INTERNATIONAL COURT OF JUSTICE

DISPUTE OVER THE STATUS AND USE OF THE WATERS OF THE SILALA

(CHILE v. BOLIVIA)

COUNTER-MEMORIAL OF THE PLURINATIONAL STATE OF BOLIVIA

ANNEXES 17 - 18

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LIST OF ANNEXES TO THE COUNTER-MEMORIAL OF THE PLURINATIONAL STATE OF BOLIVIA

VOLUME 5

ANNEXES 17 - 18

Annex 17

Danish Hydraulic Institute (DHI), *Study of the Flows in the Silala Wetlands and Springs System,* 2018

Annex G: Integrated Surface Water / Groundwater Modelling

(Original in English)

Contract CDP-I No 01/2018, Study of the Flows in the Silala Wetlands and Springs System

Product No. 2 – 2018 Final Report

Annex G: Integrated Surface Water - Groundwater Modelling

Plurinational State of Bolivia, Ministry of Foreign Affairs, Diremar

July 16, 2018

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CONTENTS

FIGURES

TABLES

DOCUMENTATION OF THE STUDY

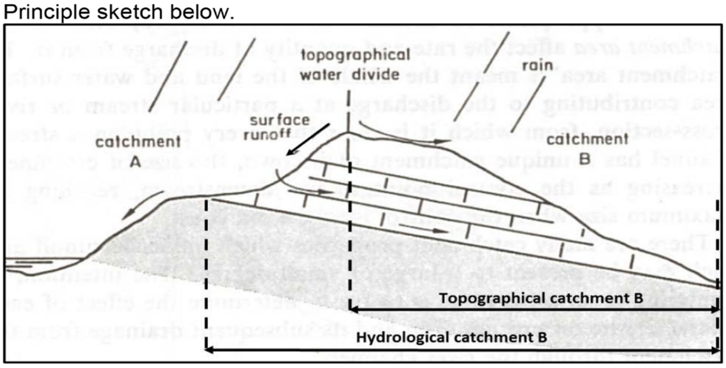
Main Report Containing the summary and conclusions

Technical Annexes:

Annex A.	The Silala catchment
Annex B.	Climate analysis
Annex C.	Surface waters
Annex D.	Soil Analyses
Annex E.	Water balances
Annex F.	Hydrogeology
Annex G.	**Integrated surface water – groundwater modelling (this annex)**
Annex H.	Natural flow scenarios
Annex I.	Questionnaire put by the Plurinational State of Bolivia to DHI

Glossary

Term	*Meaning/Definition*
Aquifer	Geological formation capable of storing, transmitting and yielding exploitable quantities of water.
Austral summer	Summer period in the Southern Hemisphere.
Basin	Area having a common outlet for its surface runoff.
Catchment	The whole of the land and water surface contributing to the discharge at particular stream cross section. This means that any cross section of a stream will have a unique catchment of its own. (Wilson, 1978).
Confined aquifer	Confined aquifers are aquifers that are overlain by a confining layer, often made up of clay or other geological formations with low permeability.
Depression, terrain depression or sink	A depression (or sink) is a low point in the terrain surrounded by higher ground in all directions. If the soil is impervious, the depression collects rain water from a local catchment. Surface water or groundwater inflows will accumulate in the depression until: - the water level reaches the nearest terrain threshold and runs off or - the evaporation from the depression is equal to its combined surface water groundwater inflows. However, a depression may also drain sub-superficially to lower lying areas through pervious soils, geological faults or groundwater aquifers.
Desert climate	Desert climate (in the Köppen climate classification BWh and BWk, sometimes also BWn), also known as an arid climate, is a climate in which precipitation is too low to sustain any vegetation at all, or at most a very scanty shrub and does not meet the criteria to be classified as a polar climate.
Digital elevation model (DEM)	Data files holding terrain levels often organised in a quadratic grid with a certain cell size (e.g. 30m by 30 m). They are very convenient tools for and often used as standard tools in Geographic Information Systems (GIS) for delineation of topographical catchment and for many other purposes.
Discharge	Volume of water flowing per unit time, for example through a river cross-section or from a spring or a well.
El Niño	El Niño is the warm phase of the El Niño Southern Oscillation (commonly called ENSO) and is associated with a band of warm ocean water that develops in the central and east-central equatorial Pacific (between approximately the International Date Line and 120°W), including off the Pacific coast of South America. El Niño Southern Oscillation refers to the cycle of warm and cold temperatures, as measured by sea surface temperature (SST) of the tropical central and eastern Pacific Ocean. El Niño is accompanied by high air pressure in the western Pacific and low air pressure in the eastern Pacific. The cool phase of ENSO is called "La Niña" with SST in the eastern Pacific below average and air pressures high in the eastern and low in western Pacific. The ENSO cycle, both El Niño and La Niña, causes global changes of both temperatures and rainfall.

Evapotranspiration	Combination of evaporation from free water and soil surfaces and transpiration of water from plant surfaces to the atmosphere.
Food and Agriculture Organization of the United Nations (FAO)	Specialized agency of the United Nations that leads international efforts to defeat hunger. FAO is also a source of knowledge and information, and helps developing countries in transition modernize and improve agriculture, forestry and fisheries practices, ensuring good nutrition and food security for all.
Geographic Information System (GIS)	A geographic information system (GIS) is a system designed to capture, store, manipulate, analyse, manage, and present spatial or geographic data.
Groundwater	Subsurface water occupying the saturated zone (i.e. where the pore spaces (or open fractures) of a porous medium are full of water).
Hydrogeological Conceptual Model (HCM)	The conceptual understanding of the individual components in a hydrologic system (i.e. groundwater, surface water, and recharge) and the processes involved between each component.
Hydrogeological Framework Model (HGFM)	A three-dimensional geologic model that defines the spatial extent of stratigraphic and structural features. The development of the HGFM incorporates topographic, geologic, geophysical, and hydrogeologic datasets.
Hydrological catchment	The hydrological catchment is the total area contributing to the discharge at a certain point. The hydrological catchment includes all the surface water from rainfall runoff, snowmelt, and nearby streams that run downslope towards a shared outlet, *as well as* the groundwater underneath the earth's surface. Since groundwater may cross the topographical divides a hydrological catchment to a point may be larger than the corresponding topographical catchment as indicated in the Principle sketch below. 
Infiltration	The movement of water from the surface of the land into the subsurface.
Penman-Monteith	Method for estimating reference evapotranspiration (Et0) from meteorological data. It is a method with strong likelihood of correctly predicting ETo in a wide range of locations and climates and has provision for application in data-short situations.
Recharge	Contribution of water to an aquifer by infiltration.
Reference evapotranspiration (Et_0)	The evapotranspiration per area unit under local climate conditions from a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23. The reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely

	shading the ground. A good approximation to the maximum evapotranspiration that under a certain climate can evaporate from an area unit covered by an ever-wet short green vegetation (e.g. a wetland)
Remote sensing	Acquisition of information about an object or phenomenon without making physical contact with the object and thus in contrast to on-site observation. In current usage, the term "remote sensing" generally refers to the use of satellite- or aircraft-based sensor technologies to detect and classify objects on Earth, including on the surface and in the atmosphere and oceans, based on propagated signals (e.g. electromagnetic radiation).
Satellite	Artificial body placed in orbit round the earth or another planet in order to collect information or for communication.
Sensitivity analysis	Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be apportioned to different sources of uncertainty in its inputs.
Spatial variation	When a quantity that is measured at different spatial locations exhibits values that differ across the locations.
Spring	A spring is a place where groundwater emerges naturally from the rock or soil. The forcing of the spring to the surface can be the result of a confined aquifer in which the recharge area of the spring water table rests at a higher elevation than that of the outlet. Spring water forced to the surface by elevated sources are artesian wells. Non-artesian springs may simply flow from a higher elevation through the earth to a lower elevation and exit in the form of a spring, using the ground like a drainage pipe. Still other springs are the result of pressure from an underground source in the earth, in the form of volcanic activity. The result can be water at elevated temperature such as a hot spring.
Topographical catchment	A catchment delineated strictly by topographical divides of the terrain. The topographical catchment includes all the surface water from rainfall runoff, snowmelt, and nearby streams that run downslope towards a shared outlet. This is the correct catchment if all discharge is surface flow (i.e. no groundwater). The topographical catchment is often a good approximation to the catchment, particularly for larger catchments.
Weather station	A facility, either on land or sea, with instruments and equipment for measuring atmospheric conditions to provide information for weather forecasts and to study the weather and climate.
Wetland	A wetland is a land area that is saturated with water, either permanently or seasonally, such that it takes on the characteristics of a distinct ecosystem. The primary factor that distinguishes wetlands from other land forms or water bodies is the characteristic vegetation of aquatic plants, adapted to the unique hydric soil. Wetlands play a number of roles in the environment, principally water purification, flood control, carbon sink and shoreline stability.

1 Introduction

This annex to the final report of the study of the flows in the Silala Wetlands and Springs System documents the set up and calibration of an integrated surface water - groundwater model of the Silala Near Field Area. The model is used in scenario analysis (Annex H).

Numerical models are widely used for simulation of hydrological systems and for prediction of impacts of water management scenarios. An integrated surface water - groundwater model is developed for the Silala Near Field area, partly to describe the current flow system and partly as a management tool to assess the effects of specific changes.

2 Objectives

An integrated hydrological modelling tool of the Silala Near Field area is developed and used in scenario analysis. The main objective of the scenario analysis is to assess the differences between the current conditions (with canals), and a scenario where the canals are removed.

The integrated model is composed by interconnected hydrological components describing the surface and subsurface flow system. (Garraud, et al., 2003).

3 Integrated model

An integrated model refers to a numerical model tool built for simulating flows and water levels in an interlinked surface - subsurface hydrological system. Due to the diverse and spatially variable features of the Silala Near Field area, distributed flow properties must be considered when analysing the combined subsurface and surface water system. For this purpose, an integrated numerical modelling system have been developed. Apart from providing simulations of current flows, the model will be used in scenario analysis to assess the effect of a given change.

For the Silala Springs System, the impact of the manmade canals and drainage networks is assessed by comparing a baseline model with canals corresponding to current conditions and a model scenario where the canal and drainage system is removed. Flow results from the scenario model run, when compared to a model run of the current situation, will provide an estimate of the impacts of the manmade canal and drainage network on both surface flow and groundwater flow.

An integrated hydrological model includes dynamic flow exchange between hydrological domains. In the one-dimensional (1-D) surface water model (MIKE11), the drainage and canal network has been set up to exchange water with both the groundwater (3-D) and the surrounding wetland areas (2-D MIKE SHE OL) as a function of water level differences. This coupling allows description of canal spills, two-dimensional (2-D) flow across the wetlands and wetland flows into the canals. The subsurface coupling between the drainage and canal network and the groundwater aquifer simulates canal seepage losses driven by local water level gradients and losses via riparian zone evapotranspiration.

4 Conceptual model

A conceptual model of the combined surface water and groundwater system forms the basis for subsequent analysis of hydrology, water balances and flows. It presents the governing processes affecting the surface flows and groundwater flows in the Silala Near Field area under the current conditions. It also serves the purpose of outlining how the canalisation has changed the hydrological/hydrogeological system and thus impacted flows. The basis for the conceptual model is partly field visits and partly surface water and groundwater data collected during the field survey campaign in 2017 or earlier.

A conceptual model for the Silala surface water system is reported in Annex C. The surface water system is described and analysed in a 5-zone subdivision:

- Zone 1 : Northern wetland
- Zone 2 : Southern wetland
- Zone 3 : Southern canal, mid-section
- Zone 4 : Southern canal, ravine section
- Zone 5 : Confluence to border

The main surface water hydrological processes are summarized in Table 1.

Table 1 Overview of Silala Near field zones and key processes affecting surface flows.

Silala Near Field sub-area	Process	Specifics
Zone 1 : Northern Canal, Northern wetland and Zone 2 : Main Canal, Southern wetland	1. Distributed spring inflows 2. Wetland interception and storage 3. Evapotranspiration in wetlands and riparian zone 4. Canal and drain system seepage gains/losses to soil and groundwater 5. Diffuse inflows by groundwater 6. Canal-wetland spills and redistribution (1-D / 2-D) 7. Inundated areas and free water surface evaporation	Attenuation by wetland storage Capillary rise of peat soils Canal spilling at canal blockages Transpiration from wetland vegetation Canal seepage
Zone 3 : Main Canal, middle section	1. Distributed spring inflows 2. Evapotranspiration in riparian zone 3. Canal seepage gains/losses to riparian fringe and groundwater 4. Canal-wetland spills and redistribution (1-D / 2-D) 5. Inundated areas and free water surface evaporation	Flow in wide flow section in non-canalised reaches Riparian zone water uptake and evapotranspiration
Zone 4 : Main Canal, narrow valley section and Zone 5 : Near border section	1. Distributed spring inflows 2. Evapotranspiration in riparian zone 3. Canal seepage gains/losses to riparian fringe and groundwater	Restricted canal flow Narrow riparian fringe interaction with canal Groundwater discharge in narrow valley section

A conceptual subsurface hydrogeological model is presented in Annex F. Surface geological maps, resistivity profiles, borehole lithology and borehole tests were merged into a 3-D conceptual hydrogeological model of all major hydrogeological subsurface units.

Although groundwater flow in fractures and faults plays a role in the Silala area, the structural hydrogeological interpretation suggests that an equivalent porous media approach can be adopted. Consequently, the groundwater flow component of the integrated hydrological model solves the differential equations of matrix flow in a porous media.

Due to data constraints, the spatial scale and process description the integrated hydrological model cannot represent the physical hydrological system in detail. Instead, the numerical model is based on the conceptual model which despite simplification is assumed valid to represent the overall, key processes of the Silala Near Field area. The numerical model results thus rely implicitly on the validity of the conceptual model to properly account for key flow processes.

4.1 Numerical model approach

A numerical model of the current conditions including the canal and drainage network is developed. It is calibrated to provide a reasonable description of the measured canal flows (Annex C) at the 7 continuous flow gauging sites (C1-C7).

Flow measurements show a large base flow contribution by groundwater discharged to springs, wetlands and canals. Temporal fluctuations in measured flow records has been attributed to measurement inaccuracy and replacement of equipment rather than through a correlation between local rainfall events and short-term canal flow changes. The local runoff contribution is thus minor and of a short-term nature. For the purposes of the study the mean flow conditions are considered essential rather than short term fluctuations.

According to the water balance calculations for the Silala Far Field presented in Annex E, the mean recharge based on long meteorological time series is estimated to 176 l/s. The analysis considers a 231 km^2 upstream catchment and the specific recharge can be calculated to 0.76 $l/s/km^2$. Assuming a similar recharge within the Silala Near Field area covering 2.56 km^2 the corresponding local recharge from precipitation is less than 2 l/s. The local recharge by precipitation in the Silala Near Field Area is thus insignificant compared to the inflows across the model boundaries that sustain the cross-border canal outflows of approximately 150 l/s plus groundwater outflow. Consequently, local precipitation and runoff has not been included in the integrated Silala Near Field model.

Temporal changes in canal flow may otherwise occur through temporal variations in groundwater recharge and groundwater levels within the near field area or the larger upstream catchment. Groundwater level data collected by pressure transducers are only available for a short period. Most time series show limited or no variation in time (Annex F). The measurements suggest no significant temporal groundwater table changes.

Therefore, it is assumed that the Silala Near Field areas is close to steady-state and a stationary model approach has been adopted. A stationary model implies that no temporal variation in model inputs nor boundaries are included. The flow and water levels of both surface water and groundwater simulated by the model will reach an equilibrium of constant flow variables, inflows and outflows.

5 Numerical model code

The interactions between groundwater fed springs, the wetlands and the canal and drainage network require a suitable model approach. It also requires a model tool which is capable of addressing all relevant processes and interactions within the coupled groundwater-surface water system, as outlined in the conceptual models (Annex C on surface water, and Annex F on hydrogeology).

Only a few model codes have been developed to deal with interconnected subsurface and surface flows and only a few have been tested and widely applied in practical projects and water management within integrated surface water – groundwater systems. For the Silala project MIKE SHE is used. The MIKE SHE modelling system comprises of hydrological modelling components which can be added and interlinked depending on the nature of the specific hydrological system and the particular analysis required.

MIKE SHE – MIKE11 is an integrated and dynamically coupled hydrological modelling system. It is a well proven modelling tool which has been applied on a wide range of integrated projects related to wetlands, groundwater, surface water, climate change etc. Figure 1 shows the structure, components and governing equations of MIKE SHE.

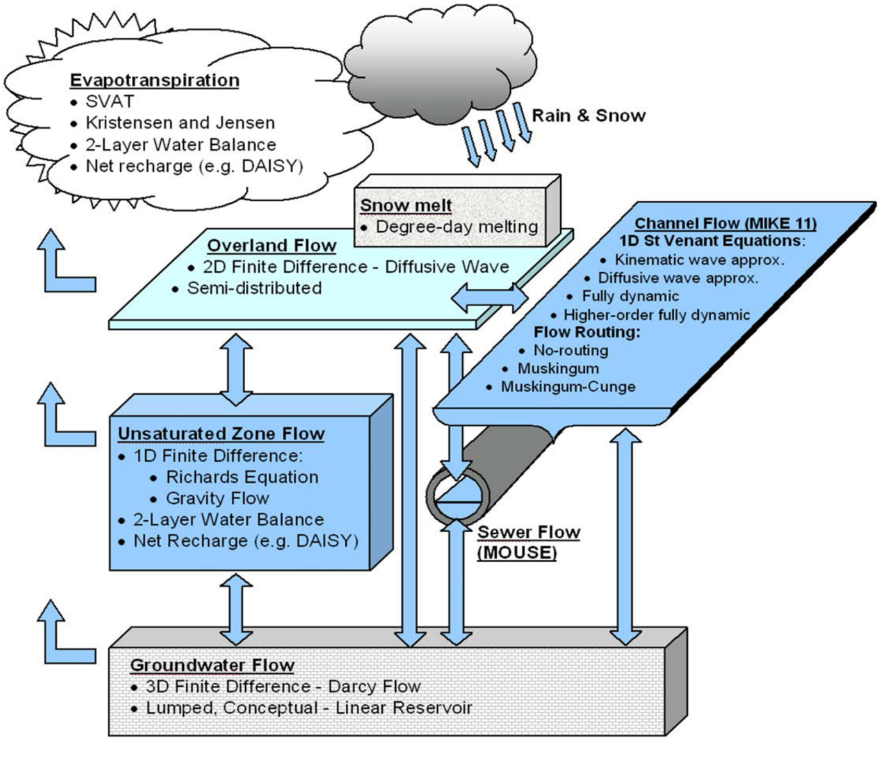


Figure 1 Model components and structure of the MIKE SHE – MIKE11 integrated model code.

A stand-alone groundwater model requires recharge as an input and interaction with surface water is described through boundary input data. This is problematic regarding Silala where the groundwater - surface water exchange is a dominating factor and essential in quantifying scenario impacts. The integrated model applied here has been chosen because exchange is a function of state variables and not fixed through boundary inputs. The coupling between model components makes the calculation of flow exchange between groundwater and surface water (through springs, diffuse sources and canal seepage) dependent on catchment specific physically properties (topography, canal geometry etc.) and actual stat variables (simulated water levels and gradients).

6 Model area and resolution

A horizontal and vertical extent of the model area must be defined. Given the purpose of the model, data availability and the key surface water features the horizontal extent of the integrated model has been chosen to incorporate the Silala Near field area. All Silala spring, wetland and canal features are represented within the model area.

The effects of removing the Silala Canals are most clearly expressed in surface water along the relatively narrow wetland and canal corridor but secondary effects of generally higher surface water levels will potentially influence the groundwater tables in a larger area. Effects on groundwater levels may not be spatially restricted to the canal and wetland corridor but may in principle propagate through the surficial aquifer towards the boundaries of the model. As a general rule, the effects of removing the canal on groundwater boundary conditions should be minimized by extending the model area sufficiently far away from the canal. Therefore, the model area is extended to cover a total of 2,56 km^2 (See Figure 2).

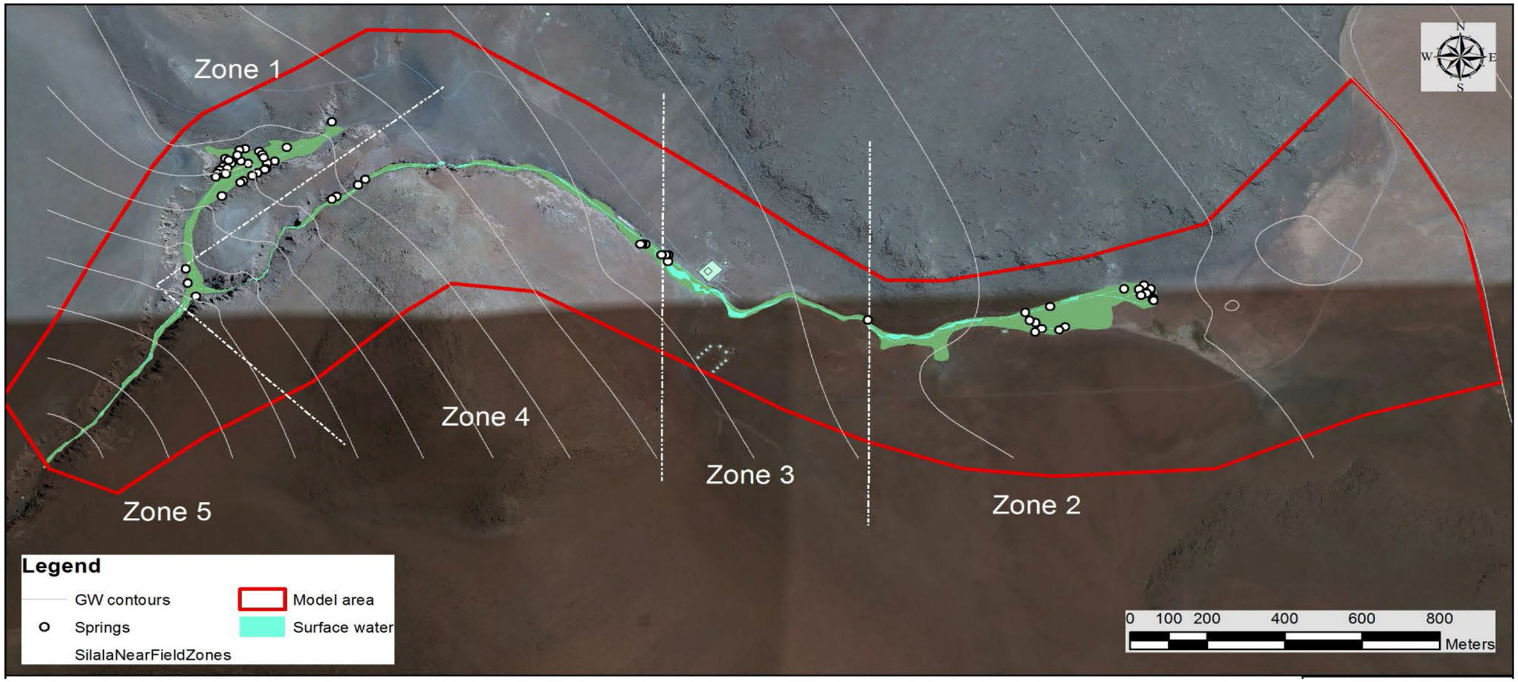


Figure 2 Silala Near Field model area.

The model area is subdivided into a finite difference grid of computational nodes. Water levels is calculated in each grid node and flow between nodes. Finite difference grid resolutions of 5 m and 10 m, respectively, were tested. The coarser resolution (10 m) provides a reasonably high resolution and is more efficient in terms of model run times. The higher resolution (5 m) takes much longer to run model simulations but is better suited for capturing details including any abrupt changes or heterogeneities e.g. in the wetlands and along the canal where simulation of water table gradients is important. Given the time constraints and the considerable time required to run calibration and scenario runs a 10 m grid was chosen. In the 10 m grid model, a total of 25632 grid elements are included in the overland flow solution and 76896 elements in the 3 layer groundwater model.

7 Hydrological model components

7.1 Groundwater

The 3-D groundwater model component is built to simulate groundwater levels, gradients, flow rates and flow direction in the subsurface of the Silala Near Field area. The groundwater discharge to the wetlands and springs and the flow exchange with the canal is of particular importance. A significant proportion of the water entering the Silala Near Field area through the subsurface as groundwater emerges as surface flow in the springs, wetlands and canal inside the Silala Near Field area. The surface water system is fed almost entirely by groundwater with a minor local runoff contribution as observed in approximately constant measured canal discharge.

7.1.1 Hydrogeological model

The 3-D hydrogeological model developed from geological maps, geophysical transects and borehole data (Annex F) is implemented in the numerical groundwater model. The hydrogeological units and their spatial extents defined in the hydrogeological model are represented in the numerical groundwater model. The hydrogeological units are described by the upper and lower interfaces of layers and lenses. Layers by definition cover the entire area while lenses have a restricted horizontal extent, only partly covering the model area.

The numerical groundwater model applies 3 layers. The top layer has varying thickness and hydrogeological properties as it incorporates all surficial lens deposits (HGU 1 – HGU 4). The second layer includes the upper Silala ignimbrite (HGU 5) and the third layer represents the deep ignimbrite layer (HGU 6). In the parametrization a distinction is made between the upper 0-200 m b.g.s. sequence as opposed to the lower 200-400 m b.g.s of HGU 6 to introduce at decreasing conductivity with depth. The fault zone (HGU 7) defined from the surface to a depth of 400 m cuts across the layers and introduces an approximately 50 m wide, high permeable flow corridor along the canals. The fault zone extends from upstream the southern and northern wetlands, joins at the confluence and continues across the border. Due to its relatively high permeability it is a key groundwater flow feature with respect to both groundwater discharge to the canals and the total groundwater flow.

Table 2 Hydrogeological units in the hydrogeological model and the numerical groundwater model.

Hydrogeologic Unit	Basic Lithology	Integrated model setup
HGU1	Colluvial deposits	Included as HGU1 lense
HGU2	Glacial deposits, sandy loams	Included as HGU2 lense
HGU3	Weathered lava flows	Included as HGU3 lense
HGU4	Felsic volcanic sequences	Included as HGU4 lense
HGU5	Ignimbrite deposits, low degree of welding	Included as HGU5 layer
HGU6	Ignimbrite deposits with a high degree of welding	Included as HGU6 layer
HGU7	Near canal fault zone	Included as HGU7 lense
HGU8	Volcanic neck of Silala Chico	Outside model area

7.1.2 Boundary conditions

In order to compute the groundwater flow and water level conditions at the outer model boundaries, boundary conditions must be assigned. As discussed in Annex E, the Silala Near Field area receives groundwater inflows from a larger catchment along parts of the model boundaries. An open flow prescribed fixed head boundary condition has been used along sections of the boundary where a head gradient allows inflow to the Silala Near Filed model area. The fixed head boundary implies that flow into the model area may change if the groundwater tables changes, e.g. due to changes in the surface water system. Increasing groundwater table inside the model propagating to the boundary will decrease flow gradients and inflow. Where the model boundary runs perpendicular to the head contour lines there is no water table gradient to drive inflows and the sections are subsequently assumed closed (no flow). At the downstream model boundary, at the border, a groundwater table gradient boundary condition is applied. ARCADIS 2017 calculated groundwater table gradients of approximately 0.05 between boreholes at the border and upstream of Quebrada Negra. The gradient boundary condition implies that groundwater flow across the boundary is adjusted to maintain the specified water table gradient.

Water level data available for the Silala Near Field area include piezometric levels from boreholes, spring water level and water levels recorded as part of the soil survey. The water level information has been processed to derive a piezometric contour map (Annex F). The highest density of observed water levels is found relatively close to the canals and wetlands, i.e. the central parts of the model area. The contour lines have been extrapolated away from the observation points which means that the uncertainty on the contours is higher at the model boundaries than the internal areas along the wetlands and canals. The contour data have been used as direct input for describing both an initial groundwater head map for the integrated model simulation and the boundary groundwater head values at the model boundaries of all groundwater layers (Figure 3). The groundwater table elevations range from 4420 m at the model boundary upstream of the southern wetland (east) to approximately 4290 m close to the downstream model boundary at the Bolivian-Chilean border (west). The groundwater contours indicate significant groundwater head gradients and inflows upstream of both the southern and northern wetland,

The observed water level data predominantly represent the near surface aquifer conditions and no data is available for the deep layer sequence of the groundwater system. The piezometric contour map has been used to define boundary conditions for all groundwater layers, which implies that any upward pressure gradients from deeper confined layers are not represented in the model boundary conditions. Horizontal flow gradients, e.g. at the southern wetland, thus drives inflows from the model boundary to the upstream springs and canals.

Pressure transducers installed in a number of boreholes were used for water level monitoring. Groundwater table elevations were collected for a relatively short period. The water tables were relatively stable with an average temporal variation of less than 0.5 m in all boreholes except two (Annex F). The groundwater head values assigned as boundary conditions in the integrated model have thus been considered constant in time. The inflow to the model area is a function of the assigned boundary head values, the hydraulic conductivity and thickness of the geological layers and the groundwater heads inside the model domain. With a fixed head upstream boundary and the downstream gradient controlled outflow boundary condition the stationary integrated model will gradually approach a steady-state equilibrium balancing upstream groundwater inflows versus downstream surface and subsurface outflows.

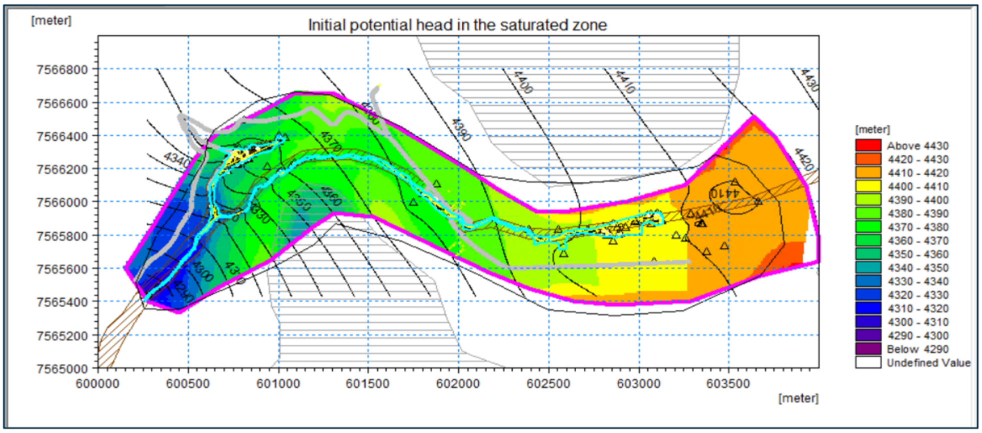


Figure 3 Groundwater level maps used in definition of groundwater component boundary conditions.

Figure 4 below shows an illustration of groundwater tables, cross sectional flow and discharge from an upstream head boundary towards a downstream surface water body.

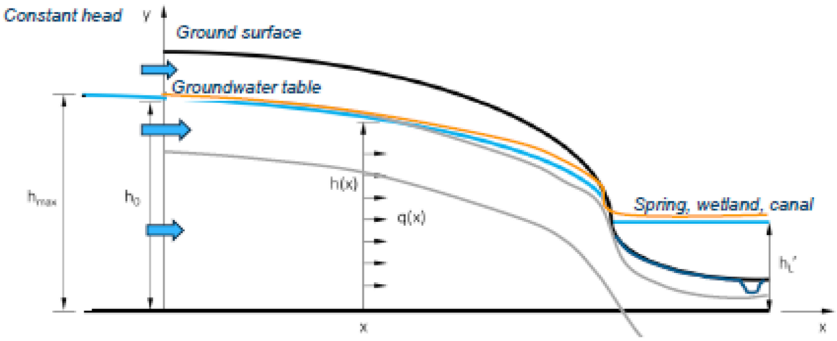


Figure 4 Illustration of groundwater boundary condition

7.1.3 Parametrization

Key parameters controlling groundwater flow and groundwater levels include vertical and horizontal hydraulic conductivities and storage coefficients. In Annex F hydrogeological parameters for the hydrogeological units are discussed based on published general ranges and Silala field data. The field data include borehole testing i.e. slug-testing, packer testing (Lugeon and Lefranc) and pumping tests to assess hydrogeological properties of the surrounding aquifer. Combining these data sources provides fairly wide parameter ranges (Table 3). However, during model calibration a narrower parameter range, mainly defined by the site-specific pump test data were used subdividing the model area by zones (see section 7.4).

