Geoscientists Without Borders: Final report

Project name

Geophysical mapping of aquifers in Bolivia

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Abstract

The project deals with geophysical mapping of aquifers in Bolivia, with field data acquisition at the Challapampa, Chocaya, Punata, Toco and Pucarani aquifers. In all cases the aquifers are poorly documented in terms of geometry and variation in aquifer properties, which is key information for adequate management and protection of the water resources. The studied aquifers are essential for the water supply of the local communities and agriculture in the respective areas, serving populations of several hundred thousand people. The aquifers are under threat of over exploitation as witnessed by decreasing groundwater levels, and as a consequence conflicts arise between local water supply companies serving urbanized areas and agricultural interests. There are furthermore threats to the groundwater quality from contamination such as mining and industrial activities, domestic waste, road transports, latrines, pesticides and fertilizers. Information about the extent of the aquifer and existence of possible protective layers with sufficient areal cover and spatial resolution is needed in order to manage and protect the groundwater for use of future generations. Local water supply and environment authorities are working in the respective areas but do not have the tools required for a comprehensive overall picture of the aquifer systems.

The aim of this project is to combine acquisition of such key information with training of students on different levels and knowledge transfer to local authorities. A specific objective is to contribute towards a better understanding of the aquifer systems in order to found a base for developing management plans to avoid over exploitation and contamination. Another specific objective is to train students on PhD, MSc and BSc level, primarily from Bolivia and Scandinavia. A final specific objective is to transfer knowledge of integrated geophysical aquifer mapping to local authorities within the groundwater and environmental sector.

The project is an expansion of an existing collaboration program between Lund University in Sweden, Universidad Mayor de San Andrés in La Paz (UMSA) and Universidad Mayor de San Simón in Cochabamba (UMSS) in Bolivia, sponsored the Swedish International Development Agency (SIDA). The academic collaboration was extended to include Aarhus University (AU) in Denmark and Universidad Técnica de Oruro (UTO) in Oruro.

The work was based on six rounds of field campaigns with TEM and ERT in each of the field areas. The first field campaign started in May/June 2016 and the last campaign ended in late 2019. The GWB funding allowed full access to 4WD field vehicles and state-of-the-art instruments, payment of expenses for Scandinavian and Bolivian students, additional supervisor trips, purchasing of computers and geophysical software.

Results were presented in theses at BSc, MSc and PhD level, conferences and peer reviewed scientific articles. We also arranged seminars and workshops to transfer results and knowledge to local authorities. Software used for data processing, inversion, visualization and archiving was transferred to Bolivia as a model for structured management of geophysical data. The GWB project allowed the work to be ramped up immediately, where we ran on a higher level of ambition, producing important geological and hydrogeological information that can be used immediately in sustainable management and protection plans.
Background information

Project Goals and Objectives

The aim of this project is to combine acquisition of key hydrogeological information with training of students on different levels, and knowledge transfer to local authorities. The specific objectives are described as follow:

- Objective 1: Contribute towards a better understanding of the aquifer systems in order to develop management plans to that avoid prevent over exploitation and contamination.
  Measure of success:
  - Geophysical data and models in databases and reports / publications.
  - Refined aquifer models presented.
- Objective 2: Train Bolivian and Swedish students on at PhD, MSc and BSc level.
  Measure of success:
  - Delivered and approved theses on respective level.
- Objective 3: Transfer knowledge of integrated geophysical aquifer mapping to local authorities within the groundwater and environmental sector.
  Measure of success:
  - Software packages installed and running on computer at Centro Agua
  - Completed seminars and workshops with participants from local authorities

Location

The investigation sites are located in the western and central part of Bolivia, where groundwater plays an important role in supplying fresh water to the main nearby urban centers. Moreover, these regions have reported groundwater problems such as pollution and overexploitation. Consequently, they were selected as pilot areas for applying the different hydrogeophysical methods. Figure 1 depicts the location of the different study areas where geophysical surveys were performed. There are three main study areas: 1) the Cochabamba valley, where investigations were performed in the regions of Punata, Toco and Chocaya, 2) the Challapampa fan, and 3) the Pucarani aquifer.

