	-13.0	-99.3
P5	G	Nov-15	-13.5	-101.2	P30	G	Jul-16	-12.7	-96.9
P6	G	Nov-15	-12.6	-96.4	P31	S	Jul-16	-11.2	-85.2
P7	G	Nov-15	-12.2	-96.7	P32	S	Aug-16	-13.2	-96.2
P9	S	Oct-15	-9.6	-80.1	P33	S	Aug-16	-12.6	-91.9
P10	S	Oct-15	-9.8	-79.0	P35	S	Aug-16	-11.5	-90.8
P11	G	Nov-15	-12.9	-98.7	P36	S	Aug-16	-10.5	-85.2
P12	G	Dec-15	-13.1	-100.1	P37	S	Aug-16	-9.7	-77.9
P13	G	Dec-15	-14.1	-106.4	P38	S	Aug-16	-12.9	-94.9
P14	G	Dec-15	-13.5	-104.0	P39	S	Aug-16	-12.6	-97.1
P15	G	Dec-15	-13.3	-100.1	P40	G	Aug-16	-13.1	-98.1
P16	G	Dec-15	-12.7	-96.9	P41	G	Aug-16	-12.9	-98.7
P17	G	Dec-15	-13.1	-99.4	P42	G	Aug-16	-12.8	-97.4
P18	G	Dec-15	-12.3	-97.0	P43	S	Aug-16	-14.5	-105.3
P19	G	Dec-15	-12.9	-98.0	P44	S	Aug-16	-14.3	-104.3
P20	G	Dec-15	-13.0	-98.2	P45	S	Aug-16	-13.5	-98.9
P21	G	Dec-15	-13.2	-99.1	P58	R	Jan-90	-8.4	-58.8
P22	G	Jul-16	-13.2	-99.0	P59	R	Jan-90	-10.1	-59.1
P23	G	Jul-16	-13.0	-97.3	P60	R	Mar-90	-12.1	-79.8
P24	G	Jul-16	-12.7	-95.8	P61	R	Mar-90	-11.5	-75.9
P25	G	Jul-16	-13.3	-100.1	P62	R	Jul-90	-10.1	-78.4

All the groundwater samples are located below and shifted to the right with respect of the GWML, which suggests an evaporation process within the groundwater samples. In Paper IV a local evaporation water line (LWEL) was estimated: $\delta^2H=5.6\delta^{18}O-24$ (Figure 20). Surface samples can be grouped in three different clusters, and possibly this is because the surface samples were collected during different seasons: samples collected during the rainy season tend to be more depleted, and samples collected during the dry season tend to be more enriched (due to evaporation processes).

When groundwater samples were analyzed, they showed less variation and were basically scattered within one group, having similar composition as the surface samples collected during the rainy season (Figure 20). In Paper IV it is explained that heavy storms of short duration, which usually trigger flash flood events, are typical during the rainy season. Since the heavy storms may be more isotopically depleted the resultant flash floods would be depleted as well, which agrees with the similar isotopic composition measured in groundwater samples and surface water samples collected during the rainy season. Therefore, it might be suggested that light rainfalls, which are more enriched in $\delta^{18}O$ and δ^2H, are of minor importance in the recharge process. Consequently, in Paper IV it is concluded that heavy storms, which lead to heavy flash flood events, are of major importance to the recharge process in the Punata alluvial fan (Gonzales Amaya et al., 2018a).

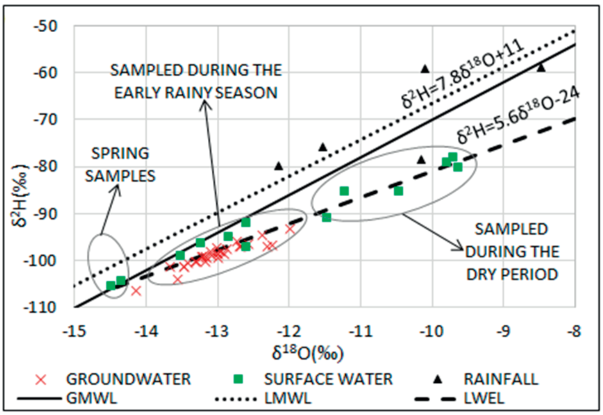

Figure 20 Variation in the ^2H and ^{18}O concentrations in water samples within the study area. The global meteoric water line (GMWL), the local meteoric water line (LMWL), and the local evaporation water line (LEWL) are also displayed. From Gonzales Amaya et al. (2018a).