Not all of the parameters are equally important and the model results are more sensitive to parameters of the main aquifer layers than local lenses. The key parameters are associated with the upper Silala ignimbrite covering the entire model area, the lower Silala ignimbrite and the high permeable fault zone (HGU 7). In comparison, HGU-1 and HGU-3 surface deposit lenses cover limited areas, are mostly dry and of low permeability.

Table 3 Initial ranges of hydrogeological parameters considered for the integrated model.

HGU	Kh (m/s)	Kv Kv:Kh-ratio	Sy (-)	Ss (-)	Comment
Colluvial/Alluvial (HGU-1)	$1e^{-6} – 1e^{-4}$	1 – 10	0.03-0.22	$5e^{-5} – 1e^{-4}$	Moderate extent, dry
Glacial, Sandy Loam (HGU-2)	$1e^{-8} – 1e^{-5}$	1 – 10	0.03-0.19	$9e^{-4} – 1.3e^{-3}$	Limited extent and flow, GW-SW exchange
Weathered Lava (HGU-3)	$1e^{-14} – 1e^{-8}$	1 – 10	0.01-0.19	$1.6e^{-6} – 2e^{-4}$	Moderate extent, mostly dry, largely impermeable
Felsic Volcanic (HGU-4)	$1e^{-13} – 1e^{-6}$	1 – 10	0.001-0.02	$3e^{-6} – 5e^{-5}$	Moderate extent, dry (confining)
Upper Silala Ignimbrite (HGU-5)	$1e^{-7} – 1e^{-5}$ ($1e^{-5} – 5e^{-4}$)	1 – 10	0.001 – 0.10	$3e^{-6} – 5e^{-5}$	Upper aquifer, local/regional flow unit. SW-GW exchange
Lower Silala Ignimbrite (HGU-6)	$2e^{-11} – 2e^{-7}$ ($1e^{-5} – 5e^{-4}$)	1 – 10	0.001 – 0.20	$3e^{-6} – 5e^{-5}$	Lower aquifer, local/regional flow unit.
Fault zone (HGU-7)	$6e^{-5} – 4e^{-4}$	1 – 10	0.01 – 0.20	$1e^{-5} – 1e^{-6}$	Key flow feature, local, SW-GW exchange

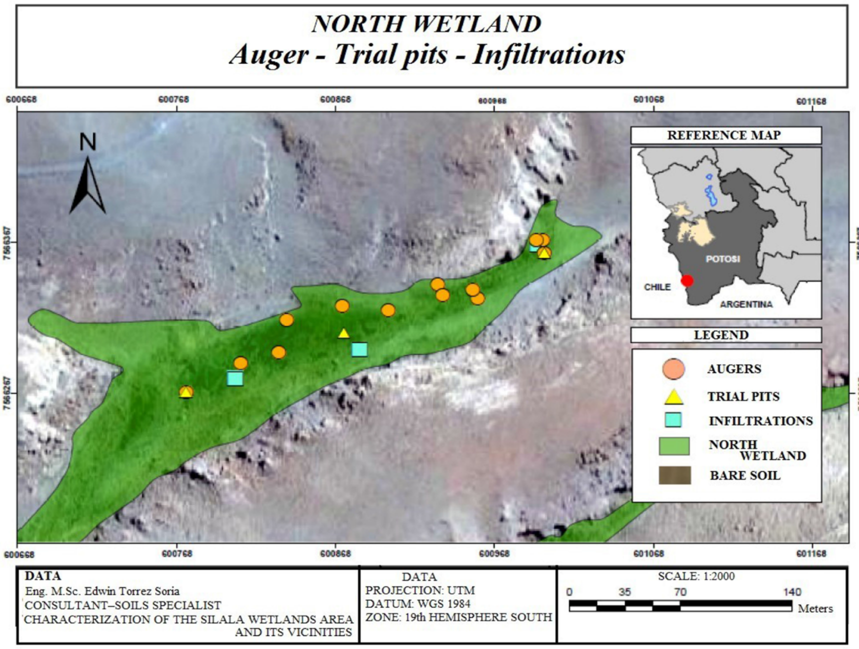
7.2 Unsaturated zone

The 1-D unsaturated zone forms an interface between the surface and the saturated conditions at the groundwater table below. Key processes included through the unsaturated zone component are infiltration or exfiltration in the vertical soil column and evapotranspiration losses occurring in the upper part of the soil profile (the root zone). In proximity of the springs, wetlands and canals where the groundwater table has been observed to be close to the surface the unsaturated soil thickness is shallow, typically within 0-1 m, but it increases towards higher elevations with relatively deep groundwater tables reaching up to hundreds of meters. The unsaturated zone normally controls the rate of infiltration of rainfall and potentially recharge of the underlying groundwater aquifer. In the Silala Near Field area local rainfall, infiltration and recharge is very low compared to the inflow of groundwater (Annexes A and E). However, at the wetlands with shallow groundwater tables the unsaturated zone may interact with the groundwater table and enhance upward directed flow by capillary forces to sustain the evapotranspiration of wetland vegetation. This is, in particular, the case in organic rich soils such as peat with a high storage capacity and high capillary potential.

The most distinct contrast between soils in the Silala Near Field area is between, on one hand, the wetland and riparian corridor soil profiles and, on the other hand the drier, higher altitude areas covering the remaining part of the model area. In the wetlands with generally shallow groundwater tables, sandy sediments and organic rich peat soils overlay the fractured rock (ignimbrite). In the higher altitudes the ignimbrite rock outcrops or is covered by a relatively thin coarse sediment layer.

7.2.1 Summary of soil survey

A field soil survey was conducted by DIREMAR, 2017, with the purpose of mapping soil profiles, estimating soil thicknesses and estimating soil hydraulic properties. A number of hand-dug pits and auger holes were carried out in the wetlands to characterize profiles (see Figure 5).



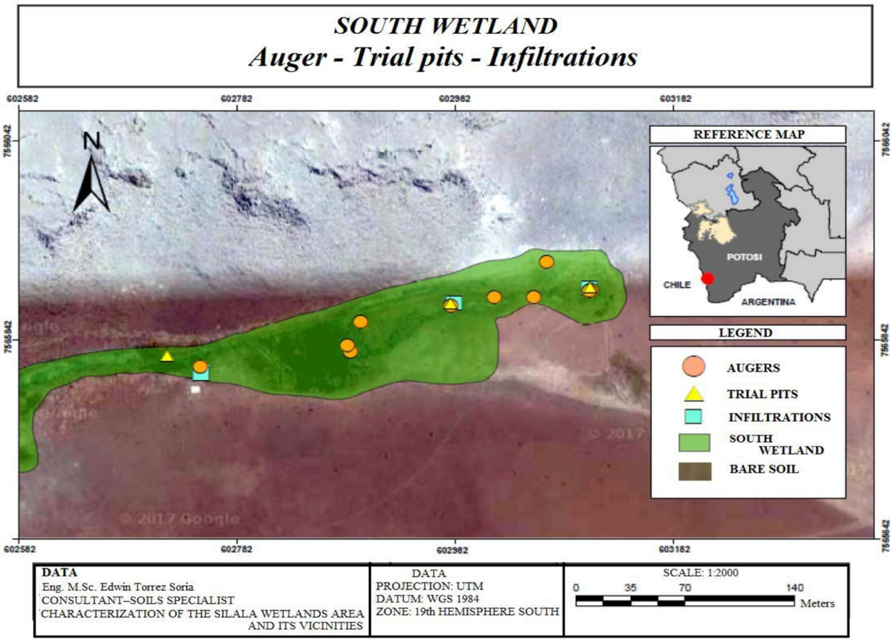


Figure 5 Soil sampling sites in Northern and Southern wetland.

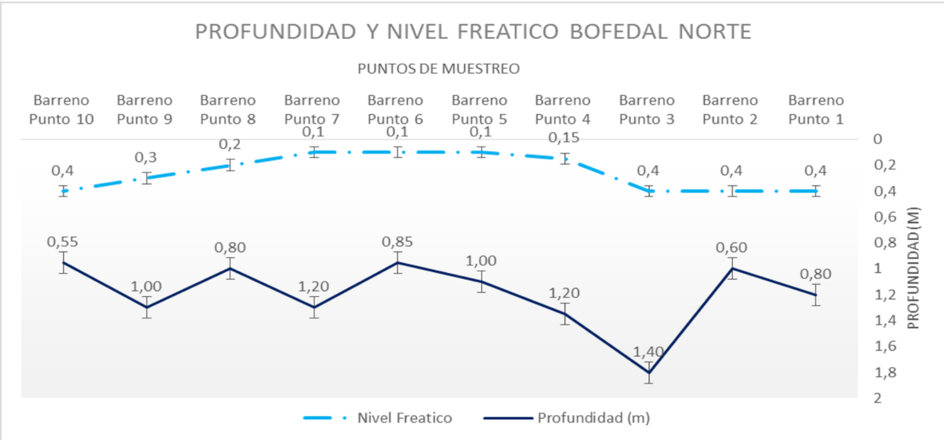


Figure 6 Soil thickness and ground water table profile, Northern wetland (in m below ground surface).

The soil profiles have been described by depth, i.e. from the ground surface to the underlying base rock (Figure 6). The soil profile depths range from 0.55 – 1.40 m in the northern wetland and 0.40 – 1.20 m in the southern wetland. The profiles are described by an organic material horizon followed by a predominantly mineral, sandy loam or gravel material. Organic material horizons of 0-40 cm were found. However, observations during the field trip showed peat soil depths of up to 60-70 cm at the edges of undisturbed patches of the northern wetland (Figure 7).

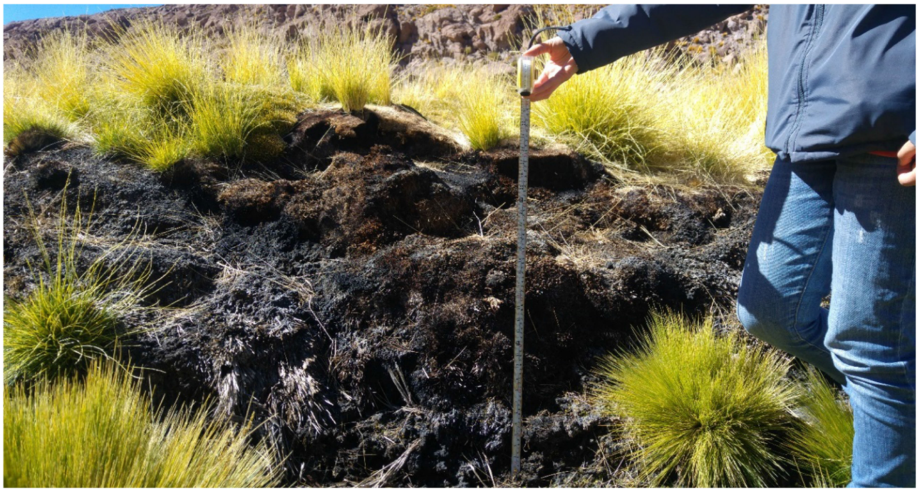


Figure 7 Peat soil profile at northern wetland.

Six characteristic soil profiles have been introduced in the Silala near field area to describe the vertical and horizontal hydraulic properties:

1. Rock, Ignimbrite : 0 – 100 m
2. Shallow soil on rock, Sandy loam : 0 – 0.15 m, Ignimbrite : 0.15 m – 100 m
3. Deep soil on rock, Sandy loam : 0 – 0.5 m, Ignimbrite : 0.15 m – 100 m
4. Shallow organic on sandy loam, Peat : 0-0.2 m, sandy loam : 0.2-1.0 m, ignimbrite : 1-100 m
5. Medium organic on sandy loam, Peat : 0-0.4 m, sandy loam : 0.4-1.0 m, ignimbrite : 1-100 m
6. Deep organic on sandy loam, Peat : 0-0.6 m, sandy loam : 0.6-1.2 m, ignimbrite : 1-100 m

The six profiles have been distributed across the Silala Near Field area. In the wetlands the distribution of shallow versus deep organic soils has been carried according to the soil survey, field visits and satellite images. Deep organic soils are only found in a limited number of undisturbed areas of the northern wetland. The shallow to medium organic soil are distributed within the remaining wetland areas and riparian corridor (Figure 8).

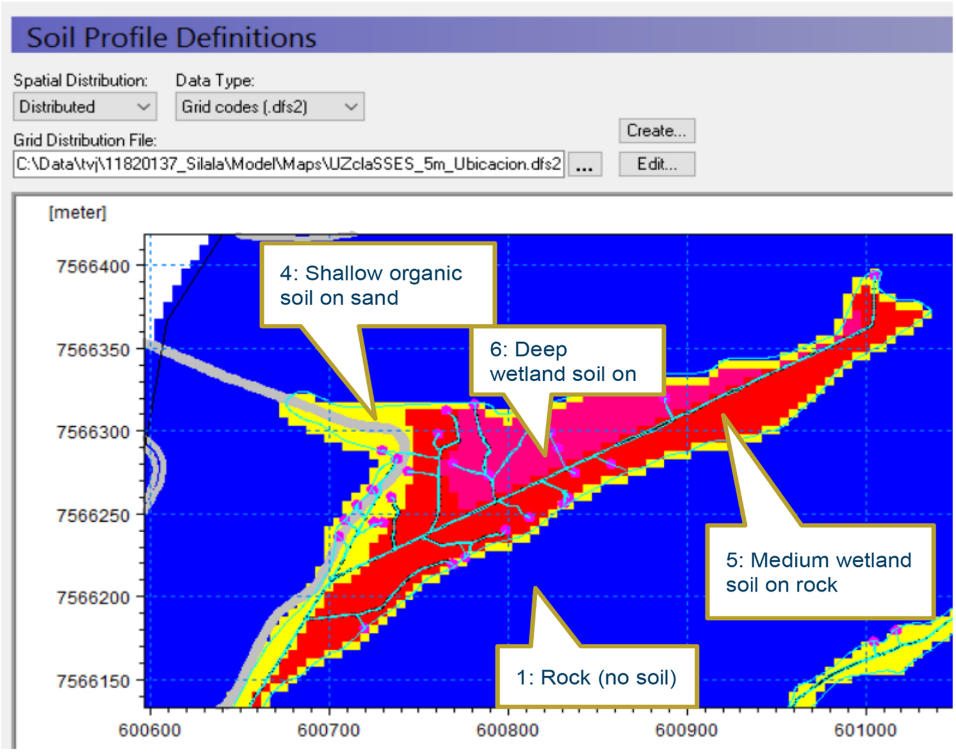


Figure 8 Soil profile distribution map (codes 1-6 referring to the above description), northern wetland.

7.2.2 Parametrization

The unsaturated zone component of the integrated hydrological model requires that a number of characteristic vertical soil profiles are defined and distributed across the model area. The profiles are described by depth intervals of specific soil types with associated hydraulic parameters in terms of soil water retention (relation between soil water content and pressure) and hydraulic conductivity curve (relation between hydraulic conductivity and pressure).

Hydraulic conductivity curves and retention curves have not been estimated as part of the Silala soil survey and laboratory tests. Londra P., 2010, tested a range of mixes between peat and mineral fractions to calculate van Genuchten parameters for both retention and hydraulic conductivity (Figure 9). The shape of the curve with water contents above 50 % at saturation and a significant drop to field capacity (pF=2) are characteristic for organic rich soils and have been adopted in the peat soil retention curves applied in wetlands.

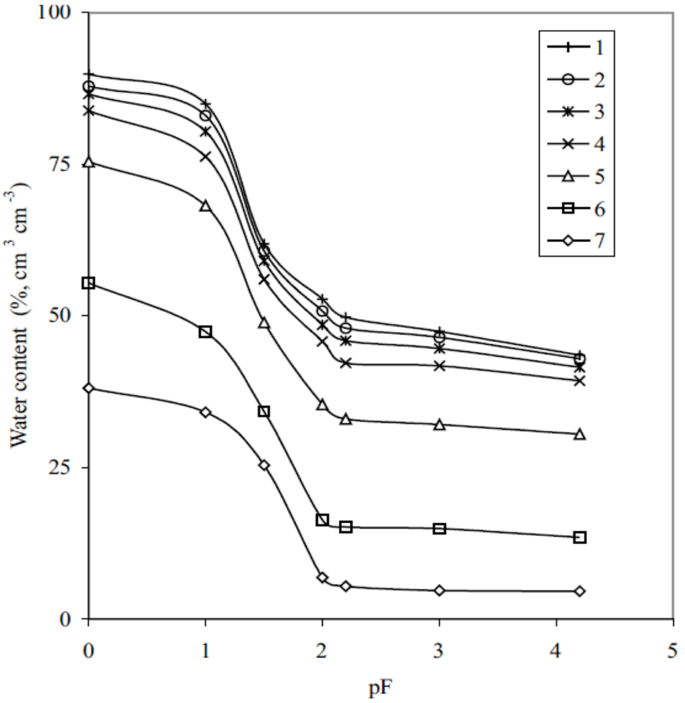


Figure 9 Soil retention curves (peat dry matter content ranging from 60 % (1) to 0 % (7)), Londra P., 2010.

Schwärzel et. al. 2006 tested decomposed peat core samples from German fen bogs to determine hydraulic properties and van Genuchten parameters in the laboratory. The van Genuchten analytical model was fitted to measured retention data points and saturated hydraulic conductivity value measured using a constant head method. All of the peat core hydraulic conductivity curves showed a similar shape but with different saturated hydraulic conductivity values (K_s). The curve shape parameters were used in parametrisation of Silala peat soil (Table 4). Both the organic rich wetland soil and finer grained sand deposits have a capillary potential. In the wetlands an upward flow can occur either by vertical groundwater flow (as observed by groundwater piezometric levels above ground level in standpipes and observation wells) or by soil capillary forces generating a capillary fringe with upward unsaturated flow. The upward flow maintains a high water content close to the ground surface in low lying areas with a continuous water supply for evapotranspiration.

Table 4 Overview of unsaturated zone property ranges

Soil	Hydraulic conductivity K_s (m/s)	Water content, saturation θ_{sat} (-)	Water content, residual Θ_r (-)	Inverse air entry suction α (cm^{-1})	Pore size distrib. n (-)
Peat soil	5e^{-7} – 5e^{-4}	0.55 - 0.75	0.10 - 0.25	0.2-0.4	1.10-1.50
Sandy loam	1e^{-6} – 1e^{-4}	0.25-0.45	0.01 – 0.10	0.01-0.1	1.00-1.45
Ignimbrite rock	1e^{-7} – 1e^{-4}	0.01-0.10	0.01-0.05	0.05-0.1	1.10-2.50

7.2.3 Evapotranspiration

Evapotranspiration (ET) losses occur partly by evaporation from the surface and the top soil and partly by transpiration by vegetation. Evapotranspiration varies temporally and spatially as a function of not only climate, soil and vegetation parameters but also water availability. The Silala area is characterised by relatively high potential rates of evapotranspiration due to the climate conditions but the actual rate of evapotranspiration is typically much lower. Actual rates of evapotranspiration approach zero in drier upland areas while in the lower lying wetland areas water is available to maintain rates of actual evapotranspiration close to the potential rate. The lack of vegetation outside the confined wetland areas is a clear sign of the contrast in water availability and thus transpiration potential.

In the distributed, integrated model, actual rates of ET are calculated as the sum of evaporation from free water surfaces, soil evaporation and transpiration by the vegetation. An assigned potential rate of ET constitutes an upper limit for the actual ET losses in each time step of the model simulation. A detailed description of the method and equations solved in the evapotranspiration component of MIKE SHE is given in DHI, 2017.

Two types of vegetation are dominant in Silala. Grass species either at the outer edges of wetlands and the riparian corridor or intrusive in drained and dry areas of wetlands. In undisturbed and permanent wet parts of the wetlands altiplano bofedal species of Distichia is dominating and forms hard, undulating cushions which in time adds to the peat accumulation (e.g. Distichia Muscoides). Outside the wetlands there is no or locally very scattered irregular grass.

Transpiration by the vegetation is a function of the density of vegetation expressed by the leaf area index (LAI) and the root depth and root mass distribution. An empirical function adjusts the actual rate of ET to LAI. Leaf area index (LAI) is a key parameter controlling the rate of actual evapotranspiration. Vegetation data have not been collected as part of the field survey. Due to the lack of site-specific vegetation property data vegetation parameters have been approximated by general and similar grassland and wetland vegetation type characteristics.

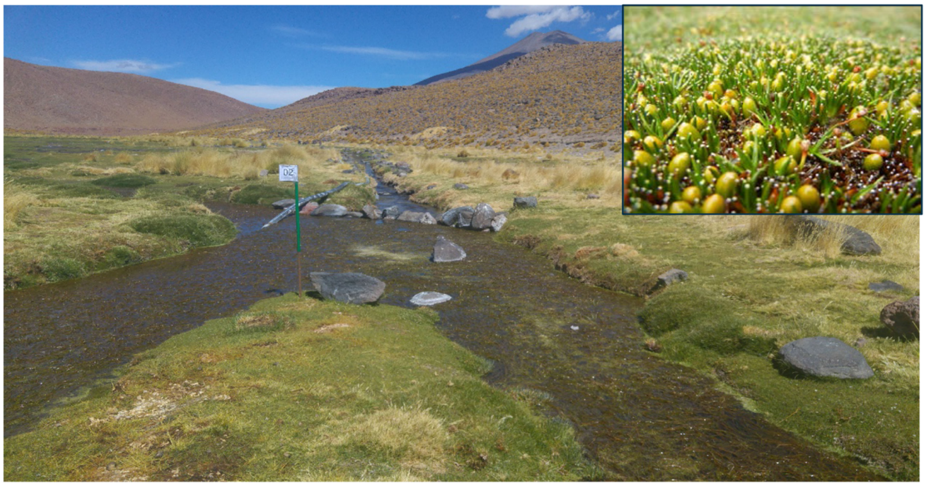


Figure 10 Grasses and cushion wetland vegetation at Silala southern wetland. Close up of distichia (photo from Fonkén 2014)

The average rate of potential ET (Annex B) ranges between 1268 mm/year – 1940 mm/year from climate stations at Sol de Manana, Laguna Colorado and Silala. At the Silala station, the long-term average is 1472 mm/year. A mean potential rate of 4 mm/day corresponding to 1460 mm/year has been used in the integrated model.

Table 5 Estimated ET parameters (LAI).

Vegetation	LAI
Grass	3.0
Wetland species	3.0

7.3 Overland and channel flow

The surface water components of the integrated hydrological model includes a 1-D canal network flow component (MIKE11) linked with a 2-D overland flow component. The 1-D model simulates flows and water levels within the canal and the 2-D overland model simulates water levels and flows on the ground, i.e. inundation in wetlands and areas adjacent to the canal. The 1-D canal flow model and the 2-D overland model are connected. Exchange of flow is described as a function of the water level gradient between the canal and adjacent flooded areas.

The surface water model has been built and tested prior to the integration with sub-surface components (Annex A). This preliminary surface water model has been tested to determine if the conceptual model, the input data and reasonable parameter ranges will provide model simulations results in accordance with measurements.

The main purpose of the Silala Springs study is to assess Silala canal flows and the effect of canalisation. The flow at the border is a function of climate, hydrogeology, hydrology and hydraulics connected in a series of upstream to downstream processes. From the net recharge and inflows feeding the spring and canal system storage, losses and gains play a key role with respect to the Silala water balance and thus, the quantity of water available for downstream canal flow.

The extent of the surface water systems in Silala is restricted to the spring areas, wetlands, the drainage and canal network and the adjacent, narrow riparian corridor. The surface water model includes a hydraulic canal component. The surface water model includes 46 canals and covers approximately 6600 meters of canal and wetland.

The data used to set up the 1-D canal model includes the canal alignment, topographical data, locations of structural changes to the undisturbed canals and boundary conditions as collected through field surveys and inspections during 2017.

7.3.1 Artificial channel alignment

The digitisation of the artificial channel alignment is primarily based on a shape file provided by DIREMAR and SENAMHI. This shape files represents known canals and drainage features. In addition to this, branches are included by inspection of the orthophoto from the 2016 drone survey. Where the photo indicates an open canal connected to the main canal system a branch is included. An overview of the area is shown in Figure 11. A more detailed view of the upstream end of the Southern Wetland can be found in Figure 12. This picture illustrates how the artificial channel alignment, represented by red lines, were constructed. Altogether, the model includes 46 individual branches with a combined length of approximately 6600 meters to describe the canal and drainage network.

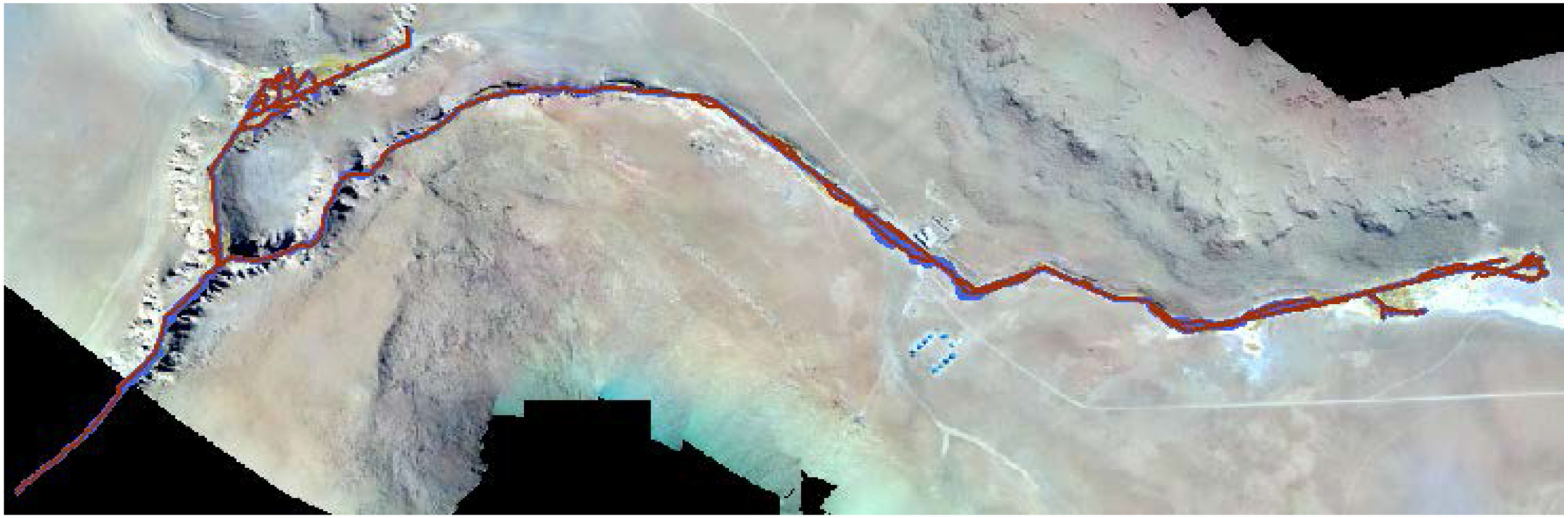


Figure 11 Layout of the artificial channel alignment in the hydraulic model shown on top of the orthophoto of the area.

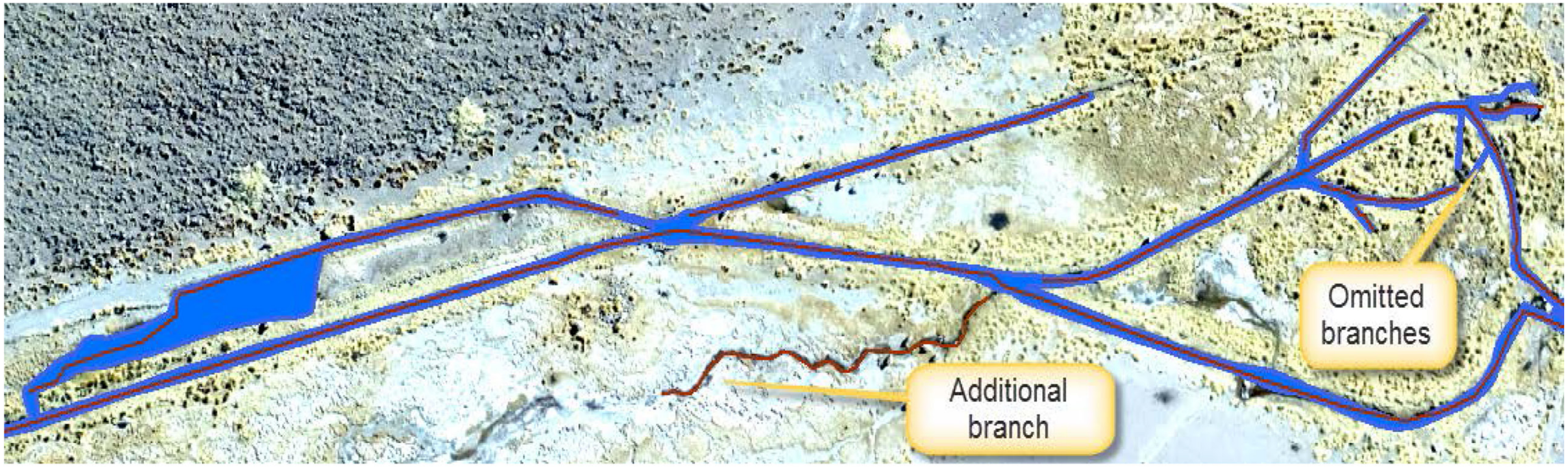


Figure 12 Artificial channel alignment in the upstream end of the Southern Catchment. The red lines represent the hydraulic model, the blue polygon is the shape file from DIREMAR showing were the canals/conveyers are located.

7.3.2 Canal cross sections

Each of the canals in the model must have cross sections attached to it. The cross sections define the storage in the canal, basically by describing the flow area, i.e. the width as a function of level. The slope and the conveyance of the canal are also defined by the cross sections. DIREMAR and SENAMHI provided a pdf file, based on data obtained by the IGM (206), showing width and depth for the canals in which cross sections has been surveyed. An overview of this file is shown in Figure 12. Close-ups of the different parts of the Main Canal System are shown are shown in Figure 13 - Figure 23. Close-ups for the North Canal System are shown in Figure 24 and Figure 25. For canals with no cross-section information an assumed cross section width is used.

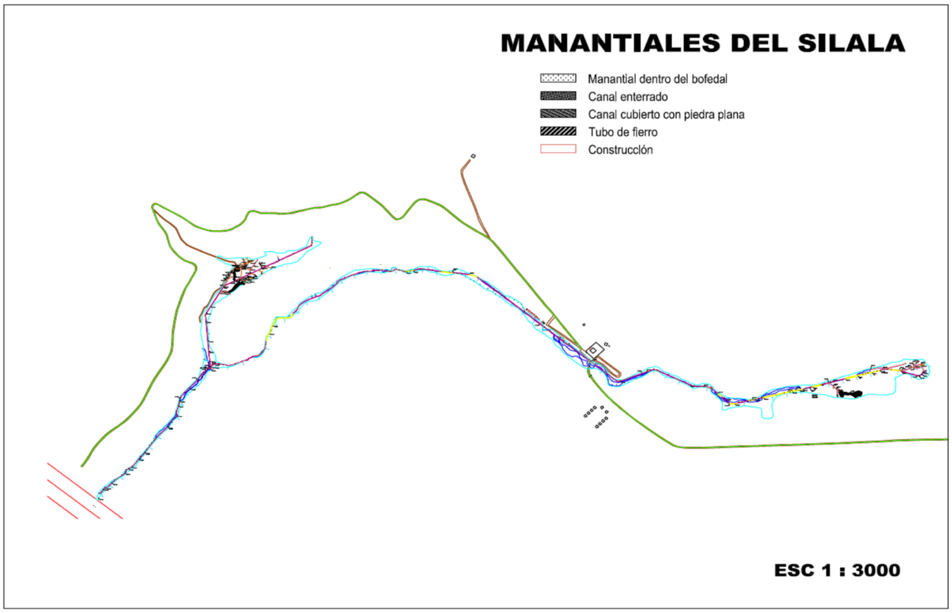


Figure 13 Map of the canal layout including width and depth of selected canals (DIREMAR and SENAMHI).