Figure 1 Location of the study areas in Bolivia. In area A1 the Punata, Toco and Chocaya aquifers are located. In area A2 the Challapampa alluvial fan is located. Within A3 the Pucarani aquifers is located.
The study areas of Punata, Toco and Chocaya are located in the macro-region known as sub-Andean valleys. In these regions the climate is semiarid. The annual precipitation is between 350 and 550 mm. The elevations in the study areas oscillate between 2850 and 2550 m.a.s.l.

The Challapampa and Pucarani aquifers are located in the highlands of Bolivia (locally known as Altiplano), where the average elevation is 3300 m.a.s.l. The climate in this region is also semiarid with an annual precipitation average lower than 500 mm.

**Geologic Setting**

In the Punata, Toco and Chocaya regions the basement is formed of Ordovician and Silurian rocks. The graben valleys are filled with unconsolidated sediments from the Quaternary; the main units are: fluvial, lacustrine, fluviolacustrine and colluvial-alluvial sediments (Figure 2). These units form terraces on riverbanks, beds and alluvial fans at the mouths of creeks and rivers. During the lower Pliocene, due to the lifting 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 was deposited (Gonzales Amaya et al., 2016).

![Figure 2 Regional geology at Punata and Toco alluvial fans. Similar geological settings are found in the Chocaya basin. Modified from Gonzales Amaya et al. (2018b).](image)

The regional geological features in Challapampa are dominated by two units; the first composed by outcrops of Silurian rocks and sporadic presence of Tertiary and Devonian sediments, and the second by Quaternary deposits controlled by glacial, lacustrine and fluvial processes (refer to Figure 3). Sedimentary units were the result of weathering and erosion of rocks in the mountains, where the action of water led to the formation of terraces and alluvial fans. The Quaternary deposits in this region are colluvium-fluvial, fluvial, fluvial-lacustrine, fluvial-glacial, and terraces, composed of coarse to fine grained sediments (pebbles, gravel, sand, silt and clay) which cover most of the flat study area (Gómez et al., 2016).
The Pucarani area forms part of the Katari basin where the Tertiary and Paleozoic sedimentary rocks are filled of Quaternary to Holocene sediments. The surrounding geological features in this area where formed by Quaternary glaciation at different ages, hence most of the sediments have a glacial erosion origin. The plains of Pucarani area are limit by Devonian and Tertiary formations, and filled by Quaternary lacustrine sediments. The Geometry of these Quaternary deposits such as thicknesses and spatial continuity are not well known (Avilés et al., 2020).

Geophysical need

Previous studies

There is a bilateral cooperation between Sweden and Bolivia with financial support from SIDA with PhD students from UMSA and UMSS in Bolivia registered at a number of Swedish universities. Two of these students were registered at Engineering Geology at LU, namely Etzar Gomes from UMSA and Andres Gonzalez from UMSS. Their respective thesis works focused on developing the understanding of the aquifer systems of Challapampa and Punata respectively. Andres and Etzar performed some geophysical surveys between 2014 and 2015 in Punata and Challapampa, respectively. The funding allocated for field investigations in the bilateral collaboration is very limited, hence there was a severe limitation in acquiring desired amounts of data due to poor field logistics, limited access to equipment, and lack of funds to cover travel and accommodation for students.