The spatial distribution of the ion concentrations can assist in determining flow patterns and associations with possible groundwater recharge sources. Figure 21 displays the concentration of major ions in circular diagrams. It can be seen that surface water tends to have lower ion concentrations, which is reproduced among groundwater samples located close to the river discharge areas (i.e. Pucara and Pocoata rivers). Ion concentrations in groundwater samples tend to increase toward the distal part of the fan, especially in the northwestern part of the fan. The rise in ion concentrations might be due to the fact that the infiltrated water travels into the subsurface where there is an interaction of water/soil/rock where additional ions are transported by groundwater.

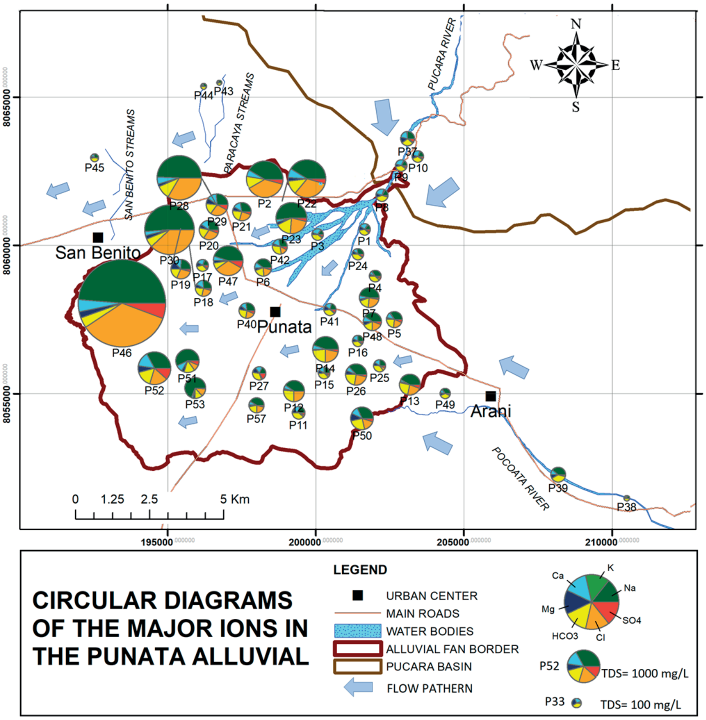

Figure 21 Circular diagrams of the major ions of the 57 water samples collected within the alluvial fan. Note that the diameter of circular diagrams is proportional to TDS content. Modified from Gonzales Amaya et al. (2018a).

Moreover, the hydrochemical analysis reported an increase in the salt content in groundwater samples in the middle and distal part of the fan (Figure 22). Paper IV discussed four possible causes that influence the groundwater salinization: i) dissolution of halite, ii) infiltration of irrigation waters and/or excess on the use of fertilizers, iii) vertical diffuse recharge through the unsaturated soil, iv) or existence of saline deposits lying in the lacustrine bottom of the local aquifer system. The non-presence of halite deposits in the region (analysis from regional and local geology description), the complex genesis of alluvial fans where it is very likely to find impermeable lenses/layers in the subsoil, and 1-dimensional water movement modeling in the subsoil assisted in rejecting hypotheses i), ii), and iii). Hydrochemical analyses and geophysical surveys coincide in pointing out that hypothesis iv) seems to explain the origin of groundwater salinization.