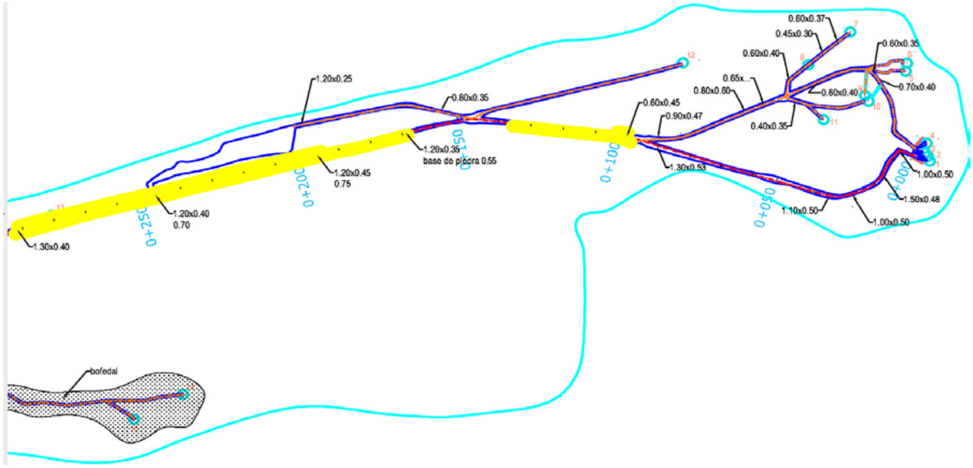


Figure 14 A close-up of the information of width and depth for canals in the Main Canal System from upstream end to approximately 300 meters downstream (Southern wetland).

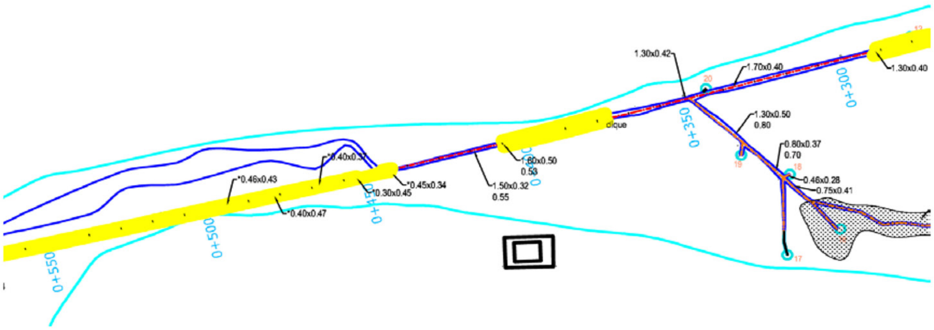


Figure 15 A close-up of the information of width and depth for canals in the Main Canal System from chainage 300 meters to chainage 600 meters (Southern wetland).

Figure 16 A close-up of the information of width and depth for canals in the Main Canal System (southern) from chainage 600 meters to chainage 900 meters.

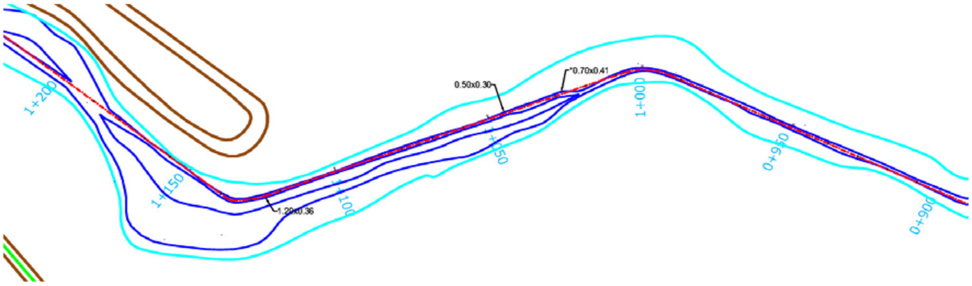


Figure 17 A close-up of the information of width and depth for canals in the Main Canal System (southern) from chainage 900 meters to chainage 1200 meters.

Figure 18 A close-up of the information of width and depth for canals in the Main Canal System (southern) from chainage 1200 meters to chainage 1500 meters.

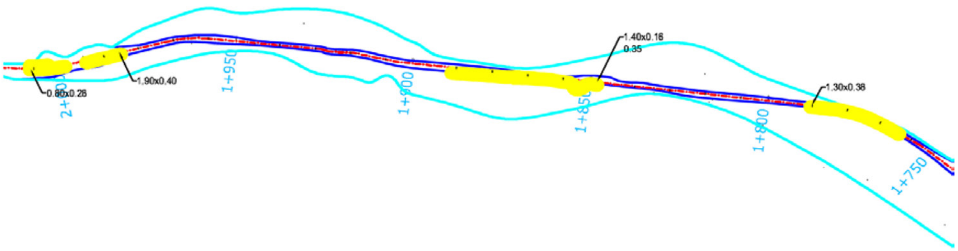


Figure 19 A close-up of the information of width and depth for canals in the Main Canal System (southern) from chainage 1500 meters to chainage 2000 meters.

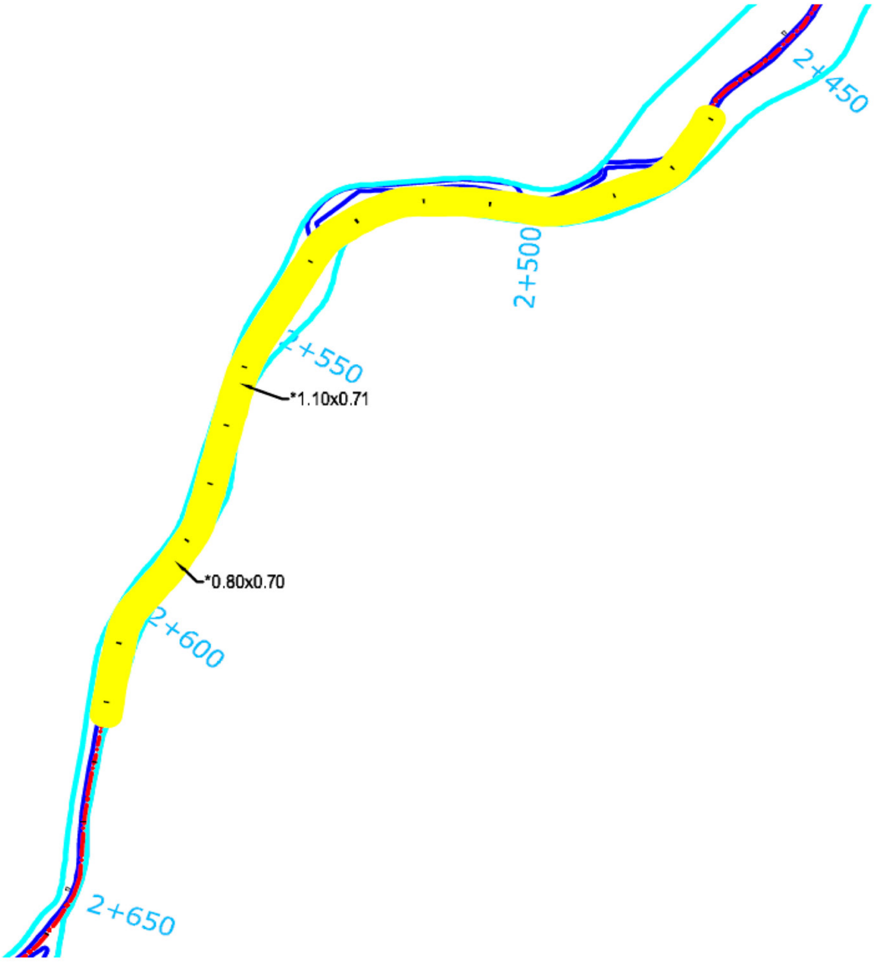


Figure 20 A close-up of the information of width and depth for canals in the Main Canal System (southern) from chainage 2450 meters to chainage 2650 meters (no measurements from chainage 2000 to chainage 2450).

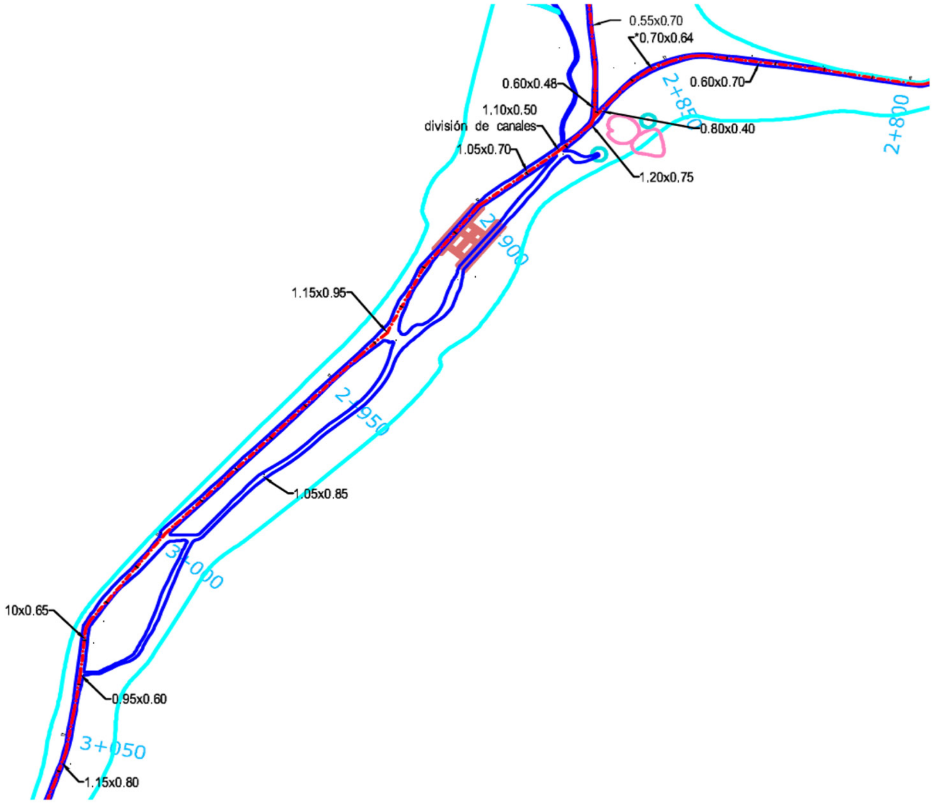


Figure 21 A close-up of the information of width and depth for canals in the Main Canal from chainage 2800 meters to chainage 3100 meters (no measurements from chainage 2450 to chainage 2800.)

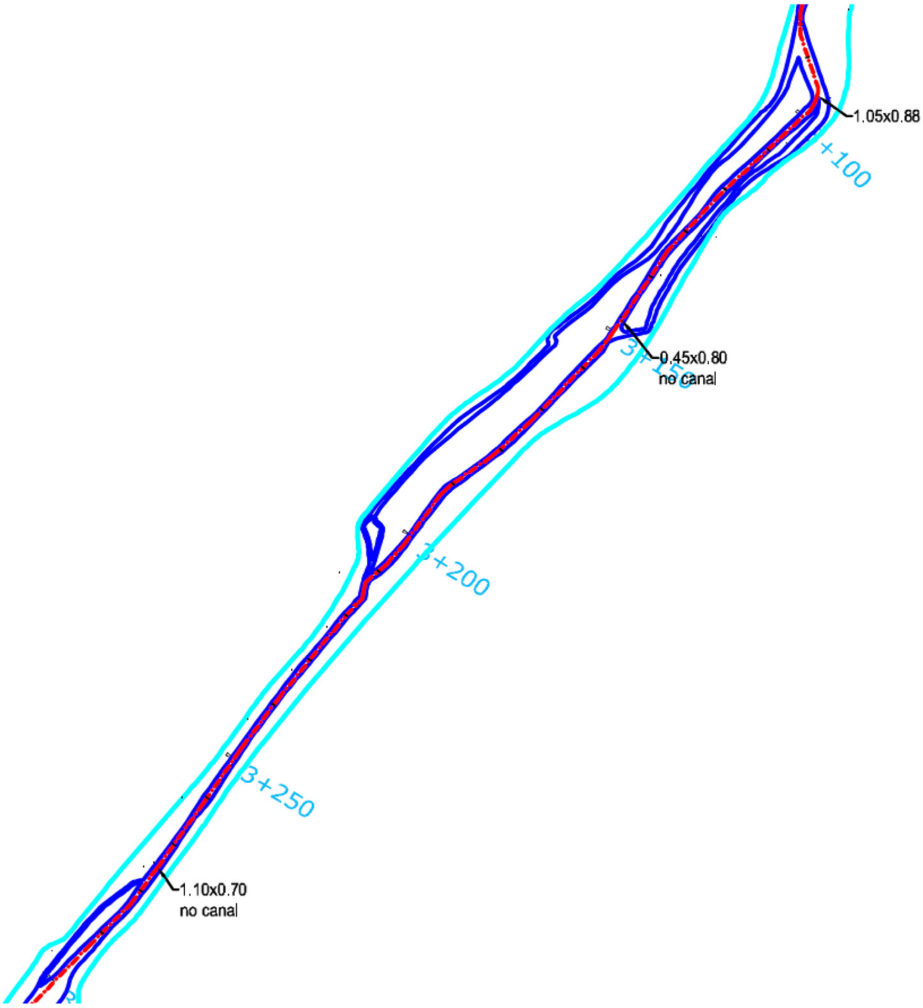


Figure 22 A close-up of the information of width and depth for canals in the Main Canal from chainage 3100 meters to chainage 3300 meters.

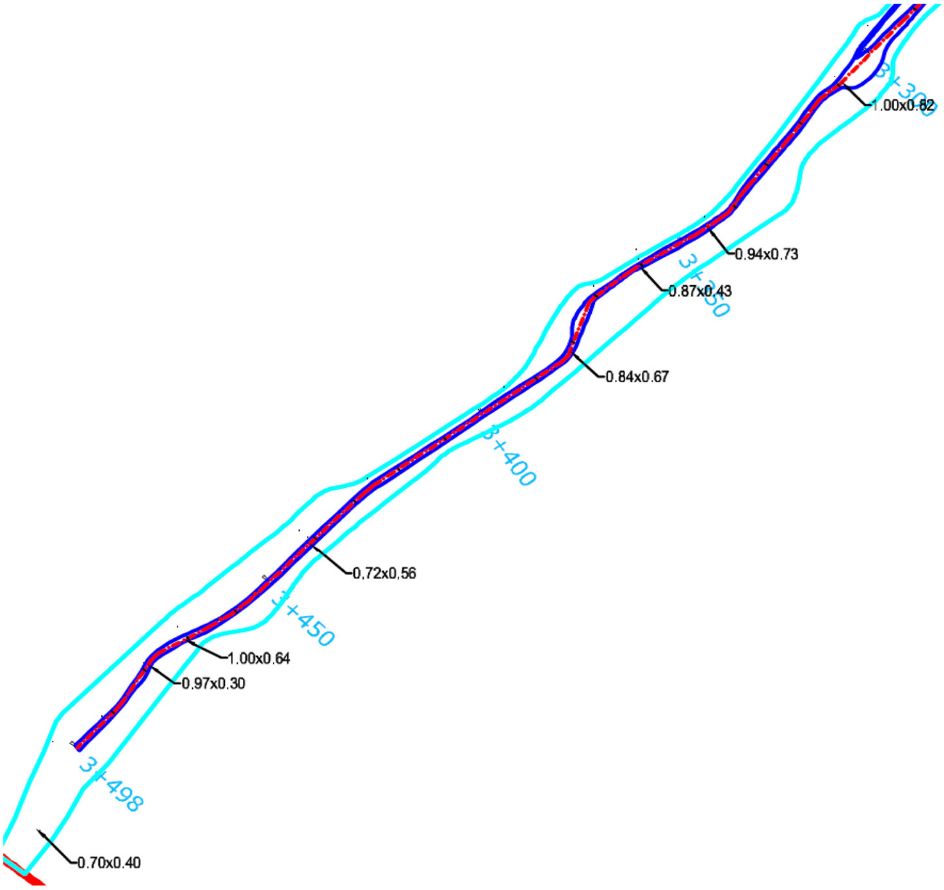


Figure 23 A close-up of the information of width and depth for canals in the Main Canal System from approximately chainage 3300 meters to the border.

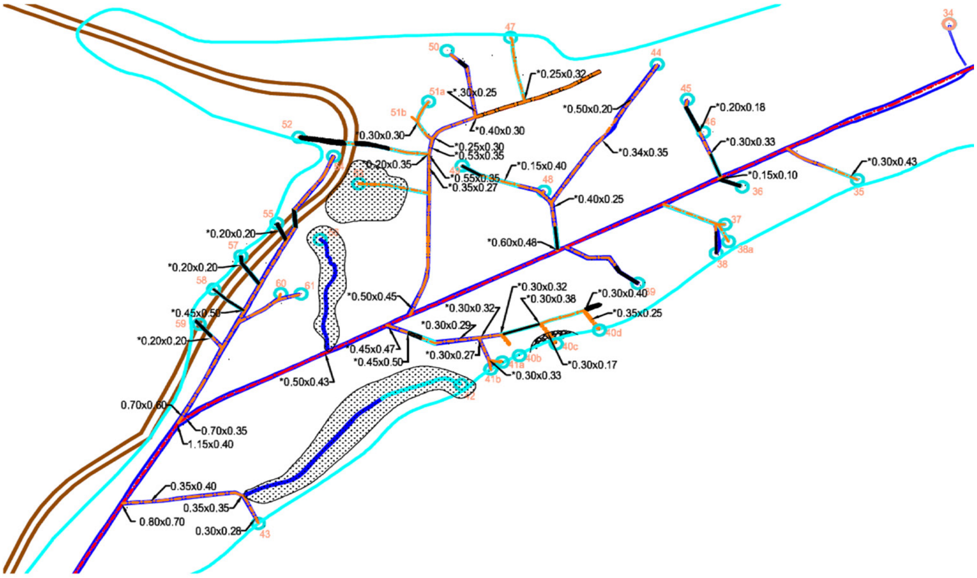


Figure 24 A close-up of the information of width and depth for canals in the Northern Canal.

Figure 25 A close-up of the information of width and depth for canals in the Northern Canal.

Canal cross sections were processed in the following steps:

1. If there are no cross sections at the upstream or downstream end of the branches, the nearest cross section is copied to any of the ends with missing cross sections.

2. Since the cross sections (which at this point is still only width and depth and no elevation) can be located quite a distance apart they are interpolated to ensure that we have cross sections, i.e. depth and width, with a maximum distance no more than 20 meters.

3. Cross sections are extended to the left and to the right perpendicular to the flow direction of the canal by use of elevations from the digital surface model (DSM). In Figure 26, an example is shown where the main canal is surrounded by a loop on each side. The red alignment lines define the extent of

the cross sections for each canal and thus the extent of the 1-dimensional description. Note that at locations where loops are present the neighbouring canals will have alignment lines in common. This process of defining alignment lines was repeated for all canals included in the model.

4. After extending the simple cross sections and combining them with the digital surface model (DSM) it is now ensured that the canal part (i.e. the depth-width cross sections) matches the bed level found by combining it with the DSM. Notice that since the interpolation was performed before merging the depth-width cross sections with the DSM, the information in the DSM is used directly in the final cross sections. Thus variation in the bottom level reflects the variation in the terrain, (see Figure 27).

Figure 26 Example of how to define the extent of each canal by using alignment lines (in red). Blue lines represent canals and the green one the cross sections in the canals.

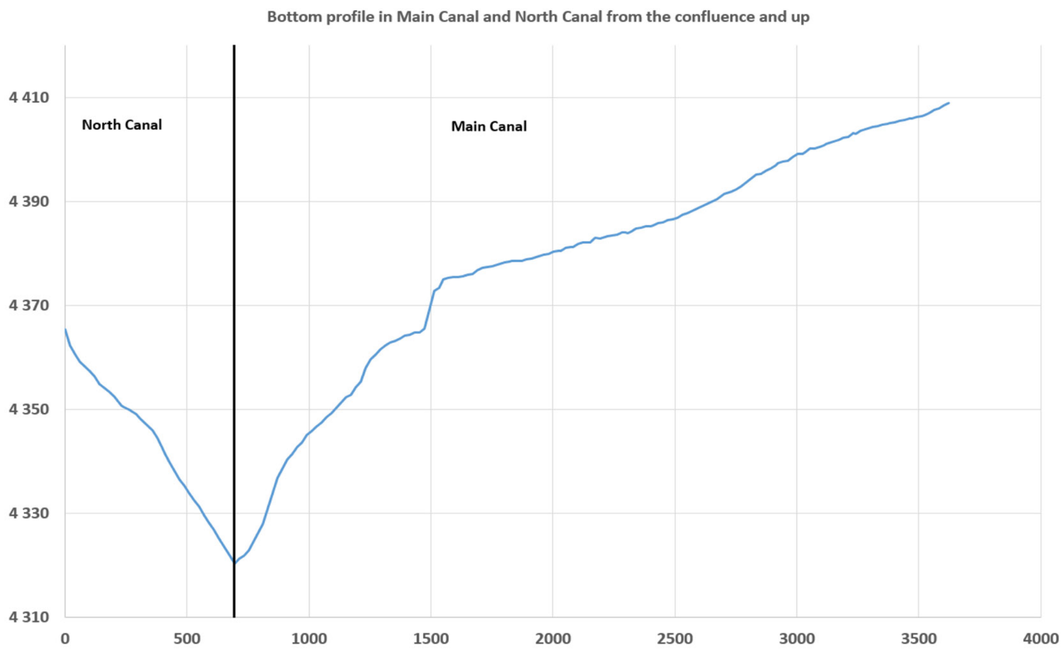


Figure 27 Variation in bottom level for the Main Canal and the North Canal from the confluence and upstream.

The cross sections created for the canal and drainage network combining SENAMHI canal dimension surveys and the digital surface model (DSM) refers to specific canals (by name) and specific locations (canal chainage). The cross sections are organised in a database containing all the geometric information of the canal network (Figure 28).

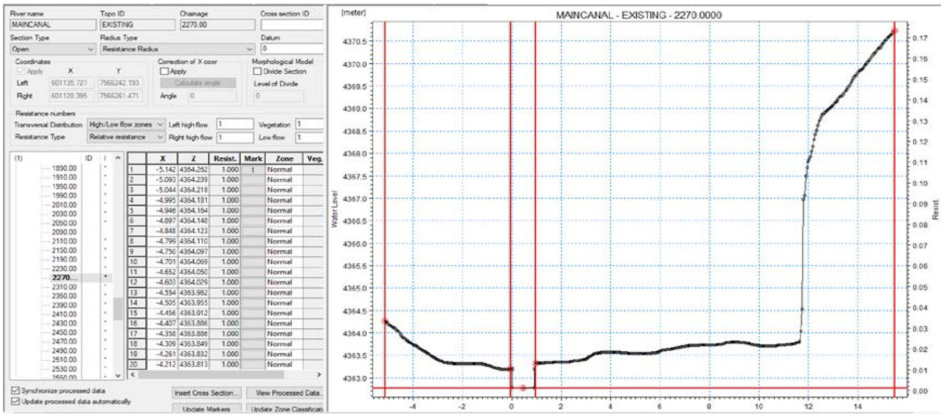


Figure 28 Canal cross sections organised in the MIKE11 cross section database.

7.3.3 Structural changes

At several locations rocks across the flow path expands the flow area and introduce local head losses. These rocks introduce an increased resistance to the flow that cannot be described by the traditional flow equation used in a hydrodynamic model. To include the effect in the model, energy losses are introduced in the model at selected locations. The locations are identified by inspection of the orthophoto made during the drone flight and by field inspection. An example of is shown in Figure 29.

Figure 29 Example of obstructions to the flow. These obstructions should be dealt with individually in the hydraulic model as additional energy losses.

The surface water model has been tested separately prior to embedding it into the integrated model. When run as a stand-alone surface water model boundary conditions in terms of lateral inflows must be specified. A constant flow distributed according to spring flow measurements and calculation of diffuse inflows (Annex C) was used to define inflow boundaries. The preliminary canal flow model included subsurface canal seepage, wetland interaction (1D / 2-D) and canal blockage single head losses. The model has been run for a 1-year period with constant inflows adding up to 160 l/s.

Figure 30 shows the distributed flow simulated by the surface water model through the drainage and canal network increasing from upstream to the downstream. Figure 31 shows an example of results produced by the surface water model, zooming in on the Southern Wetland. The locations of spring discharge to the canal network are shown by red dots. The spring water enters the canal and stays within the canal section until it reaches a downstream blocked section.

Locally where the canal water level rises above the canal cross section it starts flowing into the adjacent wetland. The colour code indicates the depth of water on the surface ranging from 0 – 15 cm. Water spills out of the canal flows into the low-lying wetland area and continues further downstream where it re-enters the canal network. Comparing the extent of flooding of the model simulation results (above) with the satellite image (below) shows the wet (darker) wetland patches on the photo align well with the inundated areas appearing in the model result. The preliminary results demonstrate that the coupled canal and wetland model is able to reproduce the larger scale flooding patterns in the Southern Wetland.

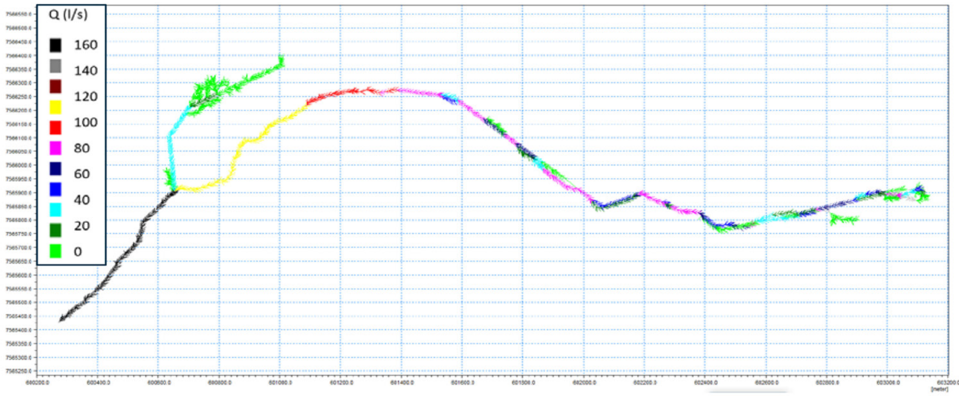


Figure 30 Simulated longitudinal profile of canal flow

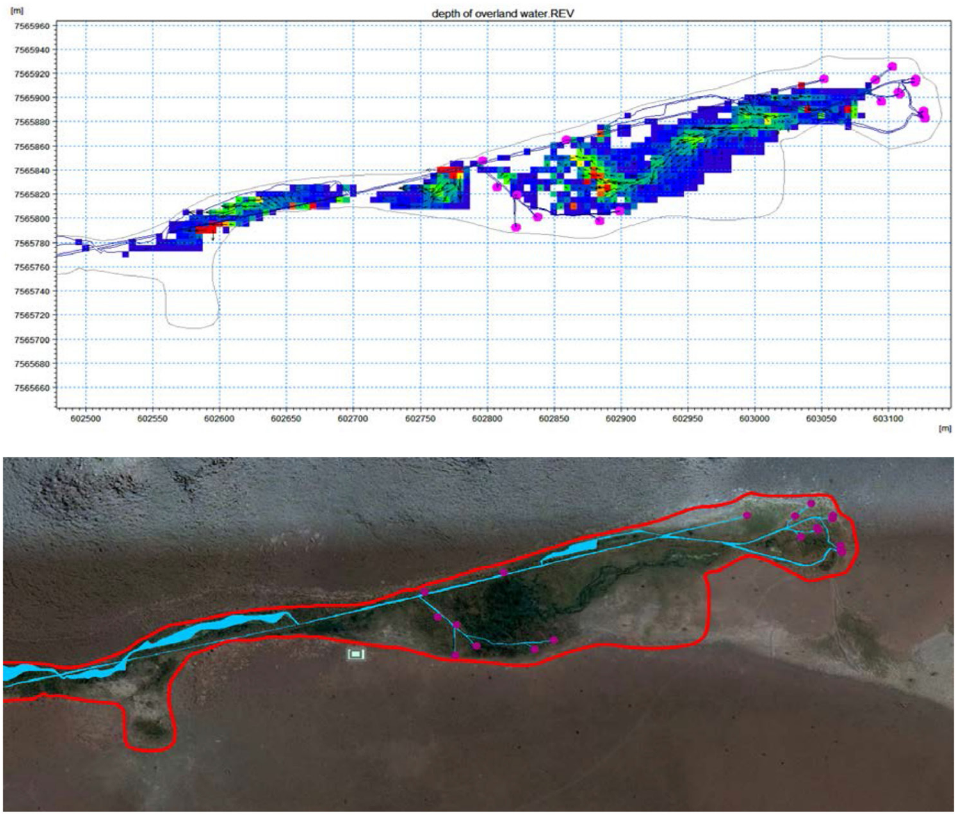


Figure 31 Simulated water depth and flow in the Southern Wetland

7.3.4 Overland flow component

The overland flow component of the integrated hydrological model simulates 2-D flow across the ground surface. The flow is calculated as a function of water table slope, topographical slope and the surface resistance to flow.

In the Silala Near field area overland flow occur in the wetlands and in the riparian corridor along the canals. Either by canals spilling onto adjacent low-lying areas or by upwelling groundwater seepage. Due to e.g. changes in canal cross section geometry, bed slope or blockages the canal spills onto wetlands. The flow in the wetlands outside the canals is handled by the 2-D overland flow component. Ponding or flowing overland water is subject to evapotranspiration losses and potentially infiltration.

Figure 32 Photo showing example of Silala canal spills (1-D) and diversion to adjacent overland area (2-D).

A key parameter controlling the rate of overland flow is the surface roughness. The surfaces are generally highly irregular, with microscale variations and with larger obstacles to flow. In the wetlands the vegetated surfaces retain water creating several micro thresholds and pools. Overland flow is dispersed on distichia surfaces even at moderate slopes. The site characteristics suggest high roughness corresponding to low values of the Mannings M roughness coefficient. In densely vegetated wetlands Manning's resistance numbers of 1-5 have been reported. In the overland component of the integrated model values in the range of 2-5 $m^{1/3}/s$ have been used.

7.4 Model calibration

Before the integrated model can be used to evaluate the current Silala hydrological system and in scenario analysis calibration must be carried out. Calibration entails adjustment of model parameters to obtain agreement between key model simulation results and field measurements.

7.5 Model calibration parameters

Groundwater discharge to surface water bodies including wetlands, the springs, the canal and through diffuse seepage faces are key hydrological processes in the Silala near field area. Due to upstream groundwater table elevation, the hydrogeological properties and the significant drop in topography across the area in general, and along the ravine in particular, groundwater flows towards the Silala Near Field area and feeds wetlands and springs. This dominant groundwater flow implies that subsurface properties and parameters are of relatively high importance in the integrated model. According to the hydrogeological model the high permeabilities and significant layer thicknesses of the upper Silala ignimbrite and the fault zone implies that hydraulic conductivities of these hydrogeological units are important calibration parameters. The parameters control not only the head gradients and inflows across the model boundaries, but also groundwater heads generally in the area and the subsurface flow across the border at the downstream model boundary.