Few geophysical surveys were performed in the vicinities of our study areas. Guérin et al. (2001) performed TEM soundings in the northwest region of Poopo Lake (somewhat 100 km away from Challapampa). Avilés et al. (2020) performed TEM soundings in the Katari basin, between the Pucarani aquifier and Titicaca lake almost at the same time as our surveys in Pucarani. In the Punata, Toco and Chocaya areas there was one study by Renner and Velasco (2000) which performed Vertical Electrical Sounding in the western part of Cochabamba valley. To our knowledge these are all the geophysical studies performed in Bolivia for hydrogeological purposes that have been published. In addition to this Bolivian authorities use primarily VES and ERT for hydrogeological applications, but these data are not publicly available. Therefore, our project is a milestone in Bolivia for the large amount of geophysical information produced and published.
Local municipalities, private companies and the National Geological Service of Bolivia drilled wells in the study areas, however they do not have adequate protocols for registering the drilled wells with their corresponding report (e.g. borehole lithology and hydraulics parameters) therefore collecting this information was a challenge.

Needs and benefits

As mentioned before the study areas are located in regions with scarce access to surface water, therefore, groundwater is the main source of water supply for drinking, industry and irrigation. Reports about possible overexploitation, contamination and impacts of climate change encourage studies about the hydrogeological settings of the local aquifers, however, in general in Bolivia, there is a lack of detailed information about geometry of aquifers and their properties. This problem motivated the execution of this project.

The beneficiaries of the project are several groups. In the first line are the students on PhD, MSc and BSc level who made their thesis projects since with funding support from GWB. In the cases of Bolivian BSc students, the funding from GWB guaranteed their fieldwork expenses, hence they were able to fulfill their thesis projects thanks to that. In other cases, the GWB funding allowed students to get much more out of the project that would otherwise run on a crippling low budget with uncertain access to adequate fieldwork logistics, and limited access to specialized equipment or transportation.

Next are the local authorities in Bolivia who are beneficiaries from getting an introduction to new technology for acquisition, processing, inversion, archiving, visualization and interpretation of geophysical data for groundwater resources mapping. The acquired data will give valuable contributions towards refining the conceptual models of the aquifers to be used for management and protection of the water resources.

The local population living in or being served by water from the investigation areas will benefit from the enhanced information about the aquifers, as base for long term management protection of the water for the citizens and the agriculture.

Field Studies

The principal methods employed in this project are TEM (Transient Electromagnetic) and ERT (Electrical Resistivity Tomography) with time-domain IP (Induced Polarization). Both methods are well proven for aquifer mapping, and we used state-of-the-art methodology, equipment and software.

The ABEM WalkTEM system was used for the TEM soundings. This equipment comes with two models of low noise air-cored receiver coils; one optimized for high resolution shallow soundings and the other with a larger effective area, suitable for deeper soundings. The instrument also operates using dual-moment transmission where it automatically alternates between maximum and reduced current pulses, utilizing the benefits from both high energy fields as well as fast current pulse turn-off. In this way the system is optimized for high resolution response at shallow depth as well as maximum depth. In order to increase the depth penetration, we augmented the output current by using 24 V DC power supply instead of the standard 12 V DC, to raise the output current to about 16 A, which can be combined with different size transmitter loops. Furthermore, stacking the signal over longer periods than the standard setup is a way to increase the signal-to-noise ratio to recover late time decay signals over the noise threshold. We combined the different approaches in order to optimize depth penetration against field productivity. In light of the good depth penetration and existence of a conductive bottom layer in an area close to Challapampa reported by Guérin et al. (2001), the chance of getting a good outline of the depth of the aquifer was judged good.

For the ERT surveys we used an ABEM Terrameter LS, stainless steel electrodes and four electrode cables with 21 take-outs each were used too. ERT was measured in combination with time-domain IP (when time and conditions allowed) in order to obtain additional information that may be relevant for the hydraulic properties of the sediments, like e.g. clay content. We used newly developed signal processing and inversion software in order to extract as high quality information as possible (Olsson et al., 2016). Electrode spreads in the range 800
m, 1200 m and 1600 m were used, with electrode spacing 10 m, 15 m and 20 m respectively, depending on target depth and availability of equipment.