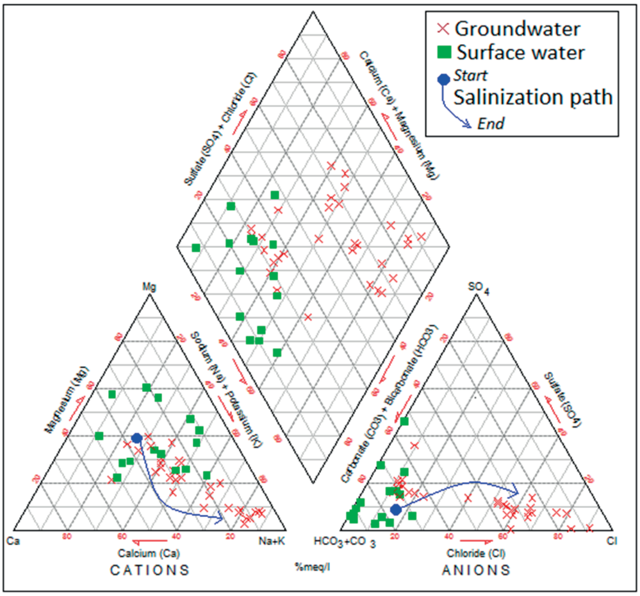

Figure 22 Piper diagram showing the evolution of water types. Surface water samples are mostly HCO_3^- type, while groundwater samples tend to evolve into Na^+ - Cl^- type.

5.4. Conclusions

The water quality in the Punata regions predominately shows no risk to human health, with exception of some areas with high concentrations of Cl^-. In terms of water quality for irrigation, there are large areas where, with time, they might have problems with salinization of soil which can affect the infiltration and permeability of soils. From the isotopic analysis, in Paper IV, it is possible to suggest that groundwater recharge is mainly taking place when flash floods occur in the Pucara and Pocoata river. Hydrochemical analysis, subsoil description, and 1-dimensional water movement modeling support the hypothesis that groundwater recharge from rainfall and irrigation are of less importance, strengthening the assumption that river flow is the main recharge source.

The identification of groundwater recharge processes and mechanisms, and the hydrochemical description of groundwater and surface water samples are quite important in the goal of achieving regional water security levels. By knowing where the main recharge areas are, it is possible to start planning policies about groundwater protection, and also it allows the measurement of the real recharge rates in order to establish better groundwater extraction practices. If a groundwater recharge source is protected and there is no overexploitation, it should be possible to assure water supply for the human activities, and in that way, the welfare of the local population can be guaranteed.

6. GENERAL DISCUSSION, CONCLUSIONS AND FUTURE WORK

Securing access to water is important for the local welfare and development of people who live in alluvial fan regions, and depend mainly on groundwater. Hence, it is important to determine an adequate/efficient usage of groundwater, and on the other hand, to have a better understanding of the local hydrogeological properties and fluxes than currently exists. For example, Denmark undertook an ambitious national program for mapping groundwater in all its territory, where ground and advanced airborne geophysical surveys combined with isotope and hydrochemical investigation were key methods. Nowadays, Denmark has a high level regarding water security, where an accurate description of Danish aquifers in terms of location, distribution, extension, interconnection, recharge rates and determination of protection zones led to a sustainable groundwater management.

Broadening the local hydrogeological information is a task that demands the application of different expertise and disciplines. Despite the fact that it is possible to use different approaches in alluvial fans for accomplishing this task, the challenge was to seek appropriate methods and tools that can be used in the Bolivian context. This type of context means that there is often a lack of primary/archive information, it is difficult to access to cutting-edge equipment, and the local idiosyncrasy might be hard to deal with. This research demonstrated that the application of multidisciplinary methods is a key approach for retrieving as much hydrogeological information as possible, which can provide improved knowledge to address the water security in the study area.

One aspect of water security that needs to be addressed is the future environment, where climate variability/climate change is an issue to be taken into consideration for planning and assessing the water resources in that region. This research seeks for approaches that requires either data from online sources and/or from local meteorological stations. These types of datasets are often easier to access for users. The results obtained and their analysis highlighted future problems where water-stress is a topic to be considered, hence the approaches used seems to assist in addressing water security.

Another aspect of water security that needs to be addressed is the hydrogeological environment, where detailed knowledge about rainfall variability, river regime, and groundwater properties and flow processes are needed. In this research a major focus was given to groundwater since it is the main water supply source in the sub-Andean regions of Bolivia. In these regions, there is an evident lack of knowledge about the main properties and processes of the local aquifers. Therefore, methods which could be used in the study area were sought. The applied methods, although constrained by the availability of equipment, showed excellent performance in terms of time, cost, and data quality and quantity. The information generated by the geophysical and hydrochemical approaches enhanced the groundwater knowledge. Therefore, if groundwater is sustainably developed and protected, it means that the water supply for the region can be guaranteed, thus providing a high water security level to the local area.