In the distributed, integrated model different parameters can be assigned for each of the 25600 computational nodes in each of the 3 groundwater layers included. This is, however, not supported by available field data and not feasible in terms of the number of independent parameters to calibrate. Instead a zonation approach has been adopted. The subdivision in zones each having uniform parameters reflect partly the zone subdivision presented in Annex C, the general near field characteristics and areas surrounding boreholes with pump tests (Figure 33). Zonation of parameters has been used for hydraulic conductivity in the upper Silala ignimbrite and the fault zone. No data exist for distributing parameters in the deep groundwater layers and uniform values have subsequently been used.

The leakage coefficient describes the degree of hydraulic contact between the canal and the groundwater. A low hydraulic contact would typically represent a low permeable lining, e.g. due to a thick fine-grained sediment deposit in the canal. This is not the case along the Silala canal and a moderate to high hydraulic conductivity has been specified. The leakage coefficient has been assigned and calibrated for different canal network segments.

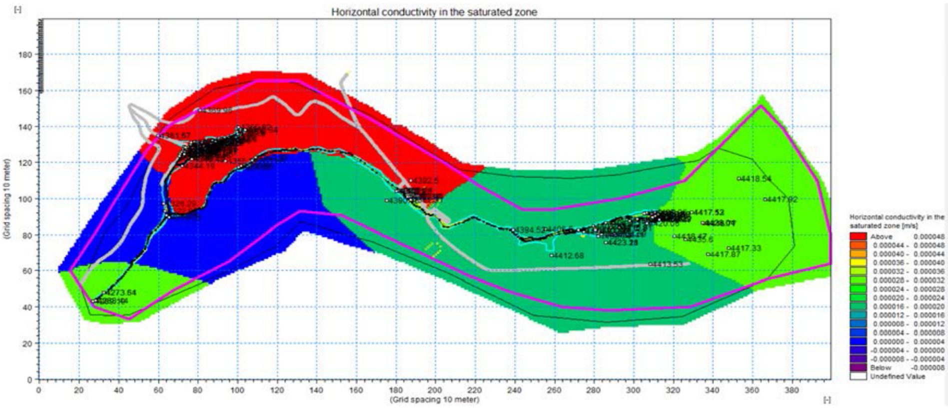


Figure 33 Example of zonation, horizontal hydraulic conductivity of Upper Silala Ignimbrite ($5e^{-6}$ – $5e^{-5}$ m/s).

Calibrated key model parameters are listed in Table 6. The final set of calibrated parameters reflects a calibration process focusing on the hydrogeological model (Annex F) with respect to keeping the parameter ranges within the initial ranges (Table 3), assigning conductivities decreasing with depth, keeping higher conductivities in the fault zone relative to the surrounding ignimbrite layers and applying a high vertical to horizontal conductivity ratio to reflect vertical fault and fractures. Canal discharge by groundwater to surface water is a key process which requires a positive gradient between the aquifer and the canal. The groundwater parameters were initially adjusted to obtain sufficiently high groundwater tables along the canals and total discharges in accordance with the measured mean canal flows. Secondly the canal-aquifer leakage coefficients were revisited and adjusted reach by reach.

Both the deep ignimbrite layer (HGU 6) and the fault zone (HGU 7) with an assumed depth of 400 m were subdivided in an upper sequence (upper 200 m) and a lower sequence (200 –

400 m). Hydraulic parameters were assigned to each sequence and later merged into the effective parameters of the numerical model layer. The upper sequence values are typically a factor 10 -100 times larger than the deep sequence values in order to account for the decrease in conductivity with depth.

Table 6 Summary of key calibrated model parameters.

Model component	Calibrated key parameter ranges					
Groundwater (3-D)		K_h(m/s)	K_v/K_h	S_y	S_s	
	HGU-1 :	$1e^{-5}$	1	0.1	$1e^{-4}$	
	HGU-2 :	$1e^{-6}$	1	0.15	$1e^{-4}$	
	HGU-3 :	$5e^{-7}$	1	0.1	$1e^{-5}$	
	HGU-4 :	$1e^{-9}$	1	0.02	$1e^{-5}$	
	HGU-5 :	$2e^{-6}$ - $5e^{-5}$	1-10	0.05	$1e^{-5}$	
	HGU-6 :	$5e^{-7}$	1	0.1	$1e^{-5}$	
	HGU-7 :	$2e^{-6}$ - $1e^{-3}$	1-10	0.1	$1e^{-5}$	
Overland (2-D)		Mannings no. ($m^{1/3}/s$)				
	Overland roughness :	2 - 5				
Unsaturated zone (1-D)		K_s(m/s) :	θ_s (-)	θ_r (-)	α	n
	Peat soil	$1e^{-4}$	0.70	0.15	0.4	1.37
	Sandy loam	$4e^{-5}$	0.40	0.04	0.05	1.25
	Ignimbrite rock	$5e^{-5}$	0.05	0.01	0.07	1.45
Canal (1-D)		Mannings no. ($m^{1/3}/s$)				
	Canal roughness :	10				
	Leakage coefficient (s^{-1}) :	$5e^{-6}$ - $5e^{-5}$				

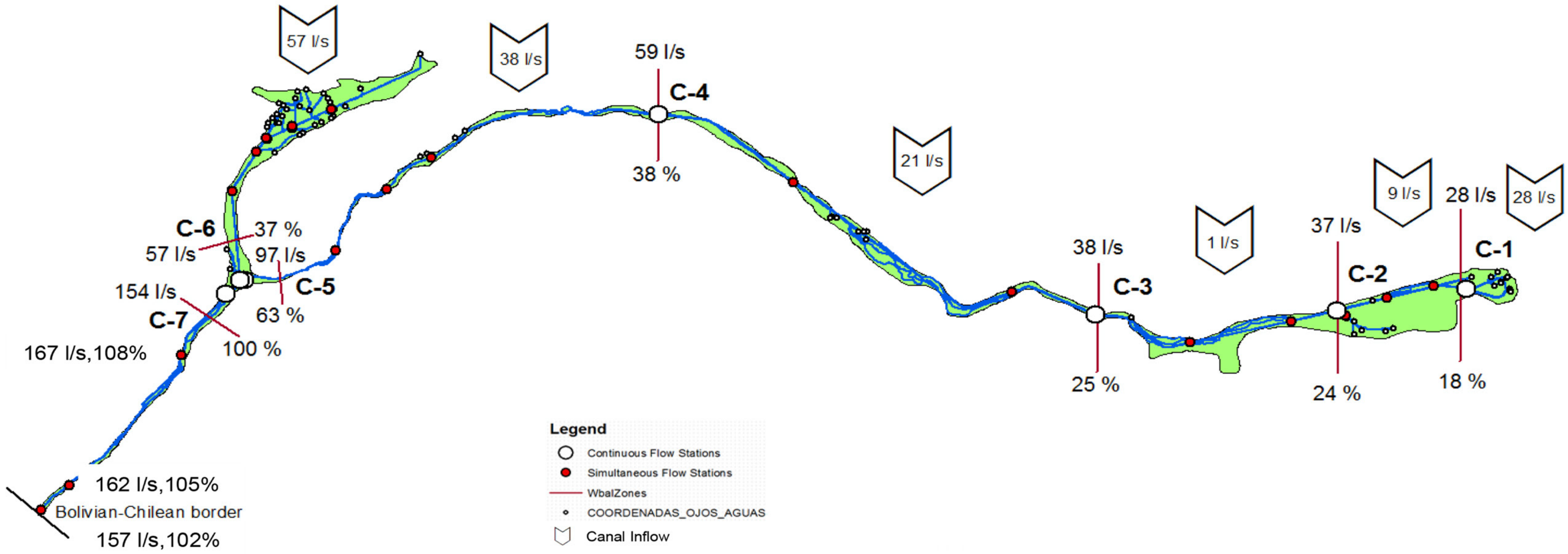


Figure 34 Mapping of flows and net inflows based on simultaneous mean canal flow measurements (in l/s), Annex C.

8 Results

Approximately 45 model simulations for calibration were run. In the process of calibration, the key model parameters were adjusted for each model run. When making parameter changes the effects propagate through the flow model. This occurs relatively quickly in the surface water system but the groundwater system has longer time scales and it takes longer to reach a steady state solution for the combined surface - groundwater system. Generally, depending on the initial conditions, it requires simulation periods of 6 months – 2 years to reach a steady state solution for the Near Field model.

For each model run, the results are evaluated in the following order of priority:

1) Measured canal flows (C1-C7)

2) Water balance

3) Observed groundwater levels

8.1 Surface water flows

The simulated canal flows are compared to the measured mean synchronous (C1-C7) flow measurements (Figure 34,Table 7). The inflow and thus the simulated canal flow at the southern wetland is slightly underestimated between C1-C3 but at C4 the simulated flow equals the measured indicating that inflows for the full C1-C4 reach are well simulated. At the confluence the model slightly underestimates the flows at C5, C6 and C7. The differences of 3-6 % are, however, small compared to measurement uncertainty. From the confluence and the siltation chamber at C-7 the flow remains unchanged indicating that the net inflow and outflow from the canal to the groundwater balances out, while the field observations indicate a very small flow increase on this stretch.

Table 7 Comparison of measured and simulated flows.

Gauging location	Measured canal flow (l/s)	Simulated canal flow (l/s)	Difference (%)
C-1	28	25	10.7
C-2	37	32	13.5
C-3	38	31	18.4
C-4	59	59	0.0
C-5	97	91	6.2
C-6	57	55	3.5
C-7 (C5+C6)	154	150	2.6
At border	157	150	4.5

8.2 Groundwater table

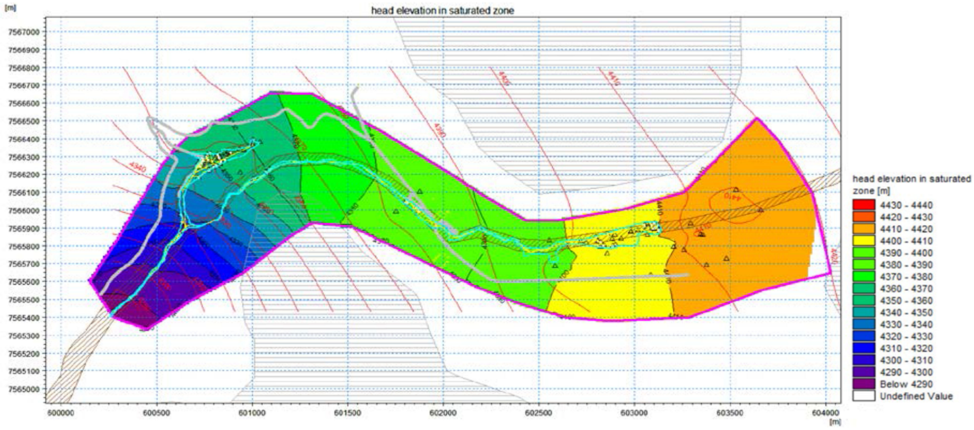


Figure 35 Groundwater table elevation contours based on measurements and model results, respectively.

The ground water table contour map derived from water level observations in borehole, springs and dug soil profile pits is used for the definition of initial conditions and boundary conditions in the groundwater component of the integrated hydrological model. In Figure 35, the contour map based on observations is shown in red versus the model simulation results in colours and lined by black contours. The model results are plotted for model layer number 2 corresponding to the Upper Silala Ignimbrite aquifer. At the area upstream of the southern wetland the model overestimates the groundwater head by 1-2 m. However, the difference levels out across the southern wetland and from the southern wetland outflow around C3 to the downstream similar groundwater head contour levels are found. The shape of the contour lines from the numerical model deviates slightly from the contour lines interpolated and extrapolated from observations reflecting the type of boundary condition specified and the canal drainage effect.

8.3 Water balance

The results of the integrated model can be processed to produce a water balance for the model area. The water balance includes all surface and subsurface inflows, outflows and storage changes for the simulation period. It also calculates error terms in case the numerical model produces water balance errors. The main water balance results are presented in Table 8, partly by flow equivalents (l/s) and partly by volume (mm) across the model area.

Approximately 253 l/s enter the model as groundwater boundary inflow. At the downstream model boundary 150 l/s flows across the border in the canal while 106 l/s is discharged through the subsurface groundwater layers. Two of the main processes of discharging groundwater to the surface water system is groundwater seepage to the canal network as baseflow and by overland flow generated by upwelling groundwater in low lying areas and wetlands. The 'Storage Change' and 'Error' terms are relatively small indicating that a steady flow situation has been reached without any significant numerical errors. Evapotranspiration losses within the model area amount to 10 l/s. Since water is only available for evapotranspiration in relatively restricted wetland and riparian corridor areas the total ET loss is limited.

Table 8 Water balance summary for the current conditions (with canals).

Water balance component	Volume equivalent (mm/y)	Flow equivalent (l/s)
Inflow	3116	253
Net canal baseflow (groundwater discharge to canal)	1113	90
Net overland flow to canal	134	11
Storage change	49	4
Evapotranspiration	125	10
Error	25	2
Outflow (canals)	1846	150
Outflow (overland)	0	0
Outflow (groundwater)	1310	106

8.4 Results by zones

The Silala Near Field area was divided in to 5 characteristic zones (Annex C). In the following selected model outputs are presented for the respective zones.

8.4.1 Zone 1: Northern wetland

The Northern wetland has been formed along the fault line and topographical depression limited by steep terrain and rock faces to the north and south. At the base of the rocks a large number of springs are formed and drained to the sloping main canal crossing the center of the wetland. The groundwater discharge to the canal and drainage network is high as illustrated in Figure 36.

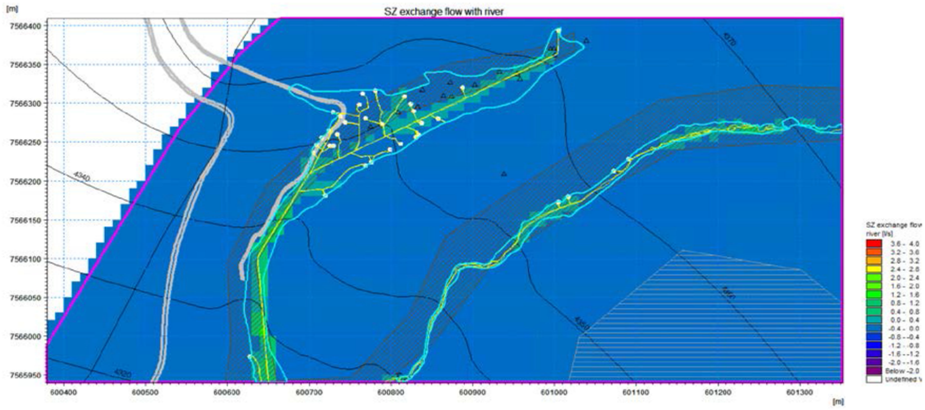


Figure 36 Simulated groundwater flow to the canal and drainage network in Northern wetland.

8.4.2 Zone 2: Southern wetland

The southern wetland is relatively flat compared to the rest of the Silala Near Field area. A cluster of springs is situated along the fault zone and receives groundwater discharge from the upstream catchment. The flow from the springs is intercepted by the dense canal network but due to local water level differences and blockages water is diverted and spread across the adjacent wetlands generating a shallow overland flow. Figure 37 shows model simulated water depths and flow vectors at the Southern wetland. The model simulated overland flow is generated by canal spills and upwelling groundwater. The flow and shallow inundation pattern follows the observed wetland extent. The inundation generally stays within the light blue polygon indicating the maximum extent of the wetland with the exception of a shallow flooded area extending to the southeast towards a dried out former wetland patch. The general overland flow downstream of the wetland is closely aligned with the canal and the narrow riparian corridor.

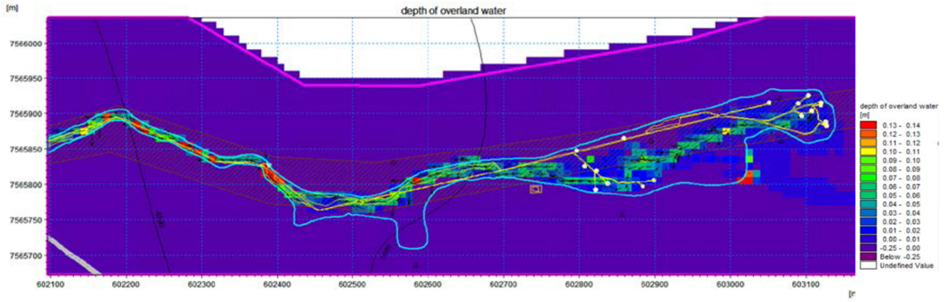


Figure 37 Simulated overland water depth (0 – 15 cm) and flow vectors in Southern wetland.

8.4.3 Zone 3: Mid-section of Southern Canal

The mid-section of the Southern Canal covers the reach from the Southern wetland at C3 to the entrance to the ravine at C4. The canal slope is moderate and the canal rock alignment has been removed in most of the reach, reestablishing flow across a wider cross section and riparian corridor. A number of canal loops branching off and rejoining the main canal are found in this reach. Figure 38 shows the simulated groundwater table (colours) ranging from approximately 4405 m upstream to 4370 m downstream. The flow vectors show the dominant groundwater flows in the fault zone along the canal. In this reach a significant groundwater volume is discharged to the canal with a simulated total inflow of 28 l/s.

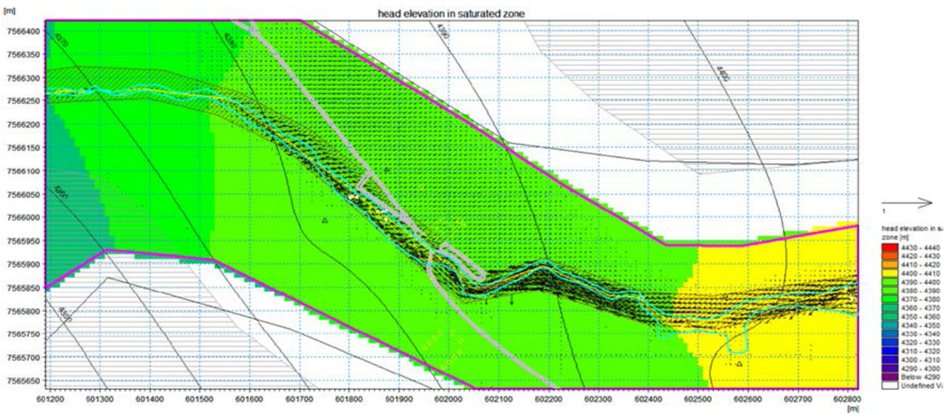


Figure 38 Simulated groundwater level and flow vectors in Zone 3.

8.4.4 Zone 4: Ravine section of Southern Canal

The Southern Canal enters the upper part of the ravine at C4. From C4 to C5, at the confluence, the ravine becomes increasingly deep with relatively high canal bed slopes. The canal, at the ravine floor, is confined to the narrow ravine profile with steep slopes. Figure 39 shows simulated groundwater discharge to the canal at each 10 m grid cell (green coloured) with flow rates of 0 – 1 l/s. The results show the distinct drainage effect of the canal and fault zone in the ravine as positive inflow of groundwater to the canal along the entire reach. The total simulated inflow between C4 and C5 is 32 l/s.

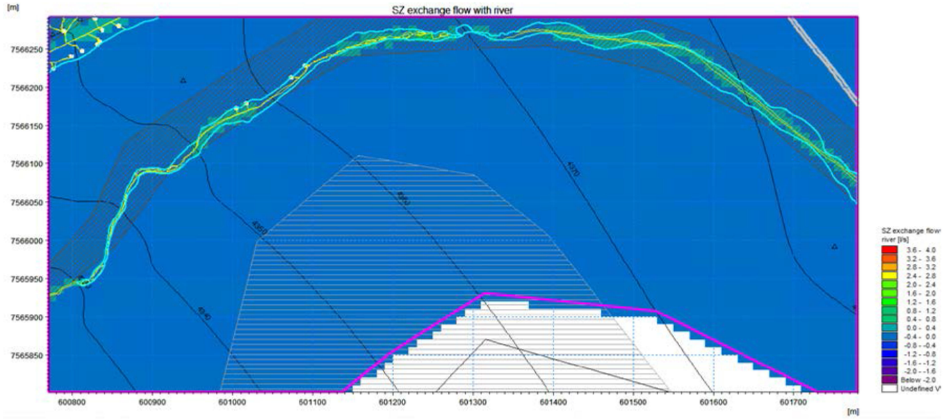


Figure 39 Groundwater discharge to the canal along the Zone 4 ravine section

8.4.5 Zone 5: Confluence to border

The Northern Canal at C6 and the southern Canal at C5 merge into the main canal (C7). From the confluence to the border the canal shape and bed slope is fairly uniform. According to the hydrogeological model (Annex F) Zone 5 is, as opposed to the remaining part of the near field area, characterized by no groundwater inflow to the canal or potentially a net loss from surface water to groundwater. The simulated canal flow entering Zone 5 at the confluence and leaving Zone 5 at the border is both 150 l/s corresponding to no net inflow. Within Zone 5 areas with both positive and negative water level gradients between the canal and the upper groundwater layer can be found indicating local canal losses and gains. However, the sum of losses and gains balances over the reach to produce zero net total inflow. Figure 40 shows a subsurface cross section at the downstream model boundary including layers and simulated ground water table. The groundwater table sits at the canal level with a slight vertical gradient from the upper to the lower ignimbrite layers.

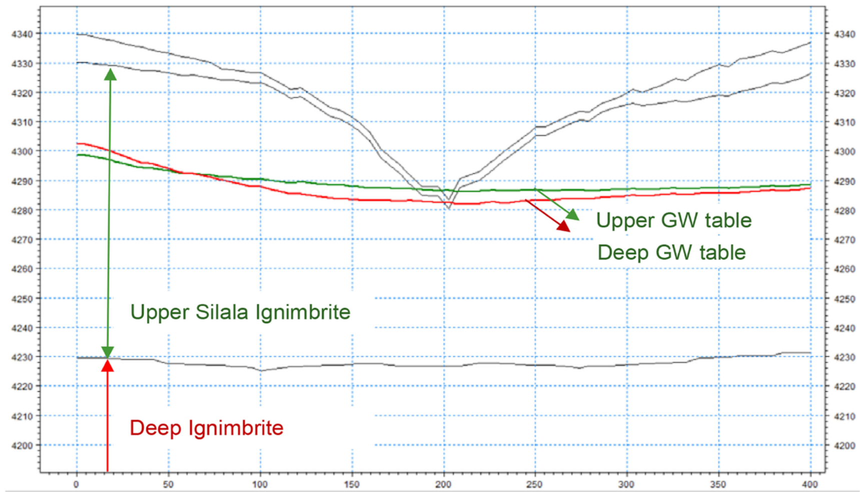


Figure 40 Cross section at the border showing groundwater layers and simulated groundwater table

9 Summary and conclusions

An integrated surface water – groundwater model has been developed to serve as a tool in scenario analysis, e.g. in order to assess the effects of removing the canals (Annex H). Before applying the model in scenario analysis, the conceptual model was implemented in the numerical model and subsequently the model was tested and calibrated it against field measurements. Partly to demonstrate that the model qualitatively describes the Silala Near Field hydrology in accordance with conceptual understanding and partly to demonstrate that the model results produced quantitatively matches the measured values.

The overall results of the integrated model agree with the conceptual model and field observations in terms of:

- Significant groundwater inflows to the Silala Near Field area through the high permeable fault zone and upper Silala ignimbrite
- Overall groundwater flow towards the low-lying wetlands, the canals and the deep cut ravine sections.
- Groundwater feeds the surface water by discharges to the springs, canal and drainage network
- Upstream gaining canal reaches versus the downstream neutral or losing reach from the confluence to the border.
- Outflow of the Silala Near Field area as combined canal and groundwater flow at the border

The calibration against field data show

- The model simulates groundwater discharge to the canal system in terms of measured mean canal flow (C1-C7) reasonably well, i.e. 0 – 18 % deviation.
- The largest relative difference is found at upstream southern canal (C1-C3). From C4 to the downstream confluence and border area including the northern branch (C6). The

model performs well with differences to the observations which are within the canal flow measurements uncertainty.

- The calibrated model water balance shows groundwater flow across the downstream model boundary in the order of 106 l/s compared to surface water flow of 150 l/s. There are no groundwater flow measurements in the cross section to verify the model simulated groundwater flow.
- Evapotranspiration mainly occurs in the wetlands and along the canal riparian corridor. Due to the restricted total area the total ET losses correspond to only 10 l/s under current conditions.

The numerical model is developed from the conceptual understanding and the field data collected. The calibrated model is able to simulate the canal flows (C1-C7) reaching approximately 150 l/s at the border. The model results suggest a considerable groundwater flow component but it cannot be compared to any measurements and is more uncertain than surface water flows. However, the model results confirm a coupled groundwater – surface water system within the Silala Near Field area extending across the border.

The calibrated model is considered suitable for use in scenario analysis (see Annex H).

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Annex 17

Danish Hydraulic Institute (DHI), *Study of the Flows in the Silala Wetlands and Springs System,* 2018

Annex H: Natural Flow Scenarios

(Original in English)

Contract CDP-I No 01/2018, Study of the Flows in the Silala Wetlands and Springs System

Product No. 2 – 2018 Final Report

Annex H: Natural Flow Scenarios

Plurinational State of Bolivia, Ministry of Foreign Affairs, Diremar

July 16, 2018

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CONTENTS

FIGURES

TABLES

DOCUMENTATION OF THE STUDY

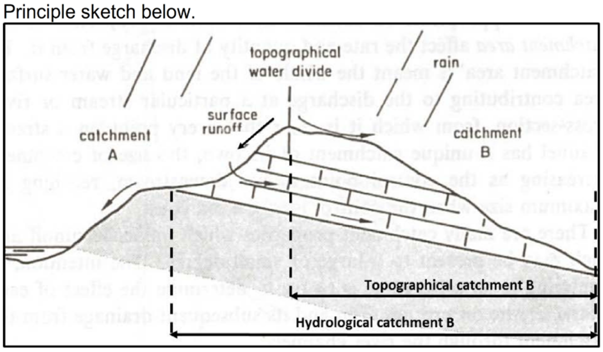
Main Report Containing the summary and conclusions

Technical Annexes:

Annex A.	The Silala catchment
Annex B.	Climate analysis
Annex C.	Surface waters
Annex D.	Soil Analyses
Annex E.	Water balances
Annex F.	Hydrogeology
Annex G.	Integrated surface water – groundwater modelling
Annex H.	**Natural flow scenarios (this annex)**
Annex I.	Questionnaire put by the Plurinational State of Bolivia to DHI

Glossary

Term	*Meaning/Definition*
Aquifer	Geological formation capable of storing, transmitting and yielding exploitable quantities of water.
Austral summer	Summer period in the Southern Hemisphere.
Basin	Area having a common outlet for its surface runoff.
Catchment	The whole of the land and water surface contributing to the discharge at particular stream cross section. This means that any cross section of a stream will have a unique catchment of its own. (Wilson, 1978).
Confined aquifer	Confined aquifers are aquifers that are overlain by a confining layer, often made up of clay or other geological formations with low permeability.
Depression, terrain depression or sink	A depression (or sink) is a low point in the terrain surrounded by higher ground in all directions. If the soil is impervious, the depression collects rain water from a local catchment. Surface water or groundwater inflows will accumulate in the depression until: - the water level reaches the nearest terrain threshold and runs off or - the evaporation from the depression is equal to its combined surface water groundwater inflows. However, a depression may also drain sub-superficially to lower lying areas through pervious soils, geological faults or groundwater aquifers.
Desert climate	Desert climate (in the Köppen climate classification BWh and BWk, sometimes also BWn), also known as an arid climate, is a climate in which precipitation is too low to sustain any vegetation at all, or at most a very scanty shrub and does not meet the criteria to be classified as a polar climate.
Digital elevation model (DEM)	Data files holding terrain levels often organised in a quadratic grid with a certain cell size (e.g. 30m by 30 m). They are very convenient tools for and often used as standard tools in Geographic Information Systems (GIS) for delineation of topographical catchment and for many other purposes.
Discharge	Volume of water flowing per unit time, for example through a river cross-section or from a spring or a well.
El Niño	El Niño is the warm phase of the El Niño Southern Oscillation (commonly called ENSO) and is associated with a band of warm ocean water that develops in the central and east-central equatorial Pacific (between approximately the International Date Line and 120°W), including off the Pacific coast of South America. El Niño Southern Oscillation refers to the cycle of warm and cold temperatures, as measured by sea surface temperature (SST) of the tropical central and eastern Pacific Ocean. El Niño is accompanied by high air pressure in the western Pacific and low air pressure in the eastern Pacific. The cool phase of ENSO is called "La Niña" with SST in the eastern Pacific below average and air pressures high in the eastern and low in western Pacific. The ENSO cycle, both El Niño and La Niña, causes global changes of both temperatures and rainfall.

Evapotranspiration	Combination of evaporation from free water and soil surfaces and transpiration of water from plant surfaces to the atmosphere.
Food and Agriculture Organization of the United Nations (FAO)	Specialized agency of the United Nations that leads international efforts to defeat hunger. FAO is also a source of knowledge and information, and helps developing countries in transition modernize and improve agriculture, forestry and fisheries practices, ensuring good nutrition and food security for all.
Geographic Information System (GIS)	A geographic information system (GIS) is a system designed to capture, store, manipulate, analyse, manage, and present spatial or geographic data.
Groundwater	Subsurface water occupying the saturated zone (i.e. where the pore spaces (or open fractures) of a porous medium are full of water).
Hydrogeological Conceptual Model (HCM)	The conceptual understanding of the individual components in a hydrologic system (i.e. groundwater, surface water, and recharge) and the processes involved between each component.
Hydrogeological Framework Model (HGFM)	A three-dimensional geologic model that defines the spatial extent of stratigraphic and structural features. The development of the HGFM incorporates topographic, geologic, geophysical, and hydrogeologic datasets.
Hydrological catchment	The hydrological catchment is the total area contributing to the discharge at a certain point. The hydrological catchment includes all the surface water from rainfall runoff, snowmelt, and nearby streams that run downslope towards a shared outlet, *as well as* the groundwater underneath the earth's surface. Since groundwater may cross the topographical divides a hydrological catchment to a point may be larger than the corresponding topographical catchment as indicated in the Principle sketch below. 
Infiltration	The movement of water from the surface of the land into the subsurface.
Penman-Monteith	Method for estimating reference evapotranspiration (Et0) from meteorological data. It is a method with strong likelihood of correctly predicting ETo in a wide range of locations and climates and has provision for application in data-short situations.
Recharge	Contribution of water to an aquifer by infiltration.
Reference evapotranspiration (Et_0)	The evapotranspiration per area unit under local climate conditions from a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23. The reference surface closely resembles an extensive surface of green,

	well-watered grass of uniform height, actively growing and completely shading the ground. A good approximation to the maximum evapotranspiration that under a certain climate can evaporate from an area unit covered by an ever-wet short green vegetation (e.g. a wetland)
Remote sensing	Acquisition of information about an object or phenomenon without making physical contact with the object and thus in contrast to on-site observation. In current usage, the term "remote sensing" generally refers to the use of satellite- or aircraft-based sensor technologies to detect and classify objects on Earth, including on the surface and in the atmosphere and oceans, based on propagated signals (e.g. electromagnetic radiation).
Satellite	Artificial body placed in orbit round the earth or another planet in order to collect information or for communication.
Sensitivity analysis	Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be apportioned to different sources of uncertainty in its inputs.
Spatial variation	When a quantity that is measured at different spatial locations exhibits values that differ across the locations.
Spring	A spring is a place where groundwater emerges naturally from the rock or soil. The forcing of the spring to the surface can be the result of a confined aquifer in which the recharge area of the spring water table rests at a higher elevation than that of the outlet. Spring water forced to the surface by elevated sources are artesian wells. Non-artesian springs may simply flow from a higher elevation through the earth to a lower elevation and exit in the form of a spring, using the ground like a drainage pipe. Still other springs are the result of pressure from an underground source in the earth, in the form of volcanic activity. The result can be water at elevated temperature such as a hot spring.
Topographical catchment	A catchment delineated strictly by topographical divides of the terrain. The topographical catchment includes all the surface water from rainfall runoff, snowmelt, and nearby streams that run downslope towards a shared outlet. This is the correct catchment if all discharge is surface flow (i.e. no groundwater). The topographical catchment is often a good approximation to the catchment, particularly for larger catchments.
Weather station	A facility, either on land or sea, with instruments and equipment for measuring atmospheric conditions to provide information for weather forecasts and to study the weather and climate.
Wetland	A wetland is a land area that is saturated with water, either permanently or seasonally, such that it takes on the characteristics of a distinct ecosystem. The primary factor that distinguishes wetlands from other land forms or water bodies is the characteristic vegetation of aquatic plants, adapted to the unique hydric soil. Wetlands play a number of roles in the environment, principally water purification, flood control, carbon sink and shoreline stability.