The fieldwork was performed under the supervision and coordination of Andres Gonzales and Etzar Gomez. Six field campaigns have been completed (refer to Figure 4 for locations):

- Punata and Toco July–September 2016. Conducted by Andres Gonzales, Joakim Mårdh, Tomas Gutierrez and Evelin Mendieta
- Pucarani August 2017; Conducted by Waldo Medinaceli, Nicolai Friis Mortensen, Micaela Pedrazas, Michelle Pedrazas and Giulia De Pasquale.
- Chocaya September–October 2019. Conducted by Andres Gonzales, Hannes Pilser, Daglin Camacho and Daniel Gareca

In total in Punata and Toco alluvial fan about 140 TEM sounding and more than 43 km of ERT were performed. In Chocaya about 35 TEM soundings and more than 5 km of ERT were done. In Pucarani more than 15 km of ERT and about 40 TEM sounding were conducted. Finally, in Challapampa the survey reached around 30 km with ERT and 245 soundings with TEM.

Figure 4 Location of geophysical surveys (ERT and TEM) performed in Chocaya, Punata, Toco, Challapampa and Pucarani aquifers.
The data collected during the fieldwork were quality checked using visual tools such as pseudosection plots and multi-profile plots. For ERT, the measured apparent chargeability time window data were averaged to integral chargeability. 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. The model discretization used a refinement model with cell widths of half the unit spacing. The damping parameter was set to a vertical/horizontal flatness ratio of 0.25, since the subsoil layers in the study area alluvial fan tend to be predominantly horizontal (Gonzales Amaya et al., 2016).

For TEM data, the inversion was performed in the program SPIA version 2.1.3, while the interpolation and creation of 2-D profiles were performed in Workbench version 5.2.2 and version 6.1.0 (only for Chocaya results). Both programs are distributed by Aarhus GeoSoftware. The inversions were done by selecting the Low Moment and High Moments from the antennas RC-5 and RC-200, respectively. Two types of inversion were made in SPIA: the layered model (with 3 to 5 layers), and the smooth model (with 20 layers). In order to select the best modelling from the equivalent solutions the residual value was assessed, where models with a residual value of less than one were selected. The 2D profiles in Workbench were created by using the option of kriging with exponential variogram interpolating 1D models to 2D profiles (Gonzales Amaya et al., 2018). Figure 5 and Figure 6 display ERT and TEM results with their residual error values.

![ERT Profile in the Punata alluvial fan. The mean residual is 7.8%](image1)

![Typical final Inversion of TEM soundings in the Punata alluvial fan. The data residual is 0.49](image2)

Purchase of software and a computer to run the inversions were made, which are now administrated by Andres Gonzales at UMSS. This is an important component of the project in order to secure availability of adequate software in Bolivia, as licenses that were available during Andres’ PhD work expired.
Limitations

Severe problems with access to land occurred in the Challapampa aquifer area, which lead to a stop of the activities there. The local villagers and farmers are afraid of having their wells depleted as a result of excessive water abstraction for the City of Oruro. Even if large efforts were made in explaining to them that we are not associated with the water company of the city, they were suspicious and in some regions of the aquifer area they refused to let us take measurements on their land. We also faced serious problems in getting logistic support from UMSA, which consumed a lot of time and energy to circumvent.

In the Punata and Toco aquifer areas, there were only been minor problems with accessibility to land. On the other hand, surveying was limited by roads, houses and electrical power lines. The logistic support from UMSS was good.

The good support from UMSS also extended to the work in the Chocaya basin. Hence the first field campaign during autumn 2019 was completed according to plans. The second unfortunately had to be terminated prematurely due to the volatile political situation that emerged, but sufficient data had already been acquired for an MSc thesis.

During the spring 2020 all planned activities had to be cancelled as a result of the political situation followed by the Covid-19 pandemic. Hence the final seminar was not organized, but we hope to be able to present the project outcome on site in Bolivia in a follow up project in a near future.