This work used several techniques which are not so time-consuming and work demanding for improving the understanding of hydrogeological and hydrological variables in the Punata alluvial fan. The specific objectives of this study were accomplished as described below:

- In Paper I the hydrometeorological information pointed out that climate variability seems to have a direct effect on the precipitation rates which impacts on the river flows, and consequently, on the groundwater recharge at the Punata alluvial fan.
- Paper II and Paper III described that the use of geophysical methods together with in-situ information (lithological descriptions from drilling reports) assisted in refining the hydrogeological conceptual model in terms of layering, thicknesses, and lateral variation.
- In Paper IV the isotopic and hydrochemical analyses suggests that the main source of groundwater recharge is the Pucara and Pocoata rivers, while diffuse recharge such as precipitation and irrigation sources are of less importance.
- Paper IV reported that the coupling of geophysical surveys and hydrochemistry assisted in identifying a saline layer at the bottom of the aquifer system, which seems to be the cause of saline water reported in some wells.
- Paper V described that the integration of geophysical methods together with geomorphological information can be used for proposing an alternative technique for mapping the groundwater vulnerability in areas with scarce information.

The use of different approaches assisted in having a better conceptual model of the aquifer system in Punata (Figure 23). There are important findings in this work, such as the delimitation of a saline layer at the bottom of the aquifer system. It is also important to consider that Pucara and Pocoata rivers are the main recharge sources. Hence, the understanding of rainfall variability, consequently river flow variability, is important to know in order to plan further actions about the extraction and use of groundwater in order to avoid shortages or groundwater depletion.

Despite the fact that today's groundwater quality in the Punata fan is of relatively good quality for drinking and irrigation, it is necessary to protect the aquifer and avoid contamination from anthropogenic activities. The proposed EDIT method can be used for delimiting potential areas that are vulnerable to groundwater contamination. This method can be of particular interest in areas where there is limited information about the major hydrogeological properties, such as recharge rates, hydraulic heads, and subsoil description. All the collected information and results from this research are important for proposing plans for sustainable groundwater use and groundwater quality protection. If groundwater is safeguarded and guaranteed for this and the coming generations, it will be possible to expect a better livelihood and welfare among the local population of the Punata alluvial fan.

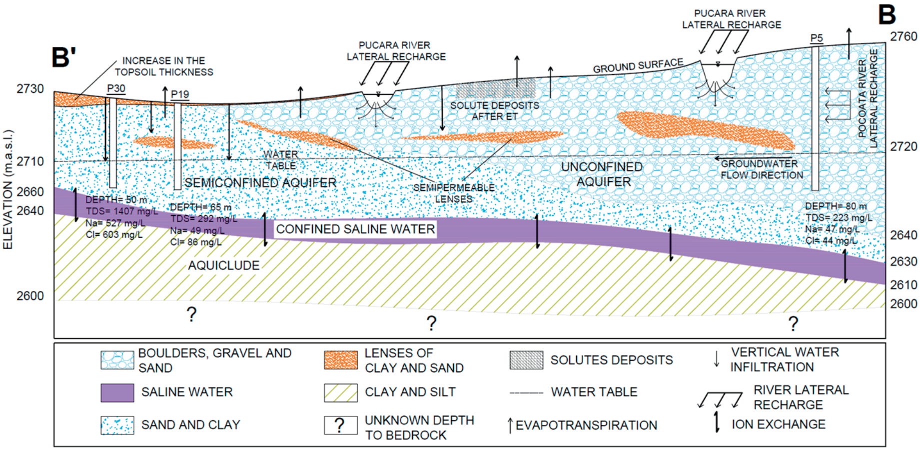

Figure 23 Hydrogeological conceptual model of the groundwater flow patterns, and recharge process within the Punata alluvial fan. Gonzales Amaya et al. (2018a).

Alluvial fans are often important geological features where groundwater can be stored. In spite of this, in developing countries such as Bolivia, there are few studies concerning these features, where groundwater has been characterized in detail. It is important to monitor and record the hydrogeological parameters (e.g. precipitation, groundwater levels, river flow and water quality) and to build long time series of such data, in order to assess future scenarios. It is also important to perform extensive field campaigns, such as geophysical surveying to gain a better understanding of the aquifer geometry. One approach is to perform this work at a local scale, where logistics can be handled easily, and therefore water security can be reached relatively quickly.