1 Introduction

An integrated model has been developed for the current Silala Near Field conditions and calibrated against recent measurements (Annex G). The purpose of the model tool is to carry out scenario analysis to investigate the effects of changes to the current hydrological system. In particular to quantify the effects of interventions to restore the Silala Springs system to a more natural state.

2 Scenarios

The specific purpose of the project and the integrated model is to assess the effects of the canal and drainage network. The following baseline and scenario models have been run:

1) **Baseline model**. Represents the current (2018) Silala Near Field area with the existing canal and drainage network. The surface water canal model includes both reaches which are more or less unchanged compared to the original canal construction but also those reaches where the canal has been removed or blocked.
2) **No canal scenario**. The entire canal and drainage network in the baseline model is removed. Surface water flow is no longer restricted to well-defined narrow canal cross sections and the direction of flow is largely controlled by the surface topographical slope.
3) **Wetland restoration scenario**. The removal of the existing canal and drainage network will lead to the gradual restoration of the degraded wetlands and riparian corridors. The scenario considers how the fully restored wetland might be expected to function by considering long-term peat accumulation in wetlands.

2.1 Scenario Results

The overall scenario results can be summarized by model water balance outputs (Table 1). In the Baseline scenario, 253 l/s enters the model area as boundary inflow. A significant part of the groundwater inflows is discharged to surface water. At the downstream boundary, the integrated model simulates a total outflow of 256 l/s comprising both groundwater (106 l/s) and canal flow (150 l/s). The storage change and error terms are relatively small compared to the inflows, indicating that steady state conditions with insignificant numerical errors have been reached. Evapotranspiration accounts for losses in the order of 10 l/s or less than 10% of canal flows.

In the ‘No Canal’ scenario, the surface water levels are generally higher than the canal water levels and because of the coupling to the groundwater , the groundwater table rises as well. Higher groundwater tables inside the model area reduce the groundwater gradients as well as the inflows at the groundwater boundary. Without the canals, there no exchange between the groundwater and a well-defined canal. Instead groundwater discharge by aquifer-overland seepage becomes the dominant exchange term. As a result, the total inflow to the springs reduces to 221 l/s and the total outflow is 209 l/s. The ratio between groundwater and surface water and groundwater outflows also changes. Without the canals the integrated model simulates a groundwater outflow of 115 l/s which is greater than the simulated surface water outflow of 94 l/s. With higher resistance to flow on the surface groundwater flow accounts for a larger proportion of the total flow. The evapotranspiration increases by 20 % compared to the baseline but in the larger water budget the actual evapotranspiration is less important.

In the ‘Wetland Restoration’ scenario, the boundary inflow adds up to 216 l/s. The outflow from the model area is 207 l/s, 107 l/s as groundwater and 90 l/s as overland flow. Compared to the baseline the evapotranspiration increases by 30%.

Table 1 Summary of key scenario results

	Baseline Scenario		No canal scenario		Restored wetlands	
Water balance component	Volume equivalent	Flow equivalent	Volume equivalent	Flow equivalent	Volume equivalent	Flow equivalent
	(mm/y)	(l/s)	(mm/y)	(l/s)	(mm/y)	(l/s)
Inflow	3116	253	2722	221	2655	216
Storage change	49	4	12	1	64	5
Evapotranspiration	125	10	150	12	164	13
Error	25	2	0	0	-2	0
Outflow (canals)	1846	150	0	0	0	0
Outflow (overland)	0	0	1159	94	1112	90
Outflow (groundwater)	1310	106	1418	115	1441	117

2.2 Scenario Details

The integrated surface water – groundwater model has been set up and run as a steady-state model as explained in the model approach (Annex G). The scenario model setups were run for a period of 1-2 years to establish a steady state solution and minimise effects of the initial conditions on the final scenario results.

2.2.1 Baseline Model

The baseline model includes coupled flow components for groundwater (3-D), unsaturated zone (1-D), evapotranspiration, overland flow (2-D) and canal flow (1-D). This is normally referred to as a fully coupled integrated model.

2.2.2 No Canal Scenario

The ‘No canal’ scenario model is identical to the baseline model except that the 1-D canal flow model has been removed from the setup. The ‘No canal’ model thus include coupled flow components for groundwater (3-D), unsaturated zone (1-D), evapotranspiration and overland flow (2-D).

Figure 1 (USGS, 1998) shows the seepage of groundwater to surface water at the base of a slope, groundwater flow to a combined canal and riparian zone cross section and groundwater flow to surface water in a cross section without canals. Due the topographical features and the hydrogeological properties of the Silala Near Field area, groundwater discharge zones in terms of springs and seepage faces are formed. The canal forms a flow conduit which drains the surrounding area. The resistance to flow in the canal is lower than the adjacent vegetated riparian zone which means that the canal increases the conveyance capacity and lowers the water table. In a coupled groundwater-surface water system, a lower surface water level increases the gradient between the aquifer and the surface water leading to a higher flow exchange rate and draining the groundwater and potentially lowering groundwater tables. With the canals removed, the surface flow cross sectional area increases and the roughness to surface flow increases causing a higher resistance and corresponding higher surface water levels. Higher resistance and lower flow velocities can potentially increase sedimentation and build-up of organic matter, especially in low slope reaches. Higher resistance and water level in surface water will affect the groundwater discharge and ground water tables.

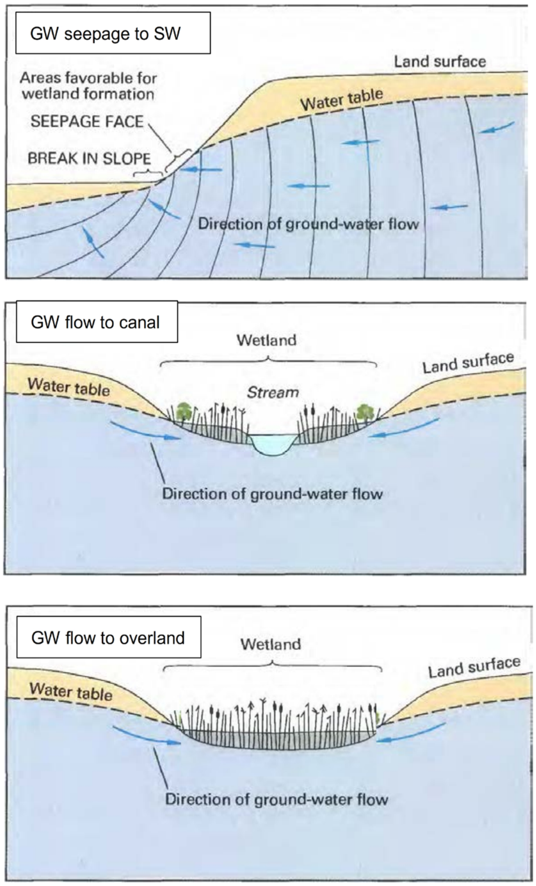


Figure 1 Groundwater flow to surface water and effects of removing canals (USGS, 1998).

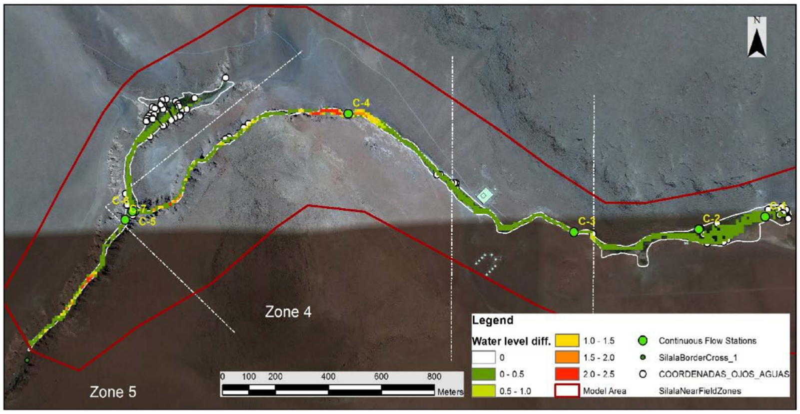


Figure 2 Change in overland water depth between the 'Baseline' and the 'No Canal' scenario.

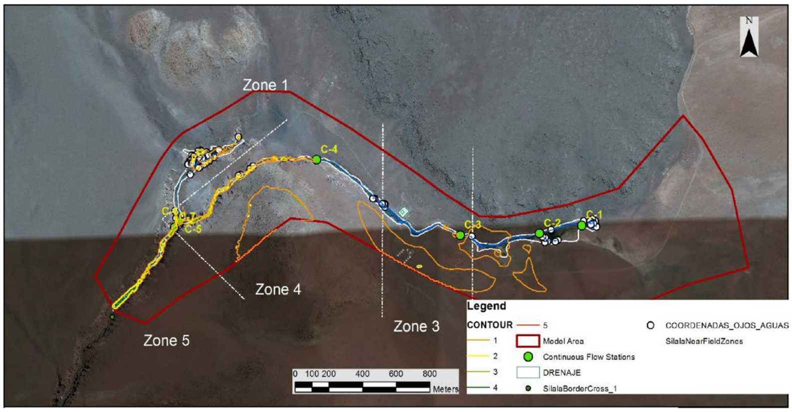


Figure 3 Change in Silala Ignimbrite groundwater table between the 'Baseline' and the 'No Canal' scenario.

Figure 2 and Figure 3 show the change in overland water depths and water table of the upper groundwater layer when removing the canal. Overland water depth increase along the canals and wetlands. Due to the higher water levels on the surface the groundwater table also increase. General increase in groundwater tables is seen in the area but the largest change is found in the ravine, at the northern wetland and from the confluence to the border.

The integrated hydrological model applies a 10 m grid resolution which is sufficient to capture the flow changes of the Silala Near Field area in general. As expected the model results showed an increase in overland water levels when removing the canals. However, in narrow sections of the southern canal ravine ponding overland water locally reach more than 2 m. The formation of these overland storage areas is due to topographical thresholds holding back pools of water and they may be a result of the grid resolution not properly representing the ravine floor levels. To investigate the scale and grid resolution effect on the overall scenario results, the topography was locally corrected to obtain a continuous downhill surface slope. Running this revised 'No Canal' test model showed that overland water levels decreased and the surface water flow at the border increased to 103 l/s compared to 94 l/s in the model run without topography corrections. The groundwater outflow reduced from 115 l/s to 113 l/s. It has not been possible to further assess the effect of grid resolution by running higher grid resolution models within the available project time frame.

2.2.3 Restored wetland scenario

The 'Restored wetland' scenario model is identical to the 'No canal' scenario model but the surface topography and unsaturated soil profile description has been modified. The 'Restored wetland' scenario model includes coupled flow components for groundwater (3-D), unsaturated zone (1-D), evapotranspiration and overland flow (2-D).

Currently, both the southern and the northern wetlands are severely degraded due the canal and drainage network lowering the water tables, subdivision by canals intercepting flow and excavations exposing peat deposits to oxygen and decomposition. Wetland restoration initiatives removing the man-made constructions will provide basis for a long term recovery and re-establishment of the wetland.

Field inspection and the wetland soil survey has shown clear contrasts in soil profiles between degraded and relatively undisturbed wetland patches especially in the northern wetland. Up to 60 cm thickness of peat soils were found in the few undisturbed areas versus 0 – 40 cm in the remaining part of the wetland with partial or heavy disturbance and degradation. The rate of peat accumulation is low in altiplano bofedales, likely in the range of 0.1 – 1 cm/year, requiring several years for recovery. In this restored wetland scenario, the maximum depth of peat across the wetlands accumulated over a long time span is assumed to reach the 60 cm found in undisturbed areas. In wetland areas with peat thicknesses less than 60 cm the peat thickness is adjusted up to 60 cm. A thicker peat layer has two main hydrological effect. It partly raises the wetland ground level and topography and it partly increase a organic top soil with specific capillary rise and water storage properties. A thicker peat layer implies a higher resistance to groundwater emerging in the wetland. Figure 4 illustrates groundwater flow through a confined/unconfined aquifer system and the artesian flow generated in a low-lying area. The flow rate at a well or a spring is a function of head gradient and the combined resistance represented by the layer thicknesses and hydraulic properties. Thicker layers imply higher resistance and lower spring flow. Thicker peat layers introduce larger water storage and higher water contents and potentially a higher upward directed flow from capillary forces.

The 'Restored wetland' scenario model has been modified by adjusting the topography to reflect a peat layer thickness increase up to 60 cm. The unsaturated zone soil profiles have been adjusted accordingly assuming 60 cm of peat in all wetland soil profiles.

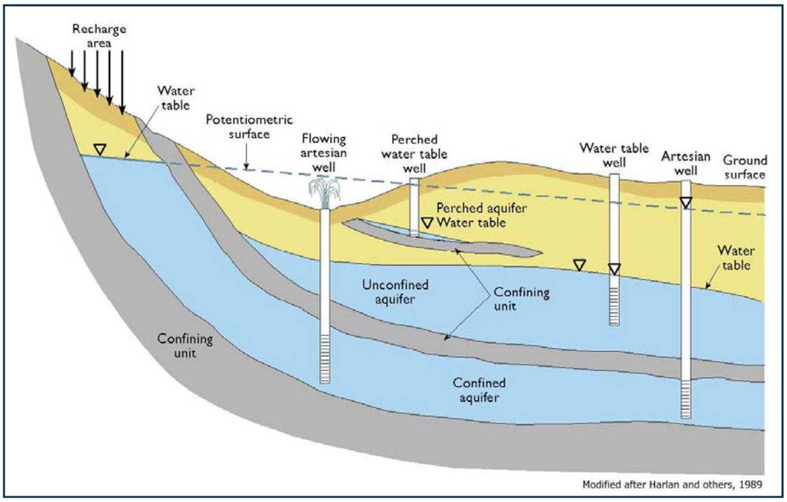


Figure 4 Illustration of a confined/unconfined aquifer system and artesian flowing well/spring.

Figure 5 and Figure 6 show the change in overland water depths and water table of the upper groundwater layer when removing the canal and restoring the wetlands. Overland water depth and the groundwater table increase, mainly along the canals and wetlands.

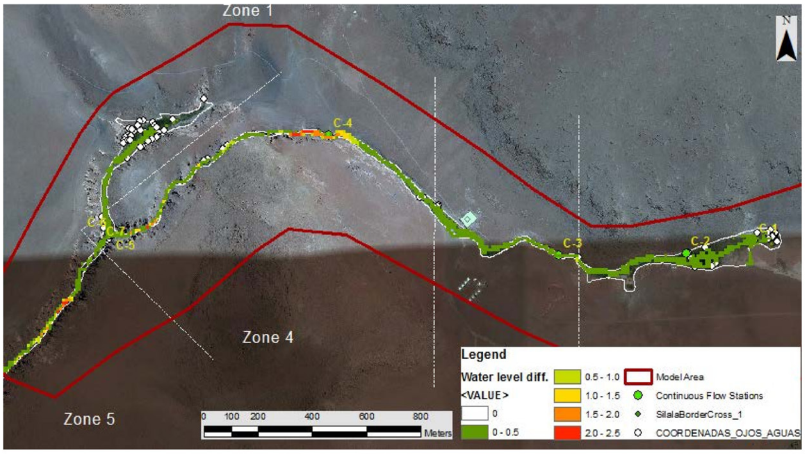


Figure 5 Change in overland water depth between the 'Baseline' and the 'Restored Wetland' scenario.

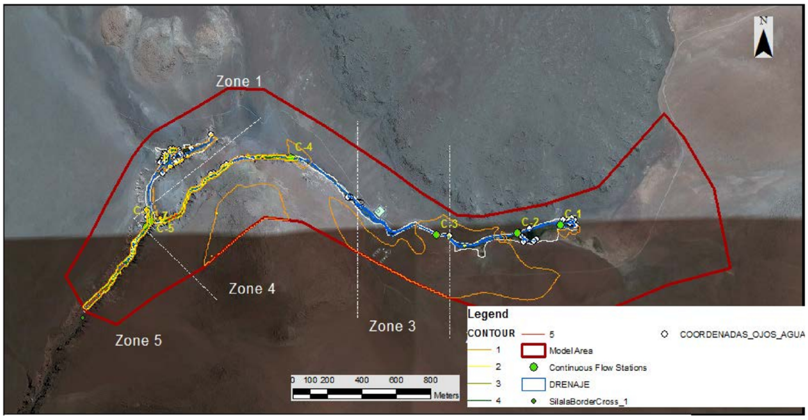


Figure 6 Change in Silala Ignimbrite groundwater table between the 'Baseline' and the 'Restored Wetland' scenario.

3 Confluence to border local model

In order to analyse more closely the surface water and groundwater flow from the confluence to the border and to assess the infiltration capacity without the canal, a local model was extracted from the Silala Near Field model and further refined. This refined local scale model is used in sensitivity analysis to explore the ranges of infiltration, groundwater flow and surface water along this reach without canals. The local confluence to border is using the integrated MIKE SHE surface water-groundwater modelling system and the model is developed from the larger Silala Near Field setup (Annex G).

As information on the hydrogeology including soil properties and surface water - groundwater interactions are very limited in the ravine area, different plausible scenarios have been investigated to provide an assessment of the likely infiltration capacity along this reach. It should be noted that no studies of soil properties or canal bed properties are available for this part of the system. Furthermore, there is very limited information on groundwater water levels or flows which could be used as a basis for model calibration. A steady-state model approach was adopted which is run with different input parameter sets to provide an assessment of the surface water and groundwater impacts without the presence of the canal.

3.1 Hydrogeology of the confluence to border zone

According to the hydrogeological model developed for the Silala springs area (Annex F), groundwater flows in a fault zone beneath the canal in a north-east south-westerly direction with limited surface water-groundwater flow exchanges along this part of the canal. Geological logs from four boreholes along this reach indicate a thin layer of eluvium underlain by highly fragmented lava deposits or andesit to a depth of approximately 1-10 m below the canal. This is in turn underlain by Ignimbrite which has been identified to a depth of 110 m below ground in borehole DS-35.

Simultaneous flow measurements taken along the in the canal in Figure 7 indicate a small gain along the upper part of the canal section and a minor loss towards the end of the ravine with a total average gain of approximately 4 l/sec along the full reach. This is supported by observed groundwater levels along the canal presented in the same figure. At the upstream end of the canal, water levels are close to the canal bed in the upper part of the lava deposits as indicated by water levels at DS-37 and a spring SP-64. This suggests that this part of the canal is a gaining reach and relatively well connected to the shallow aquifer. Further downstream, groundwater levels are located below the canal at varying depths from 17 m below ground in the ignimbrite at DS-35 to 0.8-1.6 m below ground at DS-31 and DS-32 in the shallower lava deposits. Groundwater levels in DS-35 and DS-31/DS-32 indicate that the upper deposits at DS-31 and DS-32 are not well-connected to the underlying ignimbrite aquifer but form a perched aquifer. This agrees with observations made by (Arcadis, 2017) further downstream in Chile who found the presence of intermittently saturated conditions below the canal at four locations in fluvial and alluvial deposits below the canal. Groundwater levels in the deeper ignimbrite aquifer were found at depths between 8-9 m below ground. Overall, the groundwater levels along the lower part of the canal indicate a losing reach with limited connectivity between the canal and the underlying shallow and deeper aquifers.

In terms of infiltration, limited information is currently available on soil properties in the upper deposits (eluvium and lava deposits) in this area. (Arcadis, 2017) estimated permeabilities from infiltration tests further downstream in Chile to between 0.02 – 2.05 m/d (2.3×10^{-07}- 2.4×10^{-05} m/s) for alluvial and fluvial deposits, 0.03 – 1.61 m/d (3.5×10^{-07} - 1.9×10^{-05} m/s) for fractured and weathered lavas and 0.37 – 0.48 m/d (4.3×10^{-06} - 5.6×10^{-06} m/s) for the Ignimbrite aquifer. A pumping test conducted in Chile close to the border indicates higher hydraulic conductivities of the Ignimbrite of 8-17 m/d (9.3×10^{-05} - 2.0×10^{-04} m/s). No information is available on the properties of the lining of the canal or connectivity between the canal and shallow deposits of eluvium or lava fragments.

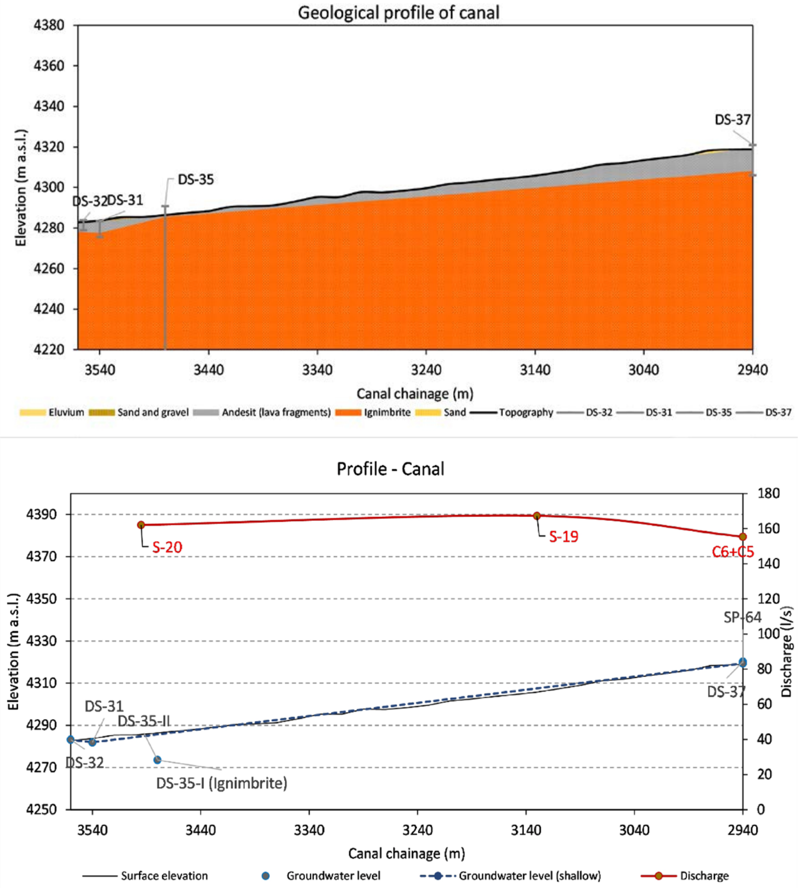


Figure 7 Geological profile C along the canal from the confluence to the border based on borehole logs (top) and profile showing spot flows and groundwater levels (bottom).

3.2 Model setup and parameters

The local model of the confluence to border section was based on the larger model with upper boundary conditions of groundwater head and aquifer properties taken from this model. It should be noted that the smaller modelling study was undertaken while the larger model was being calibrated which means that there may be some differences in groundwater inflow around the upstream boundary between the two models.

The local model area (Figure 8) uses a grid size of 10m. The model comprises geological units of sand and gravel, lavas and Ignimbrites with a high permeable fault zone of Ignimbrite along the canal overlain by eluvium and lava deposits. Upstream boundary inflows have been kept constant by fixing head and hydraulic properties at the boundary. Downstream, a gradient boundary condition of 0.05 was used in both the upper lava deposits and the Ignimbrite. This was estimated based on shallow groundwater levels in the upper deposits in DS-37 and DS-31/DS-32 and has been assumed to apply both in the shallow aquifer and deeper Ignimbrite.

The model uses a horizontal hydraulic conductivity of 10^{-4} m/s for the upper lava deposits and a 3×10^{-5} m/s for the upper Ignimbrite to a depth of approximately 60-65 m. Below this a horizontal conductivity of 1.1×10^{-5} m/s was used. The vertical conductivity was set to the same value in the upper two layers but a factor 10 lower in the lower Ignimbrite. These values are generally at the higher end of those derived by (Arcadis, 2017) (see above). In the unsaturated zone, the saturated conductivity was set to match with those used for the saturated zone with a hydraulic conductivity of eluvium of 3.5×10^{-5} m/s and 10^{-4} m/s for fragmented lava deposits.

Canal inflow at the upstream end was set to 160 l/s and the canal leakage coefficient was specified as 5×10^{-5} m/s corresponding to moderately permeable material/lining. Canal roughness and roughness of the surface in the ravine was assumed to be 5 $m^{1/3}$/s and 2 $m^{1/3}$/s respectively corresponding to fairly dense wetland vegetation.

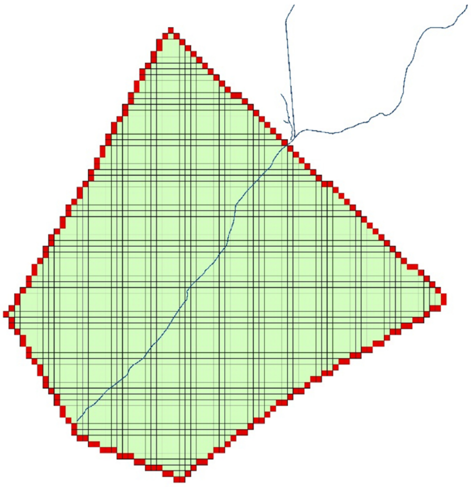


Figure 8 Model grid and boundary conditions.

3.3 Modelled infiltration capacity

To assess the infiltration capacity of the ravine, two models were run to steady-state: a model including the channel and a revised model without the canal from the confluence at the upstream boundary. The outflow across the border was then compared with and without the channel to determine the effect of removing the canal on cross-border surface water flows.

According to the model removing the canal from the ravine results in a loss of 12 l/s equivalent to 8% of the canal flow. Running the model using a finer discretisation of 5 m resulted in only a slightly increased reduction of 14 l/s indicating that the coarse model resolution of 10 m is adequate for the analysis.

A sensitivity analysis of some of the input parameters were subsequently undertaken to assess the effect of, for example, the saturated hydraulic conductivities and roughness coefficients on surface water outflows. Model parameters for the analysis were primarily selected to determine the highest plausible leakage/infiltration along the ravine while still providing an adequate representation of groundwater depths in the lava and ignimbrite aquifer. The parameter intervals tested in the analysis are summarised in Table 2.

The highest infiltration rate achieved was 39 l/s equivalent to 25% of total canal flow. This was a result of using a high horizontal hydraulic conductivity of 10^{-3} m/s in the lava deposits and 10^{-4} m/s in the upper ignimbrite and high vertical conductivities of 10^{-4} m/s in the lava and 5 x 10^{-4} m/s in the ignimbrite. These values are generally higher than the values determined by Arcadis, 2017. Using even higher conductivities is not considered realistic and produces large drops in groundwater heads in the upper Ignimbrite aquifer far below observed levels.

Table 2 Parameter intervals used for overland flow, canal flow, the unsaturated and saturated zones. (Note: some parameters were not modified for the sensitivity analysis).

Component	Parameter	Min	Max
Overland/canal	Mannings M (m1/3/s)	2	15
Unsaturated zone	Eluvium Ks (m/s)	2.74E-05	1.00E-04
	Lava Ks (m/s)	1.00E-04	1.00E-04
Saturated zone	Eluvium+Lava Kh (m/s)	1.00E-04	1.00E-03
	Eluvium+Lava Kv (m/s)	1.00E-04	1.00E-04
	Upper Ignimbrite Kh (m/s)	3.00E-05	1.00E-03
	Upper Ignimbrite Kv (m/s)	5.00E-05	5.00E-04
	Lower Ignimbrite Kh (m/s)	1.20E-05	1.20E-05
	Lower Ignimbrite Kv (m/s)	1.60E-06	1.60E-06

This local confluence to border model analysis shows that it is unlikely that removing the canal from the confluence to the Chilean border will remove all cross-border surface water flow into Chile. With the highest infiltration capacity achieved using very high conductivities, a maximum of 25% of current canal flow will be lost to the subsurface. This is associated with a high degree of uncertainty and most likely an overestimation of infiltration. A more realistic estimate is 12-15 l/s (8-10%) using lower hydraulic conductivities more in agreement with values reported by (Arcadis, 2017) and values used in the final version of the full Silala Near Field model.

4 Summary and conclusion

According to the integrated model scenario results, removing the canals and restoring wetlands will affect both groundwater and surface water and both inflows and outflows of the Silala Near Field area.

- The simulated surface water flow at the downstream model boundary (located at the Bolivian-Chilean border) is reduced by 31-40 % compared to current conditions.
- The simulated groundwater flow at the downstream model boundary (located at the Bolivian-Chilean border) increases by 7-11 % compared to current conditions.
- The total model boundary inflow at the upstream model boundary decreases by 10-15 %.
- The evapotranspiration increases by 20-30 % by removing the canals and restoring wetlands. corresponding to increases of only 2 l/s and 3 l/s respectively

- A local model sensitivity study shows that without the canals a maximum of 25 % will infiltrate to the subsurface between the confluence and the border but 8-12 % is the most realistic range. Losses are included in the Silala Near Field model scenarios.

- All the scenario results evaluated here and the local model analysis suggest that both surface water flow and groundwater flow should be expected at the border.

The flow impact percentages describe the model results ranges but not explicitly the uncertainty on model results. Despite the strength of integrated models in combining a range of site specific data, such numerical model results are inherently uncertain. Model predictive uncertainty depends on a number of factors and uncertainty sources, e.g. limitations in input data, model structure, and parametrisation and measurement errors. A strictly quantitative uncertainty analysis is not feasible and has not been attempted but model uncertainty should not be ignored in the interpretation of results.

5 References

Arcadis Detailed Hydrogeological Study of the Silala River. International Court of Justice Dispute over the status and use of the waters of Silala (Chile vs.Bolivia) [Report]. - [s.l.] : Memorial of the Republic of Chile, Volume IV, Annex 2, 2017.

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Annex 17

Danish Hydraulic Institute (DHI), *Study of the Flows in the Silala Wetlands and Springs System,* 2018

Annex I: Questionnaire put by the Plurinational State of Bolivia to DHI

(Original in English)

Contract CDP-I No 01/2018, Study of the Flows in the Silala Wetlands and Springs System

Product No. 2 – 2018

Annex I – Questionnaire put by the Plurinational State of Bolivia to DHI

Source: DIREMAR, 2017

Plurinational State of Bolivia, Ministry of Foreign Affairs, DIREMAR
July 16, 2018

Questionnaire put by the Plurinational State of Bolivia to DHI

1 Introduction

In relation with DHI's final report: "Study of the Flows in the Silala Wetlands and Springs System" the Client (Bolivia's Strategic Office for the Maritime Claim, Silala and International Water Resources – DIREMAR) has submitted seven clarifying questions to DHI. The questions and DHI's response to each of them are listed below.

2 Questions and responses

1. DHI has found the waters of Silala to be a system of springs with a "modified flow", how do you explain the concept of "modified flow"?