Interpretation of data

In addition to ERT and TEM surveys, data from drilling reports and geophysical well loggings were collected and used in order to validate and interpret the geophysical results. For instance, in the Punata alluvial fan more than 60 wells with lithological description were collected (Figure 7). After compiling the well information, the geophysical surveys were planned. A similar approach was followed in each study area.

Figure 7 Example on how boreholes with lithological information were located and distribution of geophysical surveys in the Punata alluvial fan. Modified from Gonzales Amaya et al. (2018a).
The geophysical information retrieved in this project was useful for extending the geological knowledge by inferring the continuation of faults, location of folds and outcrops, delimitation of basement and layering of different geological deposits. Moreover, the geophysical results and interpretation highlights that the used methods are suitable for areas where thermal intrusion occurs, such as in Capachos (Challapampa alluvial fan), where three faults and their connection with hydrothermal flows were investigated (see Figure 8). Results showed that hydrothermal flows in Capachos are associated with low resistivity values that aligns well with faults in the study area. The interpretation points out that the thermal water in the area circulate mainly upwards.

![Figure 8](https://example.com/image8.png)

*Figure 8 On top geophysical surveys performed in Challapampa aquifer and inferred geological structures. On bottom proposed conceptual model of geothermal flow. Modified from Gómez et al. (2019)*

The geophysical information retrieved in this project was also very useful for refining the hydrogeological conceptual models. For instance, in the Toco and Punata alluvial fans the geophysical interpretation allowed to refine the hydrogeological conceptual model from 1979, which was elaborated with very limited information. The data base elaborated by this project that consists of lithological information from drilled wells, plus large amounts of geophysical surveys allowed to highlight the most potential areas with groundwater storage (refer to Figure 9). The refined conceptual model has an extension of more than 20 Km and reach a depth of approximately 150 m below the surface (Figure 10).
Some complementary results highlight a very saline layer in the bottom of the aquifer system. This finding is important due to the fact that some reports indicate that people who drilled beyond the 120 m depth encountered water non-suitable for drinking and irrigation purposes. Therefore, the mapping and location of this saline layer made by this project, must be taken into consideration when further well are drilled (Figure 11).

The results in this project evidence that the geoelectrical methods applied are highly suitable for retrieving key information. The resistivity models from ERT and TEM complement each other very well, and from them geological and hydrogeological conceptual model can be proposed and refined. This is in line with the objectives of this project that aimed first, in apply geophysical methods for improving the local knowledge, and then the training of students at different level was done with excellent results.
Summary of Results and Key Findings

Following the description of the most important findings:

- In Challapampa it was possible to expand the hydrogeological understanding of the aquifer system by delimiting the aquifer thickness. Moreover, it was possible to detect fracture zones and other geological structures playing roles in the characteristics of the groundwater in the area, like the occurrence of saline intrusions. Likewise, estimations of aquifer characteristics were made combining geophysical information and boreholes data.
- In Punata the hydrogeological conceptual model was refined by identifying the most potential layers where groundwater is stored. Salt intrusion from deeper level was detected, hence local people should be aware of the consequences of drilling wells beyond 120 meters below surface. Groundwater origin and flow patterns were also determined. All these results need to be taken into consideration by decision and policies makers, due to the fact that groundwater is main source of water supply. Therefore, sustainable and protection plans are needed, based in the findings of this study.
- In Pucarani, the mapping of top layers indicates the location of porous aquifers. Due to the semiarid conditions of the area, and impacts of climate change in the melting of neighboring glaciers, these porous aquifers must be protected to remain a resource for further sustainable exploitation.
- In Chocaya, the geophysical results highlighted areas that are composed of fluvial deposits where urbanization is taking place. These deposits are very permeable and store large volumes of groundwater that partially supplies drinking water to the Cochabamba city (third largest city in Cochabamba). The geophysical results can be used as a proof for restricting urbanization in locations with these type of deposits, to avoid groundwater contamination from domestic and industrial waste.