In order to strengthen the water security in the study area, additional work is needed. It is recommended that groundwater recharge and discharge rates are estimated with in-situ measurements. This information can help in defining whether there is any actual groundwater over-exploitation. More isotopic analyses can be performed during different seasons of the year, and at different elevations. With these results it can be confirmed if groundwater is mainly recharged by flash floods. On the other hand, geophysical surveys can be performed for solving some remaining uncertainties, such as the delimitation of the bedrock, thickness of the bottom aquiclude, and if there is any interconnection between other neighboring aquifers.

Collaboration between national and international institutions is also important, since both can benefit from the development of new methodologies, strategies and training of personnel. However, it is also important that the national and local authorities raise concern about the importance of water security, because through this framework an enhancement and strengthening in terms of health, social, economic and environmental status can be reached which will improve the welfare of the local population.

7. REFERENCES

ALKINANI, M. & MERKEL, B. 2017. Hydrochemical and isotopic investigation of groundwater of Al-Batin alluvial fan aquifer, Southern Iraq. Environmental Earth Sciences, 76, 301.

ALOBAIDY, A. H. M. J., AL-SAMERAIY, M. A., KADHEM, A. J. & MAJEED, A. A. 2010. Evaluation of treated municipal wastewater quality for irrigation. Journal of Environmental Protection, 1, 216.

ALLEN, J. 2016. Bolivia's Lake Poopó Disappears [Online]. United States: NASA Earth Observatory. Available: https://earthobservatory.nasa.gov/NaturalHazards/view.php?id=87363 [Accessed 16/March/2017].

ALLEN, R. G., PEREIRA, L. S., RAES, D. & SMITH, M. 1998. Crop Evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome, 300, D05109.

ALLER, L., LEHR, J. H., PETTY, R. & BENNETT, T. 1987. DRASTIC: a standardized system to evaluate groundwater pollution potential using hydrogeologic settings. National Water Well Association, Worthington, Ohio, United States of America.

APHA 1995. Standard methods for the examination of water and wastewater. Washington DC, USA: American Public Health Association-America Water Works Association-Water Environment Federation.

AYERS, R. S. 1985. Water quality for agriculture, FAO and UN.

BLAIR, T. C. & MCPHERSON, J. G. 2009. Processes and forms of alluvial fans. Geomorphology of desert environments, 413-467.

BLISSENBACH, E. 1954. Geology of alluvial fans in semiarid regions. Geological Society of America Bulletin, 65, 175-189.

BRUTSAERT, W. & STRICKER, H. 1979. An advection-aridity approach to estimate actual regional evapotranspiration. Water resources research, 15, 443-450.

BULL, W. B. 1972. Recognition of alluvial-fan deposits in the stratigraphic record. Special Publication - Society of Economic Paleontologists and Mineralogists, 16, 63-83.

CENTRO-AGUA 2012. Desarrollo de capacidades y fortalecimiento organizativo para la gestión del agua en la cuenca pedagógica Pucara. Universidad Mayor de San Simon.

CRAIG, H. 1961. Isotopic variations in meteoric waters. Science, 133, 1702-1703.

CHAKRABORTI, D., DAS, B. & MURRILL, M. T. 2010. Examining India's groundwater quality management. ACS Publications.

CHEBOTAREV, I. 1955. Metamorphism of natural waters in the crust of weathering-1. Geochimica et Cosmochimica Acta, 8, 22-48.

CHRISTIANSEN, A. V., AUKEN, E. & SØRENSEN, K. 2009. The transient electromagnetic method. Groundwater geophysics, 179-226.

DAHLIN, T. 2001. The development of DC resistivity imaging techniques. Computers & Geosciences, 9, 1019-1029.

DAHLIN, T. & ZHOU, B. 2004. A numerical comparison of 2D resistivity imaging with 10 electrode arrays. Geophysical Prospecting, 52, 379-398.

DAHLIN, T. & ZHOU, B. 2006. Multiple-gradient array measurements for multichannel 2D resistivity imaging. Near Surface Geophysics, 4, 113-123.

DATTA, P. & TYAGI, S. 1996. Major ion chemistry of groundwater in Delhi area: chemical weathering processes and groundwater flow regime. Journal-Geological Society of India, 47, 179-188.