Response:
A system with modified flows is a system in which the flows have changed as a consequence of human interventions, typically in contrast to a 'natural' flow system unaffected by man.

2 What is the impact that the modifications introduced in the Silala Springs System had on the latter's surface flow?

Response:
The canalization and the excavations associated with it, have lowered the water levels and reduced the water storage in the wetlands as compared to a natural system. This has increased the hydraulic gradients, reduced hydraulic resistance through the springs and increased their discharge. The lowered water levels in the wetlands has also reduced evaporation relative to a natural wetland.
Hence, the canalization increases the drainage flows, lower the groundwater tables, reduces the evapotranspiration and alter the groundwater/surface water interactions.

3 Can the current surface flow of the Silala from Bolivia to Chile be regarded, from a hydrological perspective, as a natural water flow?

Response:

No, the canals have increased the surface water flow at the border as compared to a natural situation.
While the discharge of groundwater through the springs and by seepage in wetlands has not been introduced by man, the canals have increased surface water flow artificially.
The canal and drainage system have impacted flow, storage and water levels in Silala as compared to a natural system, i.e. a system unaffected by man. Model analyses show a decrease in surface flow without canals.

4 What is the behavior of the groundwater of Silala?

Response:

Although groundwater level gradients and hydrogeological properties clearly indicate groundwater flow from Bolivia to Chile, the total groundwater flow across the entire depth and width of the border area is not known. However, available data and modeling support that the groundwater flow across the border is at least of the same order of magnitude as surface water discharge at the border.

5 In which of the hydrogeological units, inside Bolivian territory, has the existence of aquifers in the Silala been identified? Do any of this aquifers cross the border?

Response:

Silala surface water is predominantly comprised of groundwater discharge from the aquifers through springs and diffuse inflows along the canals.

The groundwater system in Silala is complex and is comprised of a fractured ignimbrite aquifer, with variable degrees of interconnectivity between different interbedded layers. We have identified the ignimbrite layers (HGU5, HGU6) and the fault zone in the Silala ravine (HGU7) as the dominant aquifers of the system. All these aquifers cross the border

6 Taking into account the dating of the waters of Silala, could it be affirmed that part of the groundwaters are not renewable?

Response:

Analyses of groundwater samples from springs and shallow piezometers in the northern wetland and southern wetland, respectively, demonstrate significant differences in water chemistry indicative of two different sources of origin. Also the radiocarbon dating suggest that groundwater discharge to the southern wetland is significantly older (potentially on the order of thousands of years older) than that to the northern wetland, with an apparent age less than a thousand years. The water in the northern wetland may be from a combination of various sources, for example significantly younger water mixed with older water from the same source as the southern wetland or simply a more localized source of recharging waters.

Since the groundwater residence times in the Silala aquifers maybe very long, high groundwater ages do not in themselves imply that the water is non-renewable. Our analyses indicate that a substantial part of the Silala discharge may be recharged in the upstream groundwater catchment. This, however, does not preclude that a portion of the groundwater discharging to the Silala wetlands is from non-renewable sources. It has not been not possible to determine the magnitude of such portion.

7 Will the removal of the canals installed in the bofedales and in the Silala ravine in Bolivia contribute to the natural recovery of the wetland ecosystem?

Response:

Restoration of the hydrological conditions is a prerequisite for achieving a wetland ecosystem comparable to pre-canal conditions. Hence, a proper removal of the canals will contribute to a natural recovery.

Restoration of wetlands by removing the drainage and canal system will have an immediate effect on flows and hydrological processes. Reestablishing wetland vegetation and the formation of peat by biological processes will affect the eco-hydrological conditions but over a much longer time scale, probably decades.

Annex 18

Ramsar Convention Secretariat, *Report Ramsar Advisory Mission Nº 84, Ramsar Site Los Lipez, Bolivia,* 2018

(Original in Spanish, English translation)

Ramsar

CONVENTION ON WETLANDS

CONVENTION SUR LES ZONES HUMIDES

CONVENCIÓN SOBRE LOS HUMEDALES

(Ramsar, Iran, 1971)

Secretaria de la Convención Ramsar

Informe

Misión Ramsar de Asesoramiento No. 84

Sitio Ramsar Los Lipez, Bolivia

Agosto 3 de 2018

Ramsar Convention Secretariat
Report

Ramsar Advisory Mission Nº 84
Los Lipez Ramsar Site, Bolivia

3 August 2018

INDICE

Misión Ramsar de Asesoramiento Sitio Ramsar Los Lipez

INDEX

Misión Ramsar de Asesoramiento No. 84

Sitio Ramsar Los Lipez

1. Introducción General

La Convención sobre los Humedales de Importancia Internacional o Convención Ramsar es un tratado intergubernamental que proporciona el marco para la acción nacional y la cooperación internacional para la conservación y uso racional de los humedales y sus recursos. A marzo de 2017 hay 169 Países Parte en la Convención y 2,261 Humedales de Importancia Internacional, con una superficie total de 215, 277, 357 hectáreas.

La Convención basa su acción en tres pilares, el uso racional de todos los recursos de humedales en cada país, la designación de humedales de importancia internacional y su gestión, y la cooperación internacional.

1.1 Los Humedales de Importancia Internacional y disposiciones de la Convención

Las Partes Contratantes en la Convención sobre los Humedales tienen el deber, con arreglo al párrafo 4 del artículo 2, de designar por lo menos un sitio para ser inscrito en la Lista de Humedales de Importancia Internacional al firmar la Convención o depositar su instrumento de ratificación o de adhesión, de conformidad con las disposiciones del Artículo 9.

Según el artículo 1, párrafo 1 "son humedales las extensiones de marismas, pantanos y turberas, o superficies cubiertas de aguas, sean éstas de régimen natural o artificial, permanentes o temporales, estancadas o corrientes, dulces, salobres o saladas, incluidas las extensiones de agua marina cuya profundidad en marea baja no exceda de seis metros" y "podrán comprender sus zonas ribereñas o costeras adyacentes, así como las islas o extensiones de agua marina de una profundidad superior a los seis metros en marea baja, cuando se encuentren dentro del humedal" (artículo 2, párrafo 1).

La Lista Ramsar de Humedales de Importancia Internacional, de conformidad con el Artículo 2 del texto del tratado, es la piedra angular de la Convención de Ramsar y su principal objetivo es crear y mantener una red internacional de humedales que revistan importancia para la conservación de la diversidad biológica mundial y para el sustento de la vida humana a través del mantenimiento de los componentes, procesos y beneficios/servicios de sus ecosistemas. Igualmente, tiene como fin promover la cooperación entre las Partes Contratantes, y los interesados directos locales en la selección, designación y manejo de los sitios Ramsar.

La designación de sitios para ser incluidos en la Lista de Humedales de Importancia Internacional "deberá basarse en su importancia internacional en términos ecológicos, botánicos, zoológicos, limnológicos o hidrológicos" (párrafo 2 del artículo 2). Según el artículo 3 párrafo 1 de la Convención, las Partes están obligadas a "elaborar y aplicar su planificación de forma que favorezca la conservación de los humedales incluidos en la Lista y, en la medida de lo posible, el uso racional de los humedales de su territorio".

Ramsar Advisory Mission Nº 84
Los Lipez Ramsar Site

1. General Introduction

The Convention on Wetlands of International Importance, or Ramsar Convention is an intergovernmental treaty that provides a framework for national actions and international cooperation directed towards the preservation and rational use of wetlands and their resources. As of March 2017, there are 169 countries that are parties to the Convention and 2,261 wetlands of international importance registered, covering a total area of 215,277,357 hectares.

The Convention bases its actions on three pillars, i.e. the rational use of wetland resources in each country, the designation and management of wetlands of international importance, and international cooperation.

1.1 Wetlands of International Importance and the provisions of the Convention

The Contracting Parties to the Convention on Wetlands have the duty, by virtue of article 2, paragraph 4, to designate at least one site to be registered in the List of Wetlands of International Importance when signing the Convention, or when depositing their instrument of ratification or adhesion, in conformity with the provisions of Article 9.

In accordance with Article 1, paragraph 1, "wetlands are areas of marsh, fen, peat-land or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters" and, under Article 2, paragraph 1, "may incorporate riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six meters at low tide lying within the wetlands" (Article 2, paragraph 1).

The Ramsar List of Wetlands of International Importance, in accordance with Article 2 of the treaty text, is the cornerstone of the Ramsar Convention and its main objective is to create and maintain an international network of wetlands that are relevant for the preservation of global biological diversity and for the sustenance of human life by ensuring that the components, processes, and benefits/services of their ecosystems are preserved. It also aims at promoting cooperation between the Contracting Parties and local stakeholders in the selection, designation, and management of Ramsar sites.

The designation of sites to be included in the List of Wetlands of International Importance must be based on "their international significance in terms of ecology, botany, zoology, limnology or hydrology" (Article 2, paragraph 2). As per Article 3, paragraph 1 of the Convention, the Parties are under the obligation to "formulate and implement their planning so as to promote the conservation of the wetlands included in the List, and as far as possible the wise use of wetlands in their territory."

En el artículo 3 párrafo 2 de la Convención, se estipula que cada Parte Contratante tomará las medidas necesarias para informarse lo antes posible acerca de las modificaciones de las condiciones ecológicas de los humedales situados en su territorio e incluidos en la Lista, y que se hayan producido o puedan producirse como consecuencia del desarrollo tecnológico, de la contaminación o de cualquier otra intervención del hombre. Las informaciones sobre dichas modificaciones se transmitirán sin demora a la Secretaria en el marco del Artículo 8.

En el anterior sentido, las Partes Contratantes se comprometen con la designación de los sitios Ramsar a administrar dichos sitios de forma tal que se mantengan las características ecológicas de cada uno de ellos y, de esa manera, mantener las funciones ecológicas e hidrológicas esenciales que redundan en última instancia en sus "productos, funciones y atributos".

El Registro de Montreux es un registro de los humedales inscritos en la Lista de Humedales de Importancia Internacional, en los que se están produciendo, se han producido o pueden producirse cambios en las características ecológicas como consecuencia del desarrollo tecnológico, la contaminación u otra intervención del ser humano. El Registro se lleva como parte de la Lista de Ramsar.

1.2. Los conceptos de cambio en las características ecológicas, uso racional y servicios ecosistémicos

El cambio en las características ecológicas está definido en el contexto de la Convención como el que se produce en cualquiera de los componentes (biológico, químico, físico), procesos ecológicos o servicios del humedal inducidos por la acción humana.

Por su parte, el concepto de uso racional es uno de los tres pilares de la Convención y hace referencia al mantenimiento del carácter ecológico a través de la implementación de un enfoque por ecosistemas en el contexto del desarrollo sostenible.

En el marco de la Convención Ramsar las Partes Contratantes, aprobaron mediante la Resolución IX.1 Anexo A.j los aspectos referentes a los servicios ecosistémicos de los humedales de la Evaluación de Ecosistemas del Milenio. En este contexto se definen como los beneficios que las personas obtienen de los ecosistemas Tabla 1. Estos incluyen la provisión de servicios tales como alimentos, agua, servicios de regulación como control de inundaciones, sequías, degradación de tierras y enfermedades. Servicios de soporte como formación de suelos y ciclos de nutrientes; servicios culturales como recreación, espirituales o religiosos así como otros beneficios no materiales.

Suministro de servicios Productos obtenidos de los ecosistemas	**Regulación de servicios** Beneficios obtenidos de los procesos de regulación de los ecosistemas	**Servicios culturales** Beneficios no materiales obtenidos de los ecosistemas
• Alimento • Agua potable • Combustible • Fibra vegetal • Bioquímicos • Recursos genéticos	• Regulación del clima • Control de enfermedades • Regulación del agua • Purificación del agua • Polinización	• Espirituales y religiosos • Recreación y turismo • Estético • Inspiraciónal • Educativo • Sentido de identidad • Patrimonio cultural
Servicios de soporte Servicios necesarios para la producción de todos los otros servicios del ecosistema Formación de suelos Ciclado de nutrientes Producción primaria		

Tabla 1. Servicios ecosistémicos de los humedales, definidos en la Evaluación de Ecosistemas del Milenio (2005).

Article 3, paragraph 2 of the Convention provides that each Contracting Party is to take the necessary measures to be informed the soonest possible of the changes occurring in the ecological conditions of the wetlands located within their territories and included in the List—changes that may have taken place, or are likely to, as a result of technological development, pollution, or any other human interference. The information on such changes must be transmitted without delay to the Secretariat, as specified under Article 8.

In keeping with the above provisions, the Contracting Parties undertake, by designating Ramsar sites, to manage such sites in a way that preserves their ecological characteristics and, in this way, to maintain the ecological and hydrological functions that ultimately result in their "products, functions, and attributions".

The Montreux Record is a register of the wetlands included in the List of Wetlands of International Importance where changes in the ecological character have occurred, are occurring, or are likely to occur as a result of technological developments, pollution, or any other human intervention. This Record is maintained as part of the Ramsar List.

1.2 The concept of change in the ecological characteristics, rational use, and ecosystem services

The concept of change in ecological characteristics is defined in the context of the Convention as that which occurs in any of the (biological, chemical, or physical) components, ecological processes, or wetland services induced by human actions.

The concept of rational use, for its part, is one of the three pillars of the Convention and refers to the maintenance of the ecological character through the implementation of an ecosystem approach in the context of sustainable development.

In the framework of the Ramsar Convention, the Contracting Parties approved, by way of Resolution IX.1, Annex A. j, the aspects related to the ecosystem services of wetlands contained in the Millennium Ecosystem Assessment. The benefits that people obtain from ecosystems are defined in Table 1 and include the provision of services such as alimentation, water, and regulation systems such as flood, drought, land degradation, and disease control; including support services such as soil formation and nutrient cycles, cultural services such as amusement, spiritual, and religious, as well as other non-material benefits.

Service provision	Service regulation	Cultural services
Products obtained from ecosystems • Alimentation • Drinking water • Fuels • Vegetable fibers • Biochemical products • Genetic resources	Benefits obtained from ecosystem regulation processes • Climate regulation • Disease control • Water regulation • Water purification • Pollination	Non-material benefits obtained from ecosystems • Spiritual, or religious benefits • Entertainment and tourism • Esthetic • Inspirational • Educational • Sense of identity • Cultural heritage
Support Services Services necessary for the production of other ecosystem services		
Soil formation	Nutrient cycles	Primary production

Table 1. Wetland ecosystem services, as defined in the Millennium Ecosystem Assessment (2005).

1.3 Misiones Ramsar de Asesoramiento (MRA)

En el párrafo 18 de la Resolución X.13 (2008), las Partes Contratantes reafirmaron el compromiso "de aplicar plenamente los términos del Artículo 3.2 relativos a la obligación de informar sobre las modificaciones y conservar o restablecer las características ecológicas de sus sitios Ramsar, incluso mediante todos los mecanismos apropiados para abordar y resolver tan pronto como sea posible los asuntos por los que un sitio haya podido ser objeto de un informe en cumplimiento del Artículo 3.2; y, una vez resueltos dichos asuntos, presentar un nuevo informe para que las influencias positivas en los sitios y los cambios en las características ecológicas puedan reflejarse fielmente en los informes presentados a las reuniones de la Conferencia de las Partes, a fin de exponer con claridad el estado y las tendencias de la red de sitios Ramsar."

En el marco de la Convención, se concede especial atención a la prestación de asistencia a las Partes Contratantes en el manejo y la conservación de los sitios designados de la Lista cuyas características ecológicas se vean amenazadas. Esta labor se lleva a cabo mediante la Misión Ramsar de Asesoramiento (MRA), un mecanismo de asistencia técnica adoptado oficialmente mediante la Recomendación 4.7 de la Conferencia de las Partes de 1990. El principal objetivo de este mecanismo es ofrecer asistencia a los países desarrollados y en desarrollo indistintamente con el fin de que resuelvan los problemas o las amenazas que hicieron o hacen necesaria la inclusión del sitio en el Registro de Montreux.

Tras recibir una solicitud de una Parte Contratante, la Secretaría conviene en organizar la MRA con las autoridades competentes y determina el tipo de experto que hará falta incluir en el equipo de la misión. El proyecto de informe de la Misión que consigna conclusiones y recomendaciones se transmite a las autoridades competentes que han solicitado la MRA para su revisión y la versión revisada definitiva del mismo se convierte en documento público, que puede servir de base para tomar medidas de conservación en el sitio.

1.4 La aplicación de la Convención Ramsar en Bolivia

La Convención Ramsar entro en vigor en Bolivia el 27 de Octubre de 1990 e incluye como primer Humedal de Importancia Internacional Los Lipez (originalmente Laguna Colorada). A la fecha cuenta con 11 sitios Ramsar o Humedales de Importancia Internacional que cubren 14, 842,405 hectáreas, convirtiéndose en el país con más área de Humedales designados de Importancia Internacional en la Convención.

El Viceministerio de Medio Ambiente, Biodiversidad, Cambios Climáticos y de Gestión y Desarrollo Forestal es la Autoridad Administrativa de la Convención y agencia implementadora en Bolivia.

A través del Fondo de Humedales para el Futuro, Bolivia ha recibido apoyo financiero por un valor de USD$116,727 para la implementación de proyectos orientados hacia el fortalecimiento de capacidades y designación de sitios Ramsar. Igualmente, por el Fondo de Pequeñas Subvenciones se han financiado proyectos por un valor de CHF100,600.

En cuanto a otros procesos de implementación regional, Bolivia hace parte de las Iniciativas Regionales que operan en el marco de la Convención: Humedales Alto Andinos, Amazonas y Cuenca del Plata.

2. Programa de Trabajo de la Misión

1.3 The Ramsar Advisory Missions (RAM)

Under Paragraph 18 of Resolution X.13 (2008), the Contracting Parties reaffirmed their commitment "to implement fully the terms of Article 3.2 on reporting change, and to maintain or restore the ecological character of their Ramsar sites, including employing all appropriate mechanisms to address and resolve as soon as possible the matters for which a site may have been the subject of an Article 3.2 report; and, once those matters have been resolved, to submit a further report, so that both positive influences at sites and changes in ecological character may be fully reflected in the reporting to meetings of the Conference of the Parties in order to establish a clear picture of the status and trends of the Ramsar site network."

In the framework of the convention, special attention is paid to the provision of assistance to the Contracting Parties in the management and preservation of the List sites whose ecological characteristics are threatened. This task is carried out by means of the Ramsar Advisory Missions (RAM), a technical assistance mechanism adopted officially under Recommendation 4.7 of the Meeting of the Conference of the Parties held in 1990. The main objective of this mechanism is to offer assistance to developed and developing countries, indistinctively, with a view to resolving the problems or threats that had made the inclusion of their sites into the Montreux Record necessary, or that are likely to make it necessary.

After receiving a Contracting Party's request, the Secretariat arranges a RAM with the competent authorities and determines the particular expert needed for the mission's team. The Mission's draft report, including conclusions and recommendations, is transmitted to the competent authorities that requested a Ramsar Advisory Mission for them to examine it, and the final version of the report becomes a public document that can serve as the basis to take preservation measures in the site.

1.4 Application of the Ramsar Convention in Bolivia

The Ramsar Convention entered into force in Bolivia on 27 October 1990 and includes Los Lipez (originally Laguna Colorada—Red Lagoon) as Bolivia's first Wetland of International Importance. To date, Bolivia has registered 11 Ramsar sites, or Wetlands of International Importance covering an area of 14,842,405 hectares, making it the country with the largest extent of Wetlands designated as Wetlands of International Importance under the Convention.

The Vice-Ministry of Environment, Biodiversity, Climate Change, and Forest Management and Development is the Convention's Administrative Authority and the implementing agency in Bolivia.

Through the Wetlands for the Future Fund, Bolivia has received financial support equivalent to an amount of 116,727 USD for the implementation of projects directed toward strengthening its capacities and designation of Ramsar sites. Similarly, through the Ramsar Small Grants Fund, projects have been financed with a value of 100,600 CHF.

Concerning other regional implementation projects, Bolivia is part of the Regional Initiatives that operate within the framework of the Convention: High Plateau wetlands, the Amazon River, and La Plata Basin.

2. The Mission's Working Program

2. 1 Objetivo de la Misión

En nota diplomática del 29 de Julio de 2016 la Misión Permanente del Estado Plurinacional de Bolivia, transmite comunicación del Viceministro de Relaciones Exteriores mediante la cual informa a la Secretaria de Ramsar de cambios en las características ecológicas del Sitio Ramsar los Lipez (incluye bofedal del Silala y áreas conexas del sitio Ramsar Los Lipez) y solicita oficialmente una Misión Ramsar de Asesoramiento en dicho sitio.

Como respuesta a la solicitud del Gobierno de Bolivia y de acuerdo a las competencias de la Secretaria, la Misión Ramsar de Asesoramiento se realizó del 7-11 de noviembre de 2016 con el fin de proporcionar recomendaciones al Gobierno de Bolivia respecto a la problemática ambiental que presenta el sitio y que permitan el mantenimiento de sus características ecológicas.

Con base a la información técnica suministrada por el Ministerio del Medio Ambiente y Agua, complementada por las presentaciones técnicas y visita al Sitio Ramsar, el presente informe presenta una serie de conclusiones y recomendaciones a los estamentos de gobierno de Bolivia y tomadores de decisiones para el mantenimiento de las características ecológicas en el contexto de la Convención.

2. 2. Programa de Actividades

La Misión se realizó del 7-11 de Noviembre de 2016 y conto con el apoyo del personal directivo del Ministerio de Relaciones Exteriores en cabeza del Viceministro así como profesionales del Ministerio de Medio Ambiente y de diferentes instancias gubernamentales nacionales y regionales. La Secretaria de Ramsar agradece al gobierno de Bolivia a través de los anteriores estamentos sus oficiales y expertos técnicos todo el apoyo prestado para el desarrollo de la Misión.

La Misión estuvo coordinada por la Secretaria de la Convención Ramsar a través de la Consejera Regional para las Américas, e hicieron parte de la misma un experto en hidrogeología. El gobierno de Bolivia asignó un grupo de expertos técnicos del Ministerio de Medio Ambiente y otros estamentos para acompañar la Misión.

La Misión reviso la información provista por el Gobierno de Bolivia durante la visita así como la proporcionada a partir de las reuniones técnicas con los expertos. Los documentos consultados se encuentran listados en la bibliografía y el programa de la Misión en el anexo 1. Igualmente, se realizó una visita por carro al sitio Ramsar.

3. Aspectos de Línea Base del Sitio Ramsar

3.1 Aspectos generales, criterios de designación, otros aspectos

El Sitio Ramsar los Lipez (originalmente Laguna Colorada) fue designado el 27 de Junio de 1990 con un área de 1,427,717 ha. Esta localizado en el Altiplano Boliviano entre 4,200 a 6,000 m. El sitio original se extendió significativamente en el 2009 e incluye un complejo de lagunas Alto Andinas endorreicas hipersalinas así como bofedales y humedales geotérmicos. Estos humedales sustentan aves migratorias tales como el *Phalaropus tricolor* y *Calidris bairdii* los cuales usan estos humedales como sitio de parada y alimentación. Adicionalmente, 25% y 50% de las poblaciones globales del flamenco andino (*Phoenicoparrus andinus*) y flamenco de James (*Phoenicoparrus jamesi*), se concentran en esta área. Debido a su belleza paisajistica y atractivos naturales es el área protegida más visitada en Bolivia (Apro. 70,000 turistas por año)

2.1 The Mission's Objective

Through Diplomatic Note of 29 July 2016, the Deputy Foreign Minister of the Permanent Mission of the Plurinational State of Bolivia sent a communication informing the Ramsar Convention Secretariat of changes occurring in the ecological characteristics of Los Lipez Ramsar Site (which comprises the Silala wetlands and related areas of Los Lipez Ramsar Site) and officially requested a Ramsar Advisory Mission for the site.

Responding to the request made by the Government of Bolivia, and in accordance with the competences of the Secretariat, the Ramsar Advisory Mission was carried out from 7 to 11 November 2016 for the purpose of providing recommendations to the Government of Bolivia in regard to the environmental problems occurring in the site and to allow maintaining its ecological characteristics.

On basis of the technical information provided by the Ministry of Environment and Water, which was complemented with the technical presentations and site visit made to the Ramsar Site in question, this report presents a series of conclusions and recommendations for the different governmental levels and decision-makers of Bolivia to maintain the ecological characteristics of the site within the context of the Convention.

2.2 Activity Program

The Mission was carried out from 7 to 11 November 2016 and was supported by the management staff of the Ministry of Foreign Affairs, led by the Deputy Foreign Minister, as well as by professionals of the Ministry of Environment and of different national and regional government instances. The Ramsar Secretariat thanks the Bolivian Government, through its officials and expert technicians, for the support provided to carry out the mission.

The Mission was coordinated by the Secretariat of the Ramsar Convention through the Regional Advisor for the Americas and had the participation of an expert hydrologist. The Government of Bolivia appointed a group of expert technicians of the Ministry of Environment and other Government institutions to accompany the Mission.

The Mission examined the information provided by the Government of Bolivia during the visit, as well as that provided in technical meetings held with experts. The documents consulted are listed in the bibliography and Mission's Program found in Annex 1. Likewise, a site visit by car was made to the Ramsar site in question.

3. Baseline Aspects of the Ramsar Site

3.1 General Aspects, designation criteria, and other aspects

The Los Lipez Ramsar site (originally, Laguna Colorada—Red Lagoon) was designated on 27 June 1990, with an area of 1,427,717 hectares. It is found in the Bolivian High Plateau, between 4,200 and 6,000 m. The original site was significantly extended in 2009 and now includes a complex of high Andean endorheic and hypersaline lagoons, as well as geothermal wetlands and highland wetlands. These wetlands sustain migratory birds such as *Phalaropus tricolor* and *Calidris bairdii*, which use these wetlands as stop and feeding sites. Additionally, 25% and 50% of the global population of Andean flamingoes (*Phoneicoparrus andinus*) and James's flamingoes (*Phoenicoparrus james*) are found in this area. Due to its beautiful landscapes and natural attractions, this is the protected area that is visited the most in Bolivia (receiving approximately 70,000 tourists per year).

El sitio Ramsar cubre dos de los 14 sitios prioritarios de la red de humedales de importancia para la conservación de los flamencos alto andinos en Argentina, Bolivia, Chile y Perú. Una parte del sitio está protegido por la Reserva Nacional de Fauna Andina Eduardo Avaroa.

De acuerdo a la Ficha Informativa Ramsar, 2009 el sitio fue incluido en el listado de Humedales de Importancia Internacional de la Convención atendiendo a 6 de los siguientes criterios:

Criterio 1:

Son complejos de lagos permanentes salinos/hipersalinos/alcalinos, turberas como bofedales y humedales geotérmicos, ubicados en una zona árida o semiárida y de carácter endorreico.

Criterio 2

Dos de las tres especies de flamencos presentes en el sitio, *Phoenicopterus andinus* se encuentra vulnerable (VU) y *P. jamesi* como casi amenazada de acuerdo a las categorías de la UICN (2008).

Otras especies en categoría de casi amenazada son el avestruz andino andino (*Pterocnemia pennata*), el cóndor andino (*Vultur gryphus*), Fulica cornuta y en bofedales *Phegornis mitchellii.*

Entre los felinos el gato andino (*Oreailurus jacobita* o *Leopardus jacobita*)
y el gato del pajonal (*Leopardus colocolo*) corresponden a las categorías "en peligro" y "casi amenazado" de la IUCN 2008.

Criterio 3: El sitio alberga algunas especies endémicas restringidas como el anuro *Telmatobius huayra.* Entre los lacertilios están presenten algunas especies del género *Liolaemus* con endemismos regionales como *Liolaemus isulgensis erguetae* y *L. jamesi pachecoi* (Ergueta, P., H. Gómez y O. Rocha. 1997 citado en FIR 2009).

En plantas existe una alta proporción de géneros y especies endémicas. Los géneros endémicos de esta porción de la Puna son *Parastrephia, Lampaya*, *Chersodoma* y *Anthobryum* (Frankenia) (Cabrera y Willink 1973 citado en FIR, 2009). Las especies *Chersodoma candida, Ch. jodopappa* (Cabrera 1978 citado en FIR, 2009) y *Chaetanthera sphaeroidalis* (Navarro 1993, citado en FIR, 2009), son propias de las regiones áridas y frías que crecen en las acumulaciones de rocas o en los tólares, bajo la protección de los arbustos (García, 2006 citado en FIR, 2009). Entre las cactáceas en cojín, como Opuntia cf. *backebergii*, es una endémica poco conocida.

Entre las gramíneas endémicas se encuentran: *Jarava (Stipa) methei*, *Festuca petersonii*, *F. potosiana*, especies efímeras de *Hoffmannseggia* y *Nototrichie* (Ibisch et al, 2003 citado en FIR, 2009).

Criterio 4: El complejo de lagunas son sitios de parada y alimentación para aves acuáticas migratorias boreales que se encuentran en importantes concentraciones. Entre las especies más abundantes están *Phalaropus tricolor* y *Calidris bairdii*.

Laguna Colorada es el sitio de nidificación más importante para el Flamenco de James (*P. jamesi)* en toda su área de distribución (Hurlbert y Keith 1979 citado en FIR, 2009).

Criterio 5: De acuerdo a los censos de Aves Acuáticas Neotropicales (Rocha y Aguilar no publicado), This Ramsar Site covers two of the fourteen priority sites of the network of wetlands relevant for the preservation of high Andean flamingoes in Argentina, Bolivia, Chile, and Peru. A part of this site is under the protection of the Eduardo Avaroa Andean Fauna National Reserve.

In accordance with the Ramsar Information Sheet (RIS) of 2009, the site was included in the List of Wetlands of International Importance of the Convention due to the following criteria:

First,
these wetlands comprise permanent saline/hypersaline/alkaline lakes, and peatlands, such as wetlands and geothermal wetlands, found in an arid or semiarid endorheic zone.

Second,
of the three species of flamingoes present in the site, the *Phoenicopterus andinus* is vulnerable (VU) and the *P. Jamesi* is classified as nearly threatened on the IUCN's Red List (2008).

Other species classified as nearly threatened are the Andean ostrich (*Pretocnemia pennata*), the Andean condor (*Vultur gryphus*), the Fulica cornuta, and, within the wetlands, the *Phergonis mitchellii.*

Concerning feline species, the Andean mountain cat (*Oreailurus jacobita or Leopardus jacobita*) and the colocolo (*Leopardus colocolo*) are classified as "endangered" and "nearly endangered" on the IUCN's Red List for 2008.

Third,the site is home to some restricted-range endemic species such as the anuran, *Telmatobius huayra*. Among the lizard species, the site is home to some species of the *Liolaemus* genus with regional endemic species as the *Liolaemus isulgensis erguetae* and *L. Jamesi pachecoi* (Ergueta, P., H. Gomez, and O Rocha, 1997, quoted in the RIS of 2009).

Concerning plant families, there is a high amount of endemic genus and species. The endemic species of this portion of the Puna are the *Parastrephia, Lampaya*, *Chersodoma*, and *Anthobryum* (Frankenia) (Cabrera and Willink, 1973, quoted in the RIS of 2009). The *Chersodoma candida, Ch. Jodopappa* (Cabrera 1978, quoted in the RIS of 2009) and *Chaetanthera sphaeroidalis* (Navarro, 1993, quoted in the RIS of 2009) species are characteristic of the arid and cold regions and grow on rock accumulations or on tola plants (*Parastrephia lepidophylla*), protected by bushes (Garcia, 2006, quoted in the RIS of 2009). Among the pincushion cacti species, the Opuntia, cf. *backebergii*, is a little-known endemic genus.

Among the grass species, the following are present in the site: *Jarva* (*stipa*) *methei, Festuca petersonii, F. potosiana*, together with the ephemeral species of *Hoffmannseggia* and *Notorichie* (Ibisch, et al. 2003, quoted in the RIS of 2009).