Human Element

During this project many persons and institutions were involved. Following is a summary of the key participants and their contribution. It should also be mentioned that many more have been involved in supporting the project directly or indirectly within the organisations, for example by helping and advising the students in various ways.
Supervisors: They were in charge in coordinating the project. Their experience in geophysics and hydrogeology, both theoretical and in field, allowed us to plan the use of the most adequate methods. Also their experience was key for guidance during the interpretation of results. Following the list of main supervisors

- Gerhard Barmen (Lund University, Sweden)
- Torleif Dahlén (Lund University, Sweden)
- Jan-Erik Rosberg (Lund University, Sweden)
- Alfredo Mendoza (LU Lund University, Sweden)
- Esben Auken (Aarhus University, Denmark)
- Alfredo Duran (Universidad Mayor de San Simón, Bolivia)
- Galo Muñoz (Universidad Mayor de San Simón, Bolivia)
- Mauricio Villazon (Universidad Mayor de San Simón, Bolivia)
- Ramiro Pillco (Universidad Mayor de San Andrés, Bolivia)

PhD students and field logistic coordinators: Andres and Etzar were doctoral candidates that used the collected information from this project for their theses. They successfully defended their theses. They were in charge of designing, coordinating and executing the field work.

- Andres Gonzales Amaya (UMSS/LU)
- Etzar Gomez (UMSA/LU)

Master and Bachelor students: All these students participated in one of the six campaigns performed during this project. The retrieved information in each campaign was used for their MSc or BSc theses.

- Måns Larsson (Lund University, Sweden)
- Joakim Mårdh (Lund University, Sweden)
- Viktor Broman (Lund University, Sweden)
- Emil Svensson (Lund University, Sweden)
- Giulia De Pasquale (University of Lausanne, Switzerland)
- Sulmayra Zarate (Universidad Mayor de San Simón, Bolivia)
- Hanner Pilser (Lund University, Sweden)
- Alexander Bergman (Lund University, Sweden)
- Mire Persmark (Lund University, Sweden)
- Rafael Mendoza (Universidad Técnica de Oruro, Bolivia)
- Alfredo Rojas (Universidad Mayor de San Simón, Bolivia)
- Yerko Sempertegui (Universidad Mayor de San Simón, Bolivia)
- Boris Almanza (Universidad Mayor de San Simón, Bolivia)
- Tomas Gutierrez (Universidad Mayor de San Simón, Bolivia)
- Evelin Medina (Universidad Mayor de San Simón, Bolivia)
- Nicolai Friis (Aarhus University, Denmark)
- Micaela Pedrazas Hinojosa (Colorado School of Mines, USA)
- Michelle Pedrazas Hinojosa (Colorado School of Mines, USA)
- Daglin Camacho (Universidad Mayor de San Simón, Bolivia)
- Daniel Gareca (Universidad Mayor de San Simón, Bolivia)
- Veymar Gareca (Universidad Mayor de San Simón, Bolivia)

Volunteers: The following volunteers took part in the field work:

- Rafael Mendoza
- Elvis Ferrufino
- Jonathan Larrea
- Carlos Ala
Private companies: Without the support of private companies the field work and the interpretation process of data would have been difficult. Corimex supported with the access of ERT equipment during the first campaign in 2016, in-kind support in the field during several campaigns as well as logistic support. Guideline Geo contributed with valuable in-kind support, and access to equipment during one of the field campaigns. Aarhus GeoSoftware contributed by providing access to specialized software and were very helpful when enquires were needed during the pre and post processing of data.

- Aarhus GeoSoftware
- Guideline Geo
- Corimex (Bolivia)

Local governments, institutions and organizations. All the following local institutions contributed during the field work and data collection. Without the cooperation of local municipalities, the access in Cochabamba were not possible. Some other institutions collaborated by proving valuable information such as drilling and lithological reports.