DREVER, J. I. 1988. The geochemistry of natural waters, New Jersey, USA, Prentice Hall Englewood Cliffs.

ELHAG, M., PSILOVIKOS, A., MANAKOS, I. & PERAKIS, K. 2011. Application of the SEBS water balance model in estimating daily evapotranspiration and evaporative fraction from remote sensing data over the Nile Delta. Water Resources Management, 25, 2731-2742.

FAO. 2016. AQUASTAT: Total internal renewable water resources (IRWR) [Online]. Rome, Italy: Food and Agriculture Organization

Available: http://www.fao.org/nr/water/aquastat/water_res/index.stm#db [Accessed 05/05/18].

FARR, T. G., ROSEN, P. A., CARO, E., CRIPPEN, R., DUREN, R., HENSLEY, S., KOBRICK, M., PALLER, M., RODRIGUEZ, E. & ROTH, L. 2007. The shuttle radar topography mission. Reviews of Geophysics, 45, 1-33.

FETTER, C. W. 2001. Applied hydrogeology - 4th edition: International Edition, Upper Saddle River, N.J., Pearson.

FITTERMAN, D. V. & STEWART, M. T. 1986. Transient electromagnetic sounding for groundwater. Geophysics, 51, 995-1005.

FREEZE, R. A. & CHERRY, J. A. 1979. Groundwater, New Jersey, USA, Prentice Hall Englewood Cliffs.

GEOBOL 1983. Estudio geológico de la hoja de Punata cuadrángulo No 6441 (Geological study of Punata region, quadrangle No 6441). La Paz, Bolivia: GEOBOL.

GONZALES AMAYA, A., BARMEN, G. & MUÑOZ, G. 2018a. A Multidisciplinary Approach for Clarifying the Recharge Processes and Origin of Saline Water in the Semi-Arid Punata Alluvial fan in Bolivia. Water, 10, 946.

GONZALES AMAYA, A., DAHLIN, T., BARMEN, G. & ROSBERG, J.-E. 2016. Electrical Resistivity Tomography and Induced Polarization for Mapping the Subsurface of Alluvial Fans: A Case Study in Punata (Bolivia). Geosciences, 6, 51.

GONZALES AMAYA, A., DAHLIN, T., BARMEN, G. & ROSBERG, J.-E. 2018b. A geoelectrical and geomorphological based method for groundwater vulnerability assessment in alluvial fans: a case study in the Punata fan. Environmental Earth Sciences (Submitted).

GONZALES AMAYA, A., MÅRDH, J. & DAHLIN, T. 2018c. Delimiting a saline water zone in Quaternary fluvial–alluvial deposits using transient electromagnetic: a case study in Punata, Bolivia. Environmental Earth Sciences, 77, 46.

GONZALES AMAYA, A. & PARODI, G. 2010. Estimation of actual evapotranspiration by Hydrus-1D and its validation in REMEDHUS network, Spain. 1st International Congress of Hydrology in the Blue Plains. Buenos Aires, Argentina.

GONZALES AMAYA, A., VILLAZON, M. & WILLEMS, P. 2018d. Assessment of Rainfall Variability and Its Relationship to ENSO in a Sub-Andean Watershed in Central Bolivia. Water, 10, 701.

GREY, D., GARRICK, D., BLACKMORE, D., KELMAN, J., MULLER, M. & SADOFF, C. 2013. Water security in one blue planet: twenty-first century policy challenges for science. Phil. Trans. R. Soc. A, 371, 20120406.

GREY, D. & SADOFF, C. W. 2007. Sink or swim? Water security for growth and development. Water policy, 9, 545-571.

GUÉRIN, R., DESCLOITRES, M., COUDRAIN, A., TALBI, A. & GALLAIRE, R. 2001. Geophysical surveys for identifying saline groundwater in the semi-arid region of the central Altiplano, Bolivia. Hydrological Processes, 15, 3287-3301.

HARGREAVES, G. H. & SAMANI, Z. A. 1982. Estimating potential evapotranspiration. Journal of the Irrigation and Drainage Division, 108, 225-230.

HOLBROOK, N. J., BROWN, J., DAVIDSON, J., FENG, M., HOBDAY, A., LOUGH, J., MCGREGOR, S., POWER, S. & RISEBY, J. 2012. El Niño–Southern Oscillation, Camberra, Autralia, Marine Climate Change in Australia Impacts and Adaptation Responses.