Fourth, the lagoon complex is a stop and feeding site for boreal migratory waterbirds that are found in considerable concentrations. The *Phalaropus tricolor* and *Calidirs bairdii* are among the most abundant species.

Red Lagoon is the most important nesting site for the James's Flamingo (*P. jamesi*) genus throughout its area of distribution (Hurlbert and Keith, 1979, quoted in the RIS of 2009).

Fifth, in accordance with the Census of Neotropical Waterbirds (Rocha and Aguilar, unpublished), Caziani et al. (2007), Rocha (1997 y 2006), Rocha y Quiroga (1997), Valqui et al. (2000), citados en FIR, 2009 y otras publicaciones, el sitio sustenta de manera regular una población de 20.000 o más aves acuáticas.

Las especies mas abundantes son las tres especies de flamencos (*Phoenicoparus jamesi*, *P. andinus* y *Phoenicopterus chilensis*) y dos playeros migratorios boreales (*Phalaropus tricolor* y *Calidris bairdii)*.

Criterio 6: El complejo de lagunas alberga una concentración estival del 44-64% de la población total estimada de Flamenco de James (*P. jamesi*) y 22-28% de la población total estimada de Flamenco Andino (*P. andinus)* (Rocha 2006 citado en FIR, 2009).

Entre las especies aviares también está presente la gallareta cornuda (*Fulica cornuta)* y es posible que el sitio concentre a un 35% de la población total de la especie que se estima en 7.669 individuos (Rocha y Quiroga en prensa).

Características ecológicas

El sitio está conformado por un complejo de lagunas endorreicas permanentes, salinas, hipersalinas y alcalinas, con abundante presencia de tres especies de flamencos y otras aves acuáticas residentes y migratorias boreales, sitios prioritarios de nidificación regular de flamencos altoandinos (*Phoenicoparrus james y P. andinus*), con presencia de algunas especies casi amenazadas como la gallareta cornuda (*Fulica cornuta)*. Asimismo, se presentan turberas o bofedales con agua fresca, altamente productivos de materia vegetal para forraje de ganado camélido. En este sitio existen además humedales geotérmicos subterráneos interconectados. El sitio se sitúa en un paisaje esencialmente volcánico en una zona semidesértica, especialmente vulnerable al cambio climático.

El sitio se ubica en una de las regiones más pobres en especies de Bolivia y se caracteriza por la presencia de bosques relictuales de *Polylepis tarapacana,* así como por fumarolas, aguas termales, y lagunas de colores (FIR, 2009).

La vegetación es típica de la región biogeográfica de la Puna Semiárida que está caracterizada por condiciones progresivas de aridez hacia el sur. Las condiciones de elevada salinidad, determinan la presencia de una cobertura vegetal resistente a suelos halinos. La vegetación crece de forma aislada, ocupando grietas y lugares protegidos hasta los 4.800 y 5.000 ms.n.m., dominan las matas de gramíneas de los géneros *Calamagrostis* y *Festuca* con crecimiento en forma de semicírculo, debido a la muerte de la raíz principal y por los fuertes vientos (Tropico– Swedeforest 1998, citado en FIR, 2009).

En las laderas con rocas volcánicas se observa los cojines de yareta (Azorella compacta) y pequeñas comunidades de keñua (*Polylepis tarapacana)*. Se observan extensos pajonales abiertos con gramíneas en mata que se distribuyen en laderas y planicies, en un rango altitudinal amplio. La especie dominante es *Festuca ortophylla*, acompañada de *Stipa y Calamagrostis* y los cojines suaves y amarillos de *Pycnophyllum molle* (Tropico– Swedeforest 1998 citado en FIR, 2009).

Las formaciones mixtas de pastizal-matorral, con diferentes especies de tola como *Bacharis incarum*, *Parastrephia lepidophylla*, acompañadas de cactus en cojín, como *Opuntia cf. backebergii*, endémica poco conocida. Los matorrales están constituidos principalmente por la kh'iru thola (*Parastrephia lepidophylla*), ph'ulica thola (*P. quadrangularis*) y la thola (*P. lucida*). Los matorrales más abiertos presentan *Baccharis incarum*, y arbustos aislados de *Adesmia* y *Lampaya castellani* (Lampaya), en alturas menores. Los bofedales están constituidos por cojines duros de la juncácea andina *Oxychloe*

Caziani et al (2007), Rocha (1997 and 2006), Rocha and Quiroga (1997), Valqui et al (2000), quoted in the RIS of 2009 and other publications, the site regularly sustains a population of 20,000 or more waterbirds.

The most abundant species in the site are the three flamingo species (*Phoenicoparus jamesi, P. andinus,* and *Phoenicopterus chilensis*) along with two boreal migratory shorebirds (*Phalaropus tricolor* and *Calidris bairdii*).

Sixth, the complex of lagoons is also home to a summery concentration of 44-64% of the total population of the James's flamingo (*P. jamesi*) and 22-28% of the total estimated population of the Andean flamingo (*P. andinus*) (Rocha, 2006 quoted in the RIS of 2009).

Among the avian species, there is also the presence of the gallareta cornuda (Fulica cornuta) and the site is likely to concentrate a 35% of the total population of the species, which is estimated in 7,669 specimens (Rocha and Quiroga, in the press).

Ecological characteristics

The site comprises a complex of permanent endorheic, saline, hypersaline, and alkaline lagoons, characterized by an abundant presence of three flamingo species, as well as other residing and boreal migratory waterbirds. These are regular nesting sites for high Andean flamingoes (*Phoenicoparrus james* and *P. andinus*), with the presence of some species that are classified as nearly threatened, such as the gallareta cornuda (*Fulica cornuta*). Similarly, the site is also characterized by the presence of freshwater peatlands, or wetlands, that produce high amounts of forage for camelid livestock. The site also comprises interconnected underground geothermal wetlands and is located in an essentially volcanic landscape that is found in a semiarid zone which is particularly vulnerable to climate change.

The site is located in one of the most species-poor areas of Bolivia and is characterized by the presence of relict forests of *polylepis tarapacana*, as well as fumaroles, hot springs, and colored lagoons (RIS, 2009).

The vegetation is typical of the biogeographic region of the Semiarid Puna, which is characterized by progressive conditions of aridness towards the south. The conditions of high salinity result in the presence of haline-soil resistant vegetation, which grows in isolation, occupying cracks and protected areas up to 4,800 and 5,000 m.a.s.l; there is a higher presence of gramineous of the genus of *Calamagrostis* and *Festuca*, which grow forming semicircles owing to the death of their main roots and the strong winds (Tropico-Swedeforest, 1998, quoted in the RIS of 2009).

On the slopes characterized by volcanic rocks, it is possible to observe yareta cushions (*Azorella compacta*) and small communities of keñua (*Polylepis tarapacana*). Extensive open grasslands can also be observed, with forest gramineous that are distributed in the slopes and plains, in a wide altitudinal range. The dominant species is *Festuca ortophylla*, accompanied by *Stipa* and *Calamagrostis* and soft and yellow cushions of *Pycnophyllum molle* (Tropico-Swedeforest 1998, quoted in the RIS of 2009).

The mixed formations of grassland-shrubs are characterized by different tola species, such as Bacharis incarum, and *Parastrephia lepidophylla*, accompanied by pincushion cacti as *Opuntia cf*. backebergii—which is endemic but little known. The shrubs mainly consist of kh'iru thola (*Parastrephia lepidophylla*), ph'ulica thole (*P. quadrangularis*) and thola (*P. Lucida*). The most open shrubs are characterized by Baccharis incarum and isolated bushes of Adesmia and *andina* y *Distichia muscoides*, acompañadas por gramíneas de *Calamagrostis* (Tropico- Swedeforest 1998 citado en FIR, 2009).

En cuanto a la fauna además de las abundante presencia de tres especies de flamencos y otras aves acuáticas, se encuentran mamíferos como vicuñas, zorro andino, gato andino, vizcachas, tuco tuco (*Ptenomys spp.*) y lagartijas del género *Liolaemus* y ranas del género *Telmatobius* (FIR, 2009).

3.2 Servicios eco-sistémicos

De acuerdo a la propuesta de Ecosistemas del Milenio, los servicios ecosistémicos/ambientales son los bienes y beneficios que obtienen las personas de los ecosistemas. Estos incluyen los servicios de regulación, provisión y culturales que directamente afectan a las personas, además de los servicios necesarios para mantener los procesos ecológicos (soporte).

Entre los servicios ecosistémicos más relevantes del humedal Los Lipez podemos destacar los siguientes (FIR, 2009):

Las evidencias arqueológicas y actuales muestran claramente la fuerte dependencia de los pobladores "lipeños" a los recursos estratégicos de la región. Estos recursos estratégicos en la región de Lipez son: el agua dulce –escasa en la región-, porciones de tierras cultivables para quinua y papa, pastizales, bofedales y arbustales para la crianza de ganado camélido. Se hace evidente desde tiempos milenarios que los asentamientos humanos en la región dependen fuertemente de actividades ganaderas –cuidado de camélidos- que son desarrolladas principalmente en zonas de bofedales y serranías.

Hoy en día las actividades económicas se han diversificado y podemos encontrar ganadería camélida, producción textil a partir de la lana de llama, la explotación de recursos minerales no metálicos – Ulexita y ácido bórico- en las riberas de los salares y la oferta de servicios turísticos que en la última década se ha incrementado exponencialmente, considerando que esta región junto al Salar de Uyuni es la región con mayor afluencia turística en todo el país (alrededor de 70000 personas/año).

Síntesis de los servicios ecosistémicos del Sitio Ramsar Los Lipez

Suministro de servicios Productos obtenidos de los ecosistemas	**Regulación de servicios Beneficios obtenidos de los procesos de regulación de los ecosistemas**	**Servicios culturales Beneficios no materiales obtenidos de los ecosistemas**
Alimento (Quinua y papa) Agua potable Combustible (turba) Fibras vegetales (totorales) Forestería (Yareta, Queñua, Tholas) Plantas medicinales Ganado Camélido	Regulación del clima Regulación del agua Purificación del agua	Recreación y turismo Estético/paisajístico Patrimonio cultural Patrimonio arqueológico Educativo

Lampaya castellani (Lampaya), at lower altitudes. The wetlands consist of harder cushions of the Andean Juncaceae, *Oxychloe* and *Distichia muscoides*, accompanied by gramineous of *Calamagrostis* (Tropico-Swedenforest, 1998, quoted in the RIS of 2009).

In respect to the fauna, asides from the abundant presence of the three flamingo species abovementioned and other waterbirds, it is also possible to find mammals as vicunas, Andean foxes, Andean cats, viscachas, tuco tuco (*Ptenomys spp.*), lizards of the genus *Liolaemus* and frogs of the *Telmatobius* genus (RIS, 2009).

3.2 Ecosystem services

Under the Ecosystems for the Millennium proposal, ecosystem/environmental systems comprise the goods and benefits that people obtain from ecosystems. These include regulation, provision, and cultural services that directly affect the people, as well as the necessary services to maintain ecological processes (support).

Among the most relevant ecosystem services of Los Lipez wetlands, the following can be highlighted (RIS, 2009):

Archeological and present-day data clearly evidence a strong dependence of the Lipez inhabitants on the strategic resources of the region. These strategic resources found in the Lipez region comprise fresh water—scarce in the region—, portions of arable lands for quinine and potatoes, grasslands, wetlands, and shrubs to raise camelid livestock. It is evident that, since millennial times, human settlings in the region are strongly dependent on livestock activities—camelid raising—which are mainly carried out in the wetland and highland zones.

To date, business activities have diversified and it is possible to find camelid livestock, textile production of llama wool, and non-metallic mineral exploitation—ulexite and boric acid—in the sides of salt flats, together with the offer of touristic services, which has increased exponentially in the last decade—bearing in mind that this region, as well as that of the Uyuni salt flat, is the one marked with the most tourist inflow in the whole country (approximately 70,000 people per year).

Synthesis of the ecosystem services of Los Lipez Ramsar Site

Service Provision **Products obtained from the ecosystems**	**Service Regulation** **Benefits obtained from the ecosystem regulation processes**	**Cultural Services** **Non-material Benefits obtained from the ecosystems**
Alimentation (quinine and potatoes) Drinking water Fuels (peat) Vegetal fibers (cattail stands) Forestry (*Yareta*, *Queñua*, and *Tholas*) Medicinal plants Camelid livestock Non-metallic mineral resources—ulexite and boric acid	Climate regulation Water regulation Water purification	Recreation and esthetic/picturesque tourism Cultural heritage Archeological and educational heritage
Support Services Services that are necessary for the production of all the other ecosystem services		
Soil formation	Nutrient cycles	Primary production

Recursos minerales no metálicos – Ulexita y ácido bórico		
Servicios de soporte Servicios necesarios para la producción de todos los otros servicios del ecosistema		
Formación de suelos	Ciclo de nutrientes	Producción primaria

3.3 Aspectos Físicos

En esta sección se presenta el análisis de los aspectos físicos iniciando el mismo con un área más extensa que la zona del Sitio Ramsar Los Lípez; en lo subsecuente el análisis cubre más detalles en escalas cada vez más focalizadas en el sitio Ramsar, y en particular la zona del Silala.

Un análisis de esta naturaleza permite ver la integración de los aspectos físicos más relevantes del Altiplano Boliviano y sus efectos a escalas regionales, intermedias y locales.

3.3.1 Clima y geomorfología

Clima

Escala regional (ca 200’000 km^2)

El clima de la región del sudeste de Bolivia (Fig. 3.1) es de altura, seco y frío, precipitación baja, radiación solar intensa y fuertes vientos. La región occidental del Altiplano Sur está caracterizada por su bajísimo nivel de precipitación pluvial, la cual se presenta generalmente en los meses de diciembre, enero y febrero, el resto del año la precipitación es nula.

En algunas estaciones meteorológicas se han medido precipitaciones promedios, que varían sensiblemente de Norte a Sur del Altiplano, los valores más altos hacia Norte, varían entre 500 y 600 mm anuales, disminuyen paulatinamente hacia el sur con medidas inferiores a los 100 m anuales.

Las temperaturas registradas en la zona de análisis son las más bajas de Bolivia, las mínimas de invierno *(*mayo a agosto) descienden en la noche a valores extremos de -25°C hasta -30°C**,** subiendo en el día hasta los 15°C (Fig. 3.2)

3.3 Physical Aspects

This section comprises an analysis of the physical aspects of the Site, starting from a larger area than the Los Lipez Ramsar Site, and followed by an analysis that covers more details on scales that increasingly focus on the Ramsar site, particularly the Silala area.

An analysis of this kind allows the integration of more relevant physical aspects of the Bolivian High Plateau and their effects on regional, intermediate, and local scales.

3.3.1. Climate and geomorphology

Climate

Regional Scale (ca 200’000 km2)

The climate of the southeast region of Bolivia (Fig. 3.1) is high, dry, and cold, characterized by low precipitation, intense solar radiation, and strong winds. The western region of the southern High Plateau is characterized by its very low level of rainfall, which generally occurs in the months of December, January, and February; precipitation is nil the rest of the year.

Average precipitations have been measured in some meteorological stations, and have presented significant variations from the North to the South of the High Plateau. The highest values towards the North vary between 500 and 600 mm annually and decrease gradually towards the South with measures lower than 100 m annually.

The temperatures recorded in the area analyzed are the lowest in Bolivia. The lowest temperatures recorded in winter (May to August) fall at night to extreme temperatures of - 25° C, dropping to - 30° C, and rising in the day to 15° C (Fig. 3.2).

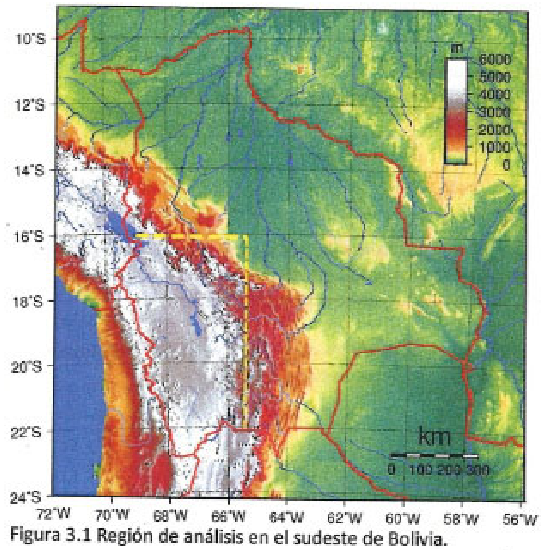


Figura 3.1 Región de análisis en el sudeste de Bolivia.

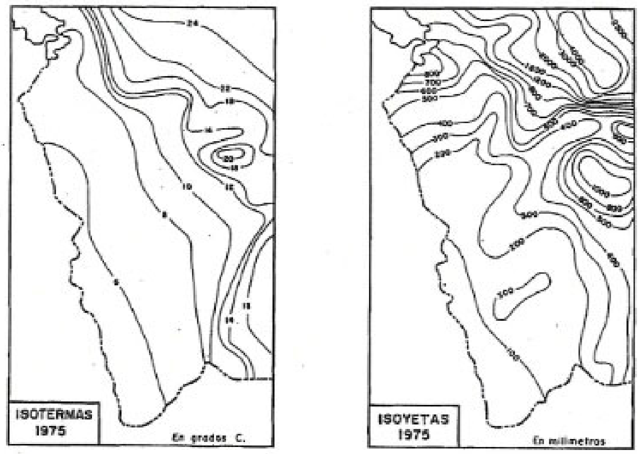


Figura 3.2 Mapas de isotermas y de isoyetas del sudeste de Bolivia.

Los meses de verano son más moderados, pero de todas maneras las heladas pueden sucederse con facilidad y el clima sigue siendo frío, presentándose diferencias térmicas de entre -3°C a 20°C. El fenómeno climático de incidencia especial en la zona es sin duda el viento, especialmente en los meses invernales donde las proporciones se elevan a niveles peligrosos de hasta 60 km/h de velocidad. Los vientos tienen una dirección predominante noreste-sudoeste, siendo una característica muy especial los cambios de intensidad y dirección según la hora del día, una vez pasadas las 16 horas este problema se acentúa.

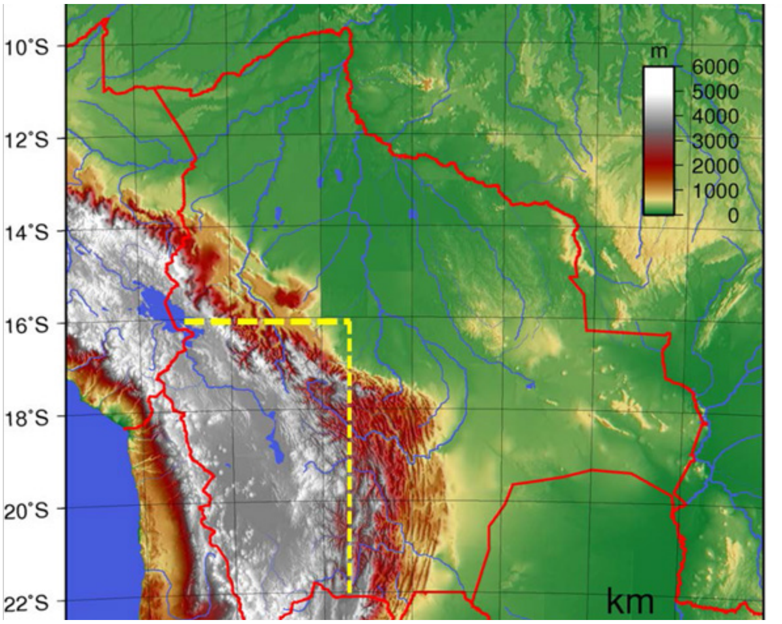


Figure 3.1. Analysis region of the southeast of Bolivia

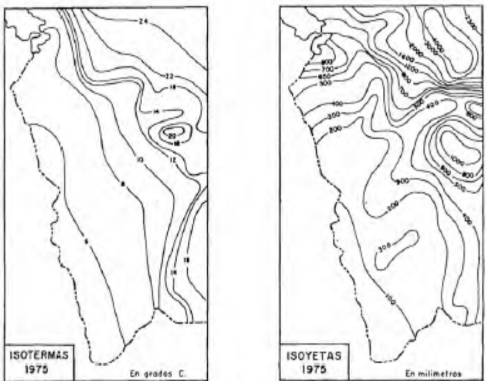


Figure 3.2. Isotherm and Isohyet Maps of the southeast of Bolivia

Summer months are more moderate, but frosts are still likely to happen and the climate is still cold, with temperatures ranging from -3° C to 20° C. The climatic phenomenon of distinctive incidence in the area is undoubtedly the wind, especially in the winter months, when the winds rise to dangerous levels of up to 60 km/h of speed. The winds have a predominant northeast-southwest direction and are characterized by changes in intensity and direction, which depend on the time of the day. This problem worsens after four o'clock.

Otro aspecto digno de mencionarse es el de insolación e irradiación solar, según las apreciaciones hechas por el programa ERTS esta zona poseen uno de los niveles de radiación solar más alto del planeta. "Por la altura en que se encuentra el Altiplano, se supone que este soporta solo las 2/3 partes de la masa atmosférica que toleran las regiones a nivel del mar, por lo tanto permiten una mayor insolación y también una mayor irradiación del suelo. Por tal motivo, existen oscilaciones diarias, que en promedio están dentro el orden de los 20ºC. (Estudio socio-económico integral del Altiplano Sur. Ministerio de Minería y Metalurgia - Bolivia).

Con respecto a la evaporación se puede decir que esta es intensa, debido en gran parte a la radiación solar, los productos generados por la escasa precipitación se ven disminuidos por la evaporación, que presenta valores extremos de hasta 6 mm diarios. Cabe notar que estos valores se ven incrementados por la existencia casi continua de fuertes vientos.

Otra característica interesante, e importante en el análisis a la escala regional, es que en realidad no hay una altura de evaporación anual definida y constante para toda la zona. Cada lago se evapora de manera particular debido a dos factores que controlan esa evaporación: la temperatura mínima de la zona y la salinidad del lago. Mientras más salada sea una laguna, menos se evapora. Por ejemplo, por cada 10 g/l de NaCl la evaporación se reduce en 1% en relación a la de una laguna de agua dulce. Por ejemplo una salmuera de 350 g/l tiene una evaporación reducida de 35%. Esta proporción de 1% puede aumentar con el contenido en magnesio (Turk, 1970). Por ello es que en la estimación de la evaporación de cada laguna siempre de deberá efectuar una corrección para las características de cada una de ellas. Pero otro factor fundamental es la temperatura de la atmosfera; mientras más frio hace, más tiempo se congela el agua y menos se evapora. Así mismo, mientras más salada sea una agua, más baja será su temperatura de congelamiento y menos tiempo quedará ésta congelada.

Como resumen, se puede decir que el análisis del clima en la región tiene una importancia considerable por cuanto a su influencia debido a la interacción de sus variables como son la altitud, el frío, las precipitaciones mínimas pero localizadas, como también la radiación, la insolación, etc., se constituyen en efectos vitales para comprender la meteorización y erosión de las rocas, cuyos productos son los que definen la calidad de los depósitos evaporíticos formados y los cuerpos de agua intermitentes o permanentes como las lagunas, los escurrimientos superficiales (muy raros), y el agua subterránea.

Escalas intermedias y locales (10,000 km^2 a 1,000 km^2)

A una escala más intermediaria y más local, las características del clima y de la morfología son similares a la escala regional pero también tienen sus propios rasgos particulares, tal es el caso de la zona cubierta por el sitio Ramsar Los Lípez (figura 3.3).

A esas escalas se distinguen los siguientes rasgos:

- Altura: 6,000 y 4,200 m
- Puna árida a semiárida.
- Presencia de Lagunas salinas/hipersalinas/alcalinas, de bofedales, de humedales geotérmicos y de cuerpos de agua endorreicos en zona desértica.
- Número limitado de fuentes de agua dulce para consumo humano.
- Condiciones climáticas aún más extremas que a la escala regional, lo cual inhibe, entre otras cosas, la agricultura.

Another worth mentioning aspect is the insolation and solar irradiation. According to the assessments made by the ERTS program, this zone has one of the highest levels of solar radiation on the planet. "Owing to the altitude of the High Plateau, it is assumed that the latter supports only two thirds of the atmospheric mass tolerated by the regions at sea level, therefore allowing greater insolation and also a greater irradiation of the soil. For this reason, there are daily oscillations, which on average are within the order of 20° C." (Comprehensive socio-economic study of the Southern High Plateau, Ministry of Mining and Metallurgy—Bolivia).

Evaporation can be said to be intense, due in large part to solar radiation. The products generated by the low precipitation are diminished by evaporation, which presents extreme values of up to 6 mm per day. It should be noted that these values are increased by the almost continuous presence of strong winds.

Another interesting and important feature of the regional analysis is that there is in fact no annual, defined, and constant evaporation mean for the whole area. Each lake evaporates in a particular way due to two factors that control evaporation: the minimum temperature of the zone and the salinity of the particular lake. The saltier a pond is, the less it evaporates. For example, for every 10 g/l of NaCl, evaporation is reduced by 1%, in relation to that of a freshwater lagoon. For example, a brine of 350 g/l has a reduced evaporation of 35%. This proportion of the 1% may increase with the magnesium content (Turk, 1970). That is why corrections must always be made on basis of the particular characteristics of each lagoon in estimating evaporation. Another fundamental factor is, however, the temperature of the atmosphere; the colder it is, the longer the water stays frozen and the less time it takes to evaporate. Likewise, the saltier the water, the lower its freezing temperature and the less time it will remain frozen.

As a summary, it can be said that the analysis of the climate in the region is of considerable importance because its influence in the interaction of the region's variables—such as altitude, cold, minimum, yet localized, precipitation, as well as radiation and insolation, etc.,—results in vital components to understand the weathering and erosion of rocks, the products of which define the quality of the evaporation deposits formed and the intermittent or permanent bodies of water, as lagoons, surface runoffs (which are quite rare), and groundwater.

Intermediate and local scales (10,000 km^2 to 1,000 km^2)

At a more intermediate and local scale, the characteristics of the climate and morphology are similar to those presented at the regional scale, but are also marked by particular features, as is the case of the area covered by the Los Lipez Ramsar site (figure 3.3).

The following features are distinguished at these scales:

- Altitude: 6,000 and 4,200 m.
- Arid to semiarid Puna.
- Presence of saline/hypersaline/alkaline lagoons, highland wetlands, geothermic wetlands, and endorheic bodies of water in the desert region.
- Limited number of sources of fresh water for human consumption.
- More extreme climate conditions than at the regional scale, which impede, among other activities, agriculture.

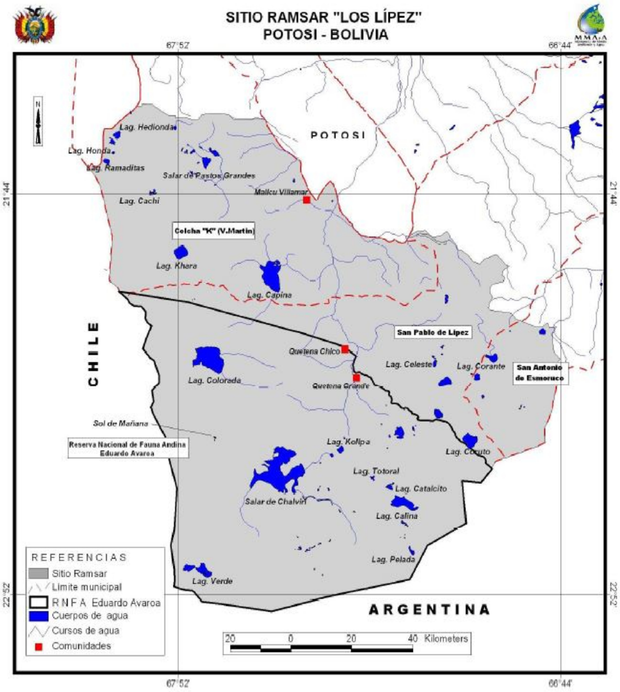


Figura 3.3 Localización del Sitio Ramsar “Los Lípez”

A la escala del sitio del sitio Silala, los datos de la estación meteorológica más cercana ubicada en la Laguna Colorada a 38 km del área de estudio y para el periodo 1985-1997 son:

- Precipitación: 59 mm de diciembre a marzo, con un máximo de 21.4 mm en enero, la sequía es entre abril y noviembre;
- Temperatura: promedio anual 14.2 C; promedio anual de las mínimas -15;
- Evaporación : más alta entre septiembre y marzo (78 mm en septiembre y 113 mm en diciembre), los valores más bajos son entre abril y agosto (la más baja con 36 mm en junio); y
- Evaporación Promedio: 914 mm.

Geomorfología

De la misma manera que para el clima, los aspectos de geomorfología de la región de análisis tendrá una mejor comprensión en su contexto general de la unidad morfo-estructural llamada Altiplano, o sea de la escala regional a las escalas intermediarias y local.

Dentro del Sitio Ramsar el área del Silala se localiza entre el paralelo 22º de latitud sur y 68º de longitud oeste a 4300 m sobre el nivel del mar. Esta área forma un valle que se extiende en

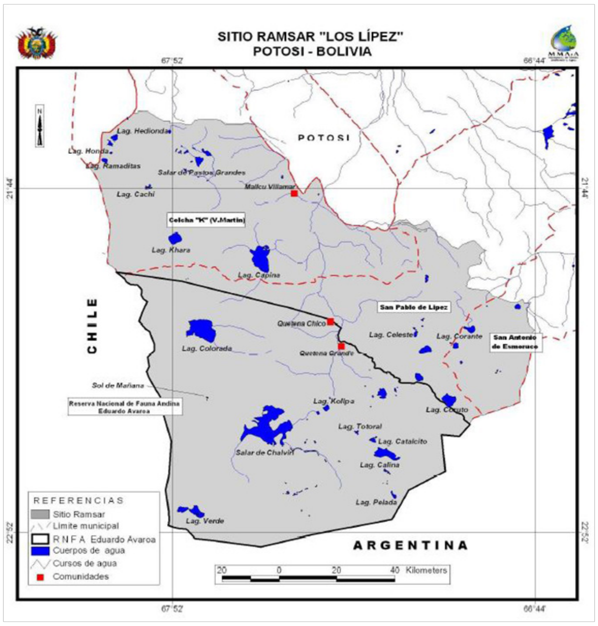


Figure 3.3. Location of Los Lipez Ramsar site

At the scale of the Silala site, the data obtained from the closest meteorological station, found on Laguna Colorada, at 38 km from the area of study, and for the period extending from 1985 to 1997, is the following:

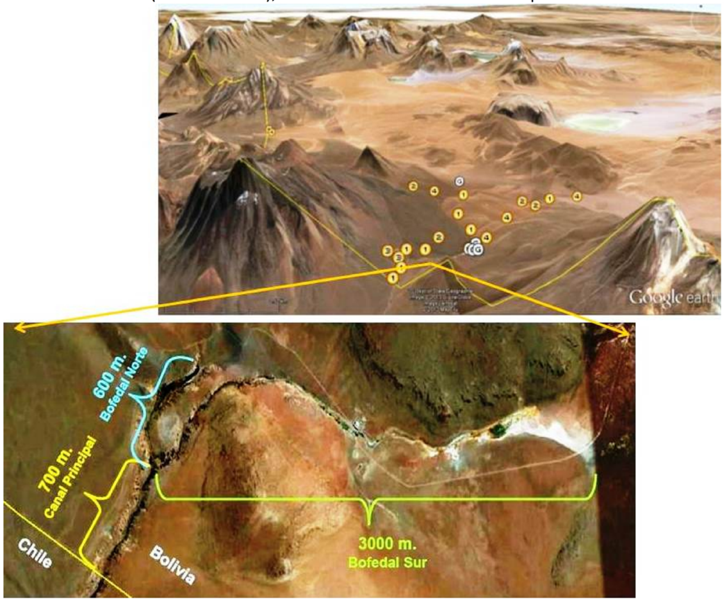
- Rainfall: 59 mm from December to March, with a maximum of 21.4 mm in January. Droughts are recorded between April and November.
- Temperature: the annual average is of 14.2 C; the annual average of the minimal temperatures is of -15;
- Evaporation: it is higher between September and March (78 mm in September and 113 mm in December); evaporation is the lowest between April and August (the lowest evaporation rate, of 36 mm, is recorded in June); and
- Average evaporation: 914 mm.