- Municipality of Punata
- UTO (Technical University of Oruro)
- SELA (Oruro’s waterworks company)
- MMAYA (Ministry of environment and water)
- SERGEOMIN (Geological survey of Bolivia)
- UNASBVI (Sanitation and housing division of Oruro’s government)
- Asociación de usuarios de pozos de Punata (Association of deep well owners in Punata)
- SEMAPA (Drinking water and waste water division of Cochabamba)

Lessons learned

Improvement of geophysical knowledge

During this project three local universities were involved: Universidad Mayor de San Simón (UMSS), Universidad Mayor de San Andrés (UMSA), and Universidad Técnica de Oruro (UTO). Each university have different units that have collaborated during this project. The most active units were: Centro Agua (UMSS), Laboratorio de Hidráulica (UMSS), CASA (UMSS), Instituto de Hidráulica e Hidrología (UMSA), and Departamento de geología (UTO). The participation of these universities allowed to train several Bolivian bachelor and postgraduate students. Something to highlight is that Geophysics is not part of any University in Bolivia, therefore, this project allowed to gain basic knowledge and application of geophysics, which will be useful in a near future for solving engineering and environmental problems.

Andres Gonzales from UMSS/LU successfully defended his doctorate thesis, including 4 published peer reviewed articles and one submitted manuscript, in October 2018 and received his degree. He has since then returned to UMSS and is now employed as permanent staff member at UMSS. This opens excellent opportunities for consolidation of the project outcomes, with regards to management and qualified use of existing equipment and software acquired within the framework of this project. Furthermore, training of new generations of students.

Etzar Gomez from UMSA/LU defended his doctorate thesis in October 2019, including 4 published peer reviewed articles. Due to the uncertain employment situation in Bolivia, with no commitment towards a position at the home university plus the unstable political situation he remains in Sweden. He is at the moment working on a project basis with processing helicopter borne TEM (SkyTEM) data at Lund University on commission from the Swedish Geological Survey.

Furthermore, the data collected from 2016 field campaigns were presented in two MSc thesis reports at Lund University, by Måns Larsson and. The data from the 2017 field campaign at Challapampa were presented in an
MSc thesis at Lund University by Viktor Broman and Emil Svensson. The 2017 Pucarani data were summarized in a BSc report at Aarhus University by Nicolai Friis Mortensen. The Chocaya results were presented in two MSc theses, one by Hanner Pilser and the other by Alexander Bergman and Mire Persmark.

Project results have also been presented in different occasions. Four public seminars have been organized in Bolivia, two each in Oruro and Cochabamba respectively. The first two seminars were held in June-July 2016 in connection with the start of the project, with the aim to inform the collaboration partners and other interested local parties in our present and planned activities. One follow-up seminar was held in each place in March 2017 to present and discuss results so far along with plans for continued work. The meetings were hosted by the local academic counterparts Geology Dept., Oruro Technical University (UTO), and Centro AGUA, Universidad Mayor de San Simon (UMSS). We intended to arrange the final seminars on site in Bolivia during spring 2020, but it was not possible due to the Covid-19 pandemic. Additionally, a one-week course was given to MSc Students from UMSS about “Introduction to Geophysics”, the teacher was Andres Gonzales Amaya.

Recommendations

In order to avoid problems during the fieldwork, we advise to first get agreements (better if they are written and signed instead of verbal communication) with the rural communities were the fieldwork is going to be held. Otherwise, it is a time consuming task doing the agreement during the fieldwork, moreover, without the agreement it might be possible that people will refuse to have people in their lands.

Both ERT/DCIP and TEM are well suited for hydrogeological applications in the test areas, and the methods complement each other well. There are several modern ERT/DCIP systems in Bolivia, at universities as well as at authorities, but no TEM equipment to our knowledge. Due to the costs and logistics of renting and bringing equipment in and out Bolivia, it is recommended to try to source funding for the purchase of a TEM system for future projects, to be managed for example by UMSS. Airborne TEM could be a valuable tool for providing areal coverage over larger areas and avoiding gaps due to restrictions in access to land. Gaps in the data coverage due to electrical disturbances could be filled in by ERT which is more robust in that sense.