INE. 2012. Censo Poblacion y Vivienda 2012 (Population and Housing Census 2012) [Online]. La Paz, Bolivia: Instituto Nacion de Estadistica. Estado Plurinacional de Bolivia. Available: http://www.ine.gob.bo/ [Accessed 05/07/17 2017].

KOCH, K., REVIL, A. & HOLLIGER, K. 2012. Relating the permeability of quartz sands to their grain size and spectral induced polarization characteristics. Geophysical Journal International, 190, 230-242.

LESMES, D. P. & FRIEDMAN, S. P. 2005. Relationships between the electrical and hydrogeological properties of rocks and soils. Hydrogeophysics. Springer.

LIMA, O. & NIWAS, S. 2000. Estimation of hydraulic parameters of shaly sandstone aquifers from geoelectrical measurements. Journal of hydrology, 235, 12-26.

LOKE, M. & DAHLIN, T. 2002. A comparison of the Gauss–Newton and quasi-Newton methods in resistivity imaging inversion. Journal of Applied Geophysics, 49, 149-162.

LOKE, M. & LANE JR, J. W. 2004. Inversion of data from electrical resistivity imaging surveys in water-covered areas. Exploration Geophysics, 35, 266-271.

MAGNUSSON, M., FERNLUND, J. R. & DAHLIN, T. 2010. Geoelectrical imaging in the interpretation of geological conditions affecting quarry operations. Bulletin of Engineering Geology and the Environment, 69, 465-486.

MAY, J.-H., ZECH, J., ZECH, R., PREUSSER, F., ARGOLLO, J., KUBIK, P. W. & VEIT, H. 2011. Reconstruction of a complex late Quaternary glacial landscape in the Cordillera de Cochabamba (Bolivia) based on a morphostratigraphic and multiple dating approach. Quaternary Research, 76, 106-118.

MILLS, T., HOEKSTRA, P., BLOHM, M. & EVANS, L. 1988. Time Domain Electromagnetic Soundings for Mapping Sea-Water Intrusion in Monterey County, California. Ground Water, 26, 771-782.

MIRANDA, G. 1998. La influencia del fenómeno El Niño y del índice de oscilación del sur en las precipitaciones de Cochabamba, Bolivia. Bull. Inst. fr. études andines, 27, 709-720.

MOGES, S. A., TAYE, M. T., WILLEMS, P. & GEBREMICHAEL, M. 2014. Exceptional pattern of extreme rainfall variability at urban centre of Addis Ababa, Ethiopia. Urban Water Journal, 11, 596-604.

MOOK, W. & ROZANSKI, K. 2000. Environmental isotopes in the hydrological cycle. IAEA Publish, 39.

MORA, D. & WILLEMS, P. 2012. Decadal oscillations in rainfall and air temperature in the Paute River Basin—Southern Andes of Ecuador. Theoretical and Applied Climatology, 108, 267-282.

NIWAS, S., TEZKAN, B. & ISRAIL, M. 2011. Aquifer hydraulic conductivity estimation from surface geoelectrical measurements for Krauthausen test site, Germany. Hydrogeology Journal, 19, 307-315.

NTEGEKA, V. & WILLEMS, P. 2008. Trends and multidecadal oscillations in rainfall extremes, based on a more than 100-year time series of 10 min rainfall intensities at Uccle, Belgium. Water Resources Research, 44.

OLIVERA, O. & LEWIS, T. 2004. Cochabamba: water war in Bolivia, South End Press.

PARMAR, K. & PARMAR, V. 2010. Evaluation of water quality index for drinking purposes of river Subernarekha in Singhbhum District. International Journal of Environmental Sciences, 1, 77.

REVIL, A., BINLEY, A., MEJUS, L. & KESSOURI, P. 2015. Predicting permeability from the characteristic relaxation time and intrinsic formation factor of complex conductivity spectra. Water Resources Research, 51, 6672-6700.

REVIL, A. & FLORSCH, N. 2010. Determination of permeability from spectral induced polarization in granular media. Geophysical Journal International, 181, 1480-1498.

REYNOLDS, J. M. 2011. An introduction to applied and environmental geophysics, John Wiley & Sons.