Geomorphology

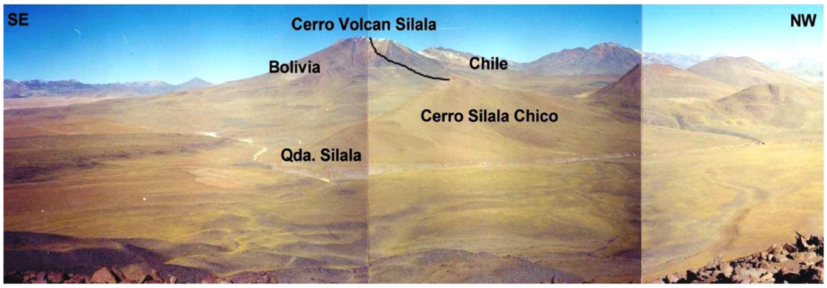
In the same way as for the climate, the geomorphological aspects of the region analyzed will be understood better in the general context of the morpho-structural unit termed the High Plateau (Altiplano); that is, starting from the regional scale and then moving on to the intermediary and local scales.

Within the Ramsar site, the Silala area is located between the 22nd parallel south and the 68th parallel west, at 4,300 m.a.s.l. This area forms a valley extending from east to dirección este a oeste (fotografía no 1). Por sus características, el área corresponde a una zona desértica de alta montaña, en donde la flora y la fauna son muy restringidas.

El área del Silala se caracteriza por tener una topografía plana-ondulada, ligeramente inclinada hacia el oeste rodeado de domos y estratovolcanes (fotografía 2). Las altitudes dentro del área varían desde los 4278 metros sobre el nivel del mar (msnm), en el límite fronterizo que cruza en la Quebrada Principal de Silala, hasta los 5701 msnm, cumbre del Volcán Silala (fotografía 2).
Tiene un clima típico de una zona desértica de alta montaña con variaciones extremas diurnas y nocturnas. La flora y la fauna es muy limitada y característica de la Cordillera Occidental y Altiplano Boliviano. Los bofedales de alta altura de Silala tienen una flora y fauna típica de los mismos. Es una región deshabitada con la población más cercana de Laguna Colorada (22 habitantes en 2001) ubicada a 38 Km al SE del Silala. Actualmente la población más cercana al Silala es Quetena con mas de 850 habitantes (SERNAP 2006), ubicada al Este a unos 60 Km aproximadamente.



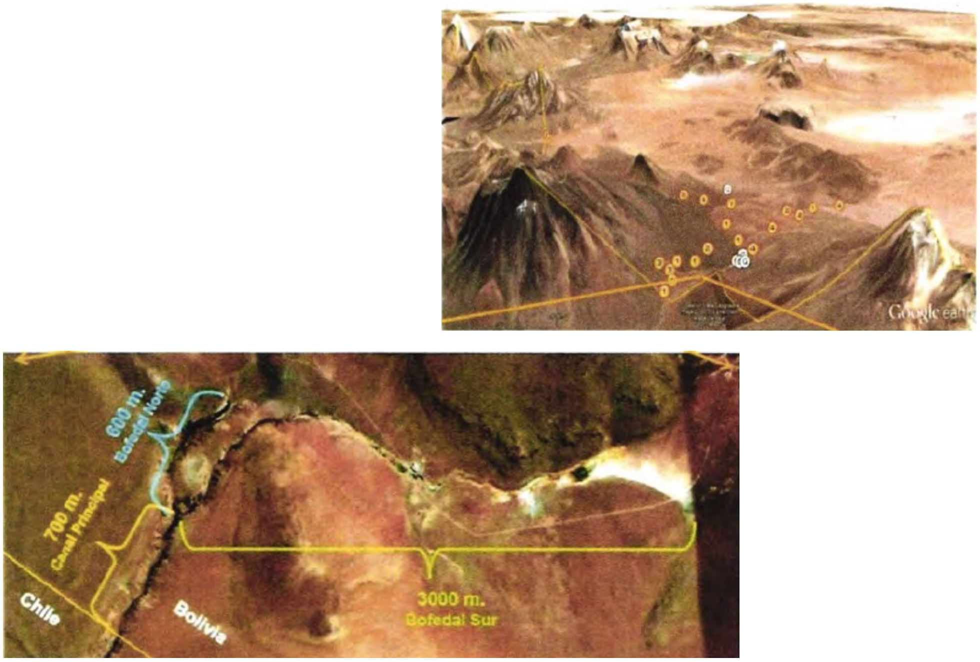
Fotografía no 1 Collage de fotos Google Earth y satelital.



Fotografía no 2 Vista panorámica del Silala, vista Sureste (Bolivia) noroeste (Chile) (fuente: Urquidi Barrau, 2003) west (picture n° 1). Due to its characteristics, the area corresponds to a high-mountain desert-like area, where flora and fauna are limited.

The Silala area is characterized by a flat-wavy topography, slightly inclined towards the west, and surrounded by domes and stratovolcanoes (picture n° 2). Altitudes vary within this area from 4,278 m.a.s.l., on the boundary line that crosses the *Quebrada Principal de Silala* [Main Silala Ravine] to 5,701 m.a.s.l. on the summit of Silala Volcano (picture nº 2).

It is characterized by a climate typical to high-mountain desert-like regions with extreme variations in the day and night. The flora and fauna are very limited and characteristic of the western Andes mountain ranges and Bolivian High Plateau. The Silala high-altitude wetlands feature a flora and fauna typical to wetlands of this kind. It is an uninhabited region, where the closest population is found in Laguna Colorada (22 inhabitants in 2001), 38 km to the southeast of Silala. Currently, the community that is closest to the Silala is Quetena, which comprises more than 850 inhabitants (SERNAP, 2006) and is located to the east, at 60 Km approximately.



Picture nº 1: Google earth and satellite pictures

Picture nº 2. Panoramic view of Silala, southeast sight (Bolivia), northeast (Chile) (Source: Urquidi Barrau, 2003)

Los aspectos geomorfológicos de la región se muestran en la figura 3.4. Esos efectos muestran los diferentes procesos y agentes geomorfológicos que han modelado el relieve del área desde hace 7.8 Mo. Todo el paquete estructural regional fue posteriormente levemente solevantado hace aproximadamente 1.7 a 1.9 Mo (Ministerio de Medio Ambiente y Agua, 2016) inclinándolo suavemente hacia el Oeste, paralelamente a lo intrusión de conos volcánicos y a la formación de estratos volcanes. Por las edades obtenidas estos rasgos geomorfológicos alterados pudieron haberse realizado hace I.4 Mo.

Durante las glaciaciones de hace 14,500 años BP, Ultimo Máximo Glaciar de la Cordillera Central de los Andes, los rasgos geomorfológicos fueron fuertemente alterados por el movimiento y deshielo de los glaciales que dieron lugar a la formación de lagos, lagunas y salares en lado del Altiplano Boliviano, así como a la formación de valles profundos, entre ellos el valle del Silala.

La actividad del deshielo de lo glaciación es otro de los rasgos geomorfológicos más notorios sobre la formación de la Quebrada de Silala. Rasgos que se formaron hace 10,000 años BP o más. A fines de éste episodio glaciar (tardi glaciar) se formaron las quebradas que son un ejemplo típico de la acción del agua de deshielo aprovechando zonas de debilidad en la roca aflorante, en este caso la falla Silala y las fallas transversales E-W de ajuste. Sin embargo, el diseño actual de la Quebrada Principal con un corte transversal geomorfológico en "U" con paredes laterales verticales (15 o 100 m de altura y 40 m de ancho) y un piso plano es la combinación de varios factores de meteorización y no solo a la acción fluvio-glacial. Es importante señalar que desde el Holoceno, la Quebrado de Silala no tiene ninguna proporción entre la profundidad y ancho del mismo con lo cantidad de agua que podía fluir en él, o sea que existe una desproporción geomorfológica notable.

Los rasgos geomorfológicos modelados durante el Holoceno hasta nuestros días son más por lo acción eólica y por diferencia térmica diaria y casi nulos por acción fluvial.

Respecto al área de Laguna Colorada y la Reserva Nacional de Fauna Andina Eduardo Avaroa, Según Navarro (2002) las principales unidades geológicas y morfológicas son las siguientes:

- Meseta ignimbritica riodacítica a riolítica (Formación Alota): constituye en la mayor parte del distrito la superficie topográfica fundamentalmente, siendo parcialmente homóloga a la formación Pérez del Altiplano Norte y a la formación Quemez del Altiplano Central. Con una altitud promedio entre 4.000-4.500 m. Se le atribuye una edad Mioceno-Plioceno.

- Estratovolcanes andesítico-dacíticos, de edad Plioceno-Pleistoceno, constituyen muchos de los volcanes que sobresalen del nivel de la meseta ignimbritica.

- Edificios volcánicos antiguos, domos y coladas de lava andesítico-dacíticos, junto a brechas volcánicas, tobas andesíticas, areniscas, conglomerados y margas. Edad Mioceno-Plioceno.

- Afloramientos sedimentarios poco extensos, situados generalmente en las laderas orientales del valle del Río Grande de Lípez. Constituidos por areniscas y lutitas rojo bermellón con yesos, de la formación Potoco (Oligoceno).

The geomorphological characteristics of the region are depicted in figure 3.4. These effects evidence the different geomorphological processes and agents that have modelled the relief of the area 7.8 million years ago. The structure of the region was then slightly altered approximately 1.7 to 1.9 million years (Ministry of Environment and Water, 2016), inclining to the west, simultaneously to the intrusion of volcanic cones and the formation of stratovolcanoes. Based on the ages recorded in the area, these altered geomorphological features are likely to have taken place 1.4 million years ago.

During the glaciation periods occurring 14,500 years before the present—the Last Glacial Maximum of the Andes Central Mountain Range—the geomorphological features were strongly altered by the movement and melting of glaciers, resulting in the formation of lakes, lagoons, salt flats, and deep valleys—as the Silala valley—all over the Bolivian high plateau.

Melting, or glaciation is another one of the most notorious geomorphological features in the formation of the Silala Ravine and were formed 10.000 years before the present. The ravines, on the other hand, were formed at the end of this glacial period (the late-glacial). These constitute a typical example of the action of meltwater on weaker zones where rocks outcrop, in this case the Silala fault and the E-W cross-section adjustment faults. However, the current design of the Main Ravine, presenting a geomorphological U-shaped cross-section with vertical lateral walls (15, or 100 m of height and 40 m of width) and a flat surface, is the result of the combination of several weathering factors and not only of fluvio-glacial action. It must be noted that since the Holocene, the depth and width of Silala Ravine does not correspond to the amount of water that might influence it, i.e. there is a notorious geomorphological disproportion.

The geomorphological features modeled from the Holocene to the present time are mainly the result of eolian action, the daily temperature differences, and rainfall.

According to Navarro (2002), the main geological and morphological units in the Red Lagoon and the Eduardo Avaroa Andean Fauna National Reserve are the following:

- Rhyolitic to rhyodacitic ignimbrite plateau (Alota formation): it constitutes most of the district of the topographical surface and is partially homologous to the Perez formation of the Northern High Plateau and the Quemez formation of the Central High Plateau, with an average height between 4,000 and 4,500 m. It is said to date back to the Miocene-Pliocene.
- Andesitic-dacitic stratovolcanoes, dating back to the Pliocene-Pleistocene; these constitute many of the volcanos that raise in the ignimbrite plateau.
- Ancient andesitic-dacitic volcanic structures, domes, and lava flows, together with volcanic breccia, andesitic tuffs, sandstones, conglomerates, and loams dating back to the Miocene-Pliocene.
- Sediment outcrops of relative extent, generally found in the eastern sides of the Rio Grande de Lipez valley. These are constituted of vermillion-red sandstones and lutite with gypsum, dating back to the Potoco formation (Oligocene).

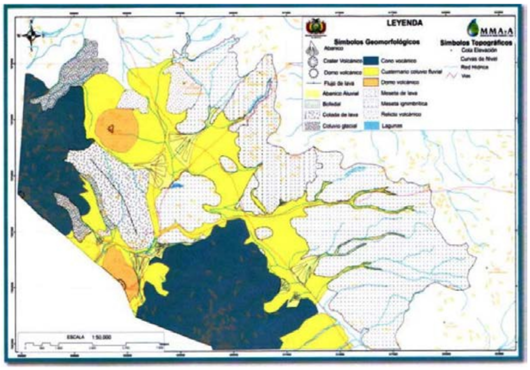


Figura 3.4 Aspectos geomorfológicos del área (Ministerio de Medio Ambiente y Agua , 2016)

3.3.2 Geología

Escala regional

El Altiplano presenta una estratigrafía distinta según los sectores (Mapa Geológico de Bolivia, 1978, YPFB-GEOBOL**)**, por ejemplo, el Altiplano Norte, está caracterizado por presentar diferentes tipos de rocas devónicas, constituidas por areniscas y lutitas. En los alrededores del lago Titicaca es fácil encontrar rocas del carbonífero, constituidas por una intercalación de areniscas y limos**.** También alrededor del Lago Titicaca se han identificado calizas fosilíferas de color gris claro, en alternancia con lutitas gris oscuras correspondientes al Pérmico.

El Terciario se encuentra ampliamente difundido en el Altiplano Norte, rocas sedimentarias de la Fm. Umala son características en el área del rio Desaguadero, areniscas, arcillas y conglomerados son los sedimentos más típicos. En el sector NO, las ignimbritas de composición riodacítica de la FM Pérez, se encuentran cubriendo superficies muy amplias.

El sistema Cuaternario también se encuentra ampliamente difundido en el Altiplano Norte, capas sub-horizontales de tobas, ignimbritas, coladas de lava, etc., son de amplia difusión. Sedimentos lacustres de la Fm. Ulloma con fósiles de vertebrados , han sido descritos por numerosos autores.

Además fuera de la litología anteriormente indicada, en este sector de la altiplanicie, se identifican sedimentos finos compuestos de calizas, margas, arenas finas, arcillas y limos, correspondientes a las hoyas lacustres conocidas como Ballivián, Minchin y Tauca.

Es de acotar que también se han identificado cuerpos de naturaleza magmática de edad mesozoica y cenozoica, que se encuentran flanqueando el Altiplano, flanco oriental, pero con gran influencia sobre este**,** son rocas que corresponden petrográficamente a granitos, granodioritas, monzonitas, fonolitas y otras.

En el Altiplano medio, en la zona de Sevaruyo y alrededores se han reconocido calizas cretácicas y cuerpos yesiferos masivos, que juntamente con las rocas paleozoicas aflorantes al Este del lago Poopó, tienen una gran influencia sobre la cuenca mencionada.

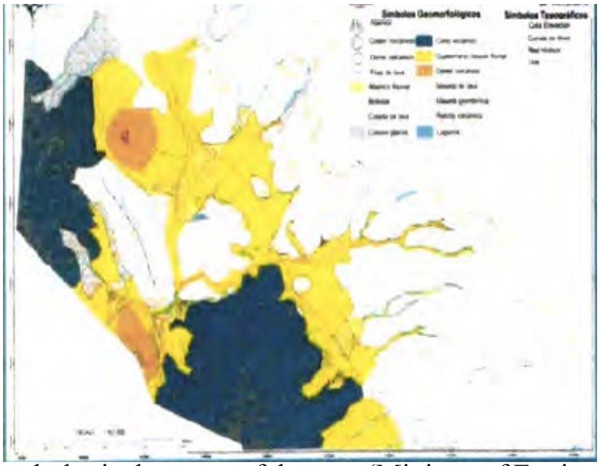


Figure 3.4. Geomorphological aspects of the area (Ministry of Environment and Water, 2016)

3.3.2. Geology

Regional scale

The High Plateau presents a stratigraphy that varies depending on its sectors (Geological map of Bolivia, 1978, YPFB-GEOBOL); for instance, the northern High Plateau is characterized by different types of Devonian rocks that are made up of sandstones and lutites. In the outskirts of Lake Titicaca, it is easy to find carboniferous rocks formed by an intercalation of sandstones and silts. Light gray fossiliferous limestones, alternating with dark gray lutites that correspond to the Permian period, have also been identified in this region.

The Tertiary period is widely spread in the northern High Plateau; sedimentary rocks of the Umala formation are characteristic in the area of the Desaguadero River. Sandstones, clays and conglomerates are the most typical sediments. In the northwestern area, ignimbrites of rhyodacitic composition of the Perez formation cover very lengthy surfaces.

The Quaternary system is also widely spread in the northern High Plateau; sub-horizontal layers of tuffs, ignimbrites, lava flows, etc., are widely distributed. Lake sediments of the Ulloma formation, with vertebrate fossils, have been described by numerous authors.

In addition to the above lithology, in this area of the plateau, fine sediments composed of limestones, loam, fine sands, clays, and silts corresponding to the lacustrine basins known as Ballivian, Minchin and Tauca are identified.

It is worth noting that bodies of magmatic nature of the Mesozoic and Cenozoic age have been identified flanking the High Plateau, to the east; however, a great influence on the latter is exerted by rocks that petrographically correspond to granite, granodiorite, monzonite, phonolite, and others.

In the mid-High Plateau, in the area of Sevaruyo and the surrounding ones, Cretaceous limestone and massive gypsum bodies have been identified; these, together with the Paleozoic rock outcrops east of Lake Poopo, have a great influence on the said basin.

Antes de empezar una descripción más completa del Altiplano Sur, nos referiremos forma muy general al sector SE del Altiplano. Esta región tiene una geología que contrasta efectivamente con el Oeste; mientras que este sector es eminentemente volcánico, el Este presenta afloramientos de rocas sedimentarias correspondientes al Paleozoico bajo y especialmente areniscas, conglomerados, arcillas, yeso con intercalaciones de tobas y lavas correspondientes al Terciario que cubren grandes áreas (Mapa Geológico de Bolivia, 1978).

El Cuaternario

La geología superficial de toda el área predominantemente es producto de una actividad volcánica del Mioceno al Reciente, las distintas geoformas observables hoy en día en el área están modelados desde hoce 7.8 Mo, iniciándose en el Mioceno Superior con la deposición de las tobas sobre rocas presumiblemente del basamento Paleozoico o rocas del Mioceno inferior.

Los procesos de meteorización, erosión y deposición están representados por sedimentos no consolidados Cuaternarios y Recientes que cubren superficies extensas del área. Los materiales depositados forman los depósitos glaciales, fluvio-glaciales, coluviales y aluviales consolidados por bloques o bolones poligénicos, clastos de diferentes rocas y tamaños, y sedimentos finos como arenas y limos.

Mesetas ignimbriticas, es una de los características más notables, se inició con la deposición de los tobas de las ignimbritas Silala, posiblemente, ha tenido lugar durante el Mioceno Superior sobre rocas presumiblemente del basamento Paleozoico o rocas del Mioceno inferior, construyendo mesetas típicas con paredes verticales y con sistemas de drenaje que no son perceptibles en la actualidad. Estas mesetas sufrieron bruscas alteraciones geomorfológicas, por el intenso diaclasamiento y el grado de soldadura de las ignimbritas, y por supuesto, por la acción meteorizante de los agentes de movimiento y deshielo de glaciares, cambios extremos de temperatura y viento. Esto dio lugar a la formación de farallones que regionalmente en algunos casos pasan de 100 metros de altura. También dieron lugar a la formación de paleosuelos de color rojizo. Flujos de lava, son las que cubrieron las mesetas ignimbríticas y a toda geoforma original creada por las ignimbritas y paleosuelos.

Las mesetas típicas con paredes verticales y con sistemas de drenaje que no son perceptibles en la actualidad. Estas mesetas sufrieron bruscas alteraciones de tipo físico, por el intenso diaclasamiento y el grado de soldadura de las ignimbritas, y por supuesto, por la acción meteorizante de los agentes de movimiento y deshielo de glaciares, cambios extremos de temperatura y viento. Esto dio lugar a lo formación de farallones que regionalmente en algunos casos pasan de 100 metros de altura. También dieron lugar a lo formación de paleosuelos de color rojizo. Estas mesetas fueron posteriormente cubiertas por fluidos de lavas que enmascaran algunos rasgos originales de las ignimbritas y paleosuelos.

Escalas intermediaria y local

El área de los Manantiales de Silala se halla localizada en el bloque sur de la Cordillera Occidental y forma parte de la Zona Volcánica Central de los Andes. La geología regional está dominada por los productos de una actividad volcánica del Mioceno al Reciente y el paisaje fue modelado por procesos resultantes de las glaciaciones Pleistocénicas-Holocénicas. El Mapa de la figura 3.5 muestra el mapeo geológico realizado en el área en una escala 1:50,000 y la Tabla No. 3.1 el detalle de la columna estratigráfica (SERGEOMIN, 2003). Los procesos de meteorización, erosión y deposición están representados por sedimentos no consolidados Cuaternarios y Recientes que cubren superficies extensas del área. Los materiales depositados forman los depósitos glaciales, Before turning to a more complete description of the South High Plateau, general reference must be made to the southeastern sector of the High Plateau. Said region presents a geology that is in sharp contract with the western region—while the latter is the most notoriously volcanic one, the East region presents sedimentary rock outcrops corresponding to the lower Paleozoic era and manly sandstones, conglomerates, clays, and gypsum interspersed with tuffs and lavas from the Tertiary, which cover vast areas (Geological map of Bolivia, 1978).

The Quaternary

The surface geology of the area is chiefly the result of volcanic activities dating from the Miocene era to the present. The different geoforms currently observable in area were modelled 7.8 million years ago, and began in the Upper Miocene with the deposition of tuffs on rock surfaces from the Paleozoic basement, or rocks from the lower Miocene.

Weathering, erosion, and deposition processes are represented by unconsolidated sediments from the Quaternary and the Recent eras, covering vast surfaces of the area. The materials deposited formed glacial, pluvial-glacial, colluvial, and alluvial deposits, consolidated by polygenic blocks or quarry stones, clasts of different rocks and different rock sizes, and fine sediments as sands and silt.

Ignimbrite plateaus are one of the most notorious characteristics. Their formation began with the deposition of tuffs from the Silala ignimbrite, which possibly occurred in the Upper Miocene on rocks of presumably Paleozoic basement, or rocks from the lower Miocene, forming average plateaus with vertical walls and drainage systems that are imperceptible at present. These plateaus endured sharp geomorphological alterations owing to intense fractures and welding of the ignimbrites, and extreme changes in the temperature and winds. These resulted in the formation of rock outcrops that regionally surpass the 100 meters of altitude, together with the formation of red paleosols. These plateaus were then covered by lava flows that have hidden some of the original features of the ignimbrites and paleosols.

The typical plateaus with vertical walls and with drainage systems that are not perceptible at present. These plateaus endured sharp geomorphological alterations owing to intense fractures and welding of the ignimbrites, and extreme changes in the temperature and winds. These resulted in the formation of rock outcrops that regionally surpass the 100 meters of altitude, together with the formation of red paleosols. These plateaus were then covered by lava flows that have hidden some of the original features of the ignimbrites and paleosols [sic].

Intermediary and local scales

The area of the Silala springs is found in the south block of the Western High Plateau and forms part of the Central Volcanic of the Andes. The regional geology is dominated by the products of volcanic activities that date back to the Miocene and Recent epochs. The landscape was modelled by the processes resulting from glaciations that date back to the Pleistocene-Holocene. The map presented in figure 3.5 depicts the geological mapping carried out in the area at a scale of 1: 50,000 and Table No. 3.1 shows the detail of the stratigraphic column for the area (SERGEOMIN, 2003). The weathering, erosion, and deposition processes are represented by unconsolidated sediments from the Quaternary and Recent epochs and cover vast regions of the area. The deposited materials form glacial, fluvio-glaciales, coluviales y aluviales constituidos por bloques o bolones poligénicos, clastos de diferentes rocas y tamaños, y sedimentos finos como arena y limo.

El tectonismo del área del Sitio Ramsar está influenciado por el solevantamiento y fallamiento del bloque regional de Lípez, conocida como la Cuña Occidental. La mayor manifestación de éste tectonismo en el área es el sistema de Fallamiento de Khenayani que cruza el área con un rumbo regional ENE, y por fallas de ajuste con el mismo rumbo y por fallas transversales de ajuste con rumbos EW y WNW. Estas últimas tienen una extensión limitada pero profunda, que facilitaron la efusión de los volcanes con la consiguiente deposición de rocas ígneas efusivas y debris piroclástico y la fracturación de las rocas ignimbríticas basales.

Por otra parte, el tectonismo, manifestado como fallamiento y diaclasamiento de las rocas efusivas del área, es de suma importancia en cuanto a la ubicación de los afloramientos de las descargas de agua en forma de manantiales del Silala.

Los bofedales se encuentran sobre rocas ignimbriticas recubiertas por depósitos superficiales no consolidados de tipo coluvial. En el margen derecho del bofedal Norte existen diferentes alumbramientos de agua que son canalizados, en este sector se observó afloramiento de roca con un nivel de piroclastos, que emergieron del volcán Inacaliri. Esta lava con algunos metros de espesor, relativamente reciente, reposa en parte sobre las lavas descritas antes, pero ante todo sobre el sustrato ignimbritico del Mioceno. Las ignimbritos tienen una coloración grisacea a rosado naranja (con alteración).

El bofedal sur, está controlado por el diaclasamiento y fallamiento en la roca ignimbrítica que fluye hacia sedimentos o suelos recientes hasta su intersección con aguas del bofedal Norte.

Actividad Volcánica

La actividad volcánica en el área es muy importante y se inicia en el Ciclo Andino del Mioceno Superior. Durante éste ciclo se edificaron varias calderas, centros y domos volcánicos, entre ellos el de Agua de Perdiz (ubicado fuera del área de estudio) que se manifiesta con la erupción y deposición de un manto ignimbrítico regionalmente extenso denominado Ignimbritas Silala. Estas ignimbritas están muy bien expuestas en el área y se encuentran parcialmente cubiertas por flujos de lavas de los estratovolcanes intruidos a través de las mismas (Fotografía No. 2). Esta es la primera fase efusiva en el área de estudio. Las estructuras volcánicas más evidentes, dentro y circundando el área, son los domos volcánicos del Cerro Silala Chico y Torito, y los estratovolcanes Inacaliri y Silala desarrollados por la acumulación de productos de fases extrusiva y efusivas. La primera fase extrusiva está representada por la formación de los domos volcánicos. La segunda fase efusiva está representada por coladas de lavas andesíticas y lavas de composición andesíticas-dacíticas.
A fines del Pleistoceno se inicia la edificación de otros centros volcánicos como el Volcán Cerro Negro, cuyo volcanismo efusivo desarrolló depósitos de lavas andesíticas, las cuales llegan a cubrir relieves preexistentes.

fluvial-glacial, colluvial, and alluvial deposits made up of polygenic blocks or quarry stones, clasts of different rocks and of different rock sizes, and fine sediments such as sand and silt.

Tectonism of the Ramsar Site area is influenced by geological uplifting and faulting of the regional block of Lipez, known as the Cuña Occidental. The major manifestation of this tectonism in the area is the Khenayani Fault system, which crosses the area with a regional ENE course, and is characterized by faults of adjustment that follow the same course and cross-section faults of adjustment that follow EW and WNW directions. The latter have a limited, yet deep, extent, which facilitated the effusion of volcanoes and the consequent deposition of effusive igneous rocks and pyroclastic debris, as well as the fracturing of basal ignimbrite rocks.

Tectonism, on the other hand, manifested by the faulting and jointing of effusive rocks found in the area, is of utmost importance for the outflows of water discharges that form the Silala springs.

The wetlands are found on ignimbrite rocks covered by unconsolidated surface deposits of a colluvial type. In the right edge of the north wetland, there are different water sources that are channeled; in this sector, rock outcrops with a level of pyroclasts that emerged from Inacaliri volcano have been observed. This lava, which is a few meters thick and relatively recent, rests partly on the lava described above, but above all on Miocene ignimbrite substrate. These ignimbrites have a grayish to pinkish orange coloration (with alterations).

The south wetland is controlled by the joints and faults of ignimbrite rocks that flow towards the recent sediments, or soils, until their intersection with the waters of the north wetland.

Volcanic activity

Volcanic activity in the area is very important and begins in the Andean Cycle of the Upper Miocene. During this cycle, several craters, centers, and volcanic domes were formed, including the Agua de Perdiz (located outside the study area), which is manifested by the eruption and deposition of a regionally extensive ignimbrite mantle known as Silala ignimbrites. These ignimbrites are highly exposed in the area and are partially covered by lava flows that come from the stratovolcanoes interloped among them (Picture Nº 2). This is the first effusive phase in the study area. The most evident volcanic structures, found within and surrounding the area, are the volcanic domes of the Silala, Chico, and Torito hills, together with the Inacaliri and Silala stratovolcanoes formed by the accumulation of extrusive and effusive phase products. The first extrusive phase is represented by the formation of volcanic domes. The second effusive phase is represented by andesitic lava flows and andesitic-dacite composition lava. At the end of the Pleistocene, the formation of other volcanic centers such as Cerro Negro Volcano began, the effusive eruption of which formed deposits of andesitic lava, which have come to cover preexisting reliefs.

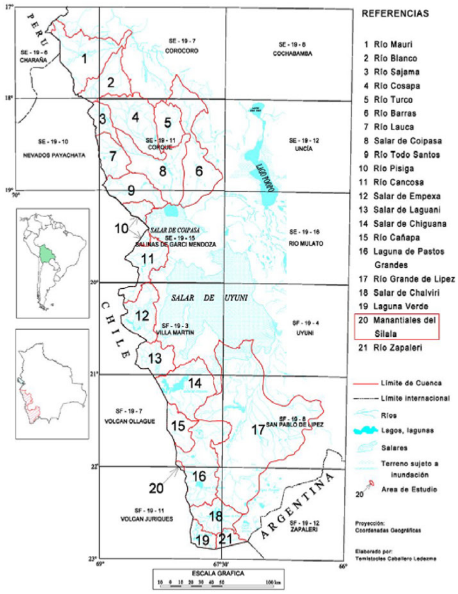


Figura 3.5 Mapa hidrológico SERGEOMIN, 2003

ERA	EDAD	PERIODO	LITOLOGIA	DESCRIPCION DE PROCESOS GEOMORFICOS	AÑOS
CENOZOICO	CUATERNARIO	HOLOCENO		ESTABILIDAD DE RELIEVE CLIMA SECO	
			DEPOSITOS ALUVIALES DEPOSITOS COLUVIALES DEPOSITOS FLUVIOGLACIALES	RELIEVES TIPICOS DE SEDIMENTOS CUATERNARIOS BOFEDALES AFLORAMIENTOS DE MANANTIALES	10.000 años BP
		PLEISTOCENO	DEPOSITOS ALUVIALES	FORMACION DE VALLES Y QUEBRADAS	
			DEPOSITOS COLUVIALES	RELIEVES ALUVIALES	14.000 años BP
			DEPOSITOS FLUVIO - GLACIALES	RELIEVES MORRENICOS	
				GLACIACION	65.000 años BP
			LAVAS ANDESITICAS BASICAS	FORMACION DE ESTRATOVOLCANES LEVES MODIFICACIONES DE PALEORELIEVES	< 1.0 Ma.
			Superficie de erosión		1.6 Ma
	NEOGENO	PLIOCENO	LAVAS ANDESITICAS A DACITICAS	FORMACIONES DE ESTRATOVOLCANES INACALIRI Y SILALA MODIFICACION