We advise to keep promoting this kind of projects in Bolivia and countries where geophysics is not part of any university career or is not well developed. The experience from this project shows that students at different levels can be excellent promoters of the advantages of geophysics for solving engineering and environmental problems, consequently in the near future we hope that the universities will be aware about the importance of having geophysics among their curricula.

Conclusion

Groundwater resources in the studied areas are under threat due to over-exploitation and risk for contamination. Informed management and planning is essential for protection of the resource.

Geophysics had a key role in increasing the knowledge on the local groundwater systems, particularly regarding aquifer geometry, groundwater flow and water quality. The new knowledge is a valuable asset for planning of sustainable use and protection of the groundwater.

A total of 93 kilometres of ERT/DCIP, and 460 TEM soundings were performed during the six field campaigns. ERT and TEM were very well suited for mapping aquifers in the field study areas, and the methods complemented each other well. DCIP (time-domain induced polarization) provided valuable additional information in some cases. Signal disturbance due to infrastructure such as powerlines, metal fences and metal trash created gaps in the data coverage for the TEM method, whereas road crossings generated gaps in the ERT/DCIP lines.

Access to the field areas was in parts of the study areas severely restricted due to social tension created by conflicts concerning the use of groundwater. A close collaboration with local authorities, as well as information to and dialogue with local communities, is essential in this type of projects.
The training of Bolivian and Scandinavian students in geophysical methods was successful. A total of 2 PhD degrees, 7 MSc degrees, 7 BSc degrees were earned.

Transfer of knowledge to local authorities were done by holding 4 seminars with local authorities. Also support to Universidad Mayor de San Simon was given by allocating a computer and software for processing and inversion of ERT/DCIP/TEM data licensed and installed on the computer. This will facilitate the data processing of future geophysical projects.

In general, the geophysical data and results from this project will be very useful for further plans where a sustainable groundwater use and protection is pursuit.
References


Eight peer reviewed scientific articles have been published in total, and one review paper intended for. Project results have also been presented in the IAH 2016 congress in Montpellier 25-29th September, the GWB session at SAGEEP 2017 in Denver 19-23 March, at the annual meeting SEG 2017 in Houston 24-27th September, at the NovCare 2017 conference in Dresden 6-9 June, at the IAH 2017 congress in Dubrovnik 25-29th September, at the 3rd International Conference on New Approaches to Groundwater Vulnerability 2018 in Ustron 4-8 June, at The 5th IAHR Europe Congress in Trento 12-14th June 2018, and at the 24th Near Surface Geoscience Conference and Exhibition 2018 in Porto 9-12 September.

Peer review articles:


Conference abstracts / proceedings


Student theses and reports

• Larsson M. (2016) TEM investigation on Challapampa aquifer, Oruro Bolivia, Geology Dept., Lund University, Master’s thesis no 494, 44p.
• Gutierrez T. and Medina E. (2019), Modelación directa e inversa del campo electromagnético inducido y resistividad eléctrica para un medio con anisotropía azimutal en presencia de campo electromagnéticos transitorios, Universidad Mayor de San Simon, BSc thesis (written in Spanish).
• Torrico A. (2016) Caracterización de las unidades hidrogeológicas en el abanico aluvial de Punata mediante el uso de métodos geo-eléctricos, Universidad Mayor de San Simón, BSc thesis (written in Spanish).
Appendix 2: Photos and Videos

We have published a significant number of pictures on our website:
http://bolivia.blogg.lu.se/

Pictures are found on many of the pages, but the following five can be mentioned in particular:
http://bolivia.blogg.lu.se/projects/challapampa/pictures/
http://bolivia.blogg.lu.se/projects/punata/pictures/
https://bolivia.blogg.lu.se/projects/pucarain-el-alto/pictures/
https://bolivia.blogg.lu.se/projects/chocaya/pictures/