RWASOKA, D., GUMINDOGA, W. & GWENZI, J. 2011. Estimation of actual evapotranspiration using the Surface Energy Balance System (SEBS) algorithm in the Upper Manyame catchment in Zimbabwe. Physics and Chemistry of the Earth, Parts A/B/C, 36, 736-746.

SATGÉ, F., ESPINOZA, R., ZOLÁ, R. P., ROIG, H., TIMOUK, F., MOLINA, J., GARNIER, J., CALMANT, S., SEYLER, F. & BONNET, M.-P. 2017. Role of Climate Variability and Human Activity on Poopó Lake Droughts between 1990 and 2015 Assessed Using Remote Sensing Data. Remote Sensing, 9, 218.

SIMSEK, C. & GUNDUZ, O. 2007. IWQ index: a GIS-integrated technique to assess irrigation water quality. Environmental Monitoring and Assessment, 128, 277-300.

SLATER, L. & LESMES, D. P. 2002. Electrical-hydraulic relationships observed for unconsolidated sediments. Water Resources Research, 38, 1-13.

STIMSON, J., FRAPE, S., DRIMMIE, R. & RUDOLPH, D. 2001. Isotopic and geochemical evidence of regional-scale anisotropy and interconnectivity of an alluvial fan system, Cochabamba Valley, Bolivia. Applied Geochemistry, 16, 1097-1114.

SU, Z. 2002. The Surface Energy Balance System (SEBS) for estimation of turbulent heat fluxes. Hydrology and Earth System Sciences, 6, 85-99.

TABARI, H., AGHAKOUCHAK, A. & WILLEMS, P. 2014. A perturbation approach for assessing trends in precipitation extremes across Iran. Journal of hydrology, 519, 1420-1427.

TACHIKAWA, T., KAKU, M., IWASAKI, A., GESCH, D. B., OIMOEN, M. J., ZHANG, Z., DANIELSON, J. J., KRIEGER, T., CURTIS, B. & HAASE, J. 2011. ASTER global digital elevation model version 2-summary of validation results. NASA.

TAYE, M. T. & WILLEMS, P. 2012. Temporal variability of hydroclimatic extremes in the Blue Nile basin. Water Resources Research, 48.

THAPA, R., GUPTA, S., REDDY, D. & KAUR, H. 2017. An evaluation of irrigation water suitability in the Dwarka river basin through the use of GIS-based modelling. Environmental Earth Sciences, 76, 471.

UN-WATER 2013. Water Security and the Global Water Agenda. Ontario, Canada: Institute for Water, Environment & Health (UNU-INWEH).

UNDP-GEOBOL 1978a. Proyecto Integrado de Recursos Hídricos Cochabamba (Integrated Water Resources Project Cochabamba). Cochabamba, Bolivia: United Nations Development Programme.

UNDP-GEOBOL 1978b. Proyecto Integrado de Recursos Hidricos Cochabamba (Integrated Water Resources Project Cochabamba). Cochabamba, Bolivia: United Nations Development Programme.

VEREECKEN, H., BINLEY, A., CASSIANI, G., REVIL, A. & TITOV, K. 2006. Applied hydrogeophysics. Applied Hydrogeophysics, 1-8.

VILLAZON, M. F. 2015. Looking for climate variability, trends and effects of El Niño event (2015-2016) in Bolivia. XVI Congreso Bolivariano de Ingenieria Sanitaria, Medio Ambiente y Energias Renovables. Santa Cruz - Bolivia: ABIS.

WELLER, A., SLATER, L. & NORDSIEK, S. 2013. On the relationship between induced polarization and surface conductivity: Implications for petrophysical interpretation of electrical measurements. Geophysics, 78, D315-D325.

WHO, W. H. O. 2004. Guidelines for drinking-water quality, World Health Organization.

WUTICH, A. & RAGSDALE, K. 2008. Water insecurity and emotional distress: coping with supply, access, and seasonal variability of water in a Bolivian squatter settlement. Social science & medicine, 67, 2116-2125.

XU, C.-Y. & SINGH, V. 2005. Evaluation of three complementary relationship evapotranspiration models by water balance approach to estimate actual regional evapotranspiration in different climatic regions. Journal of Hydrology, 308, 105-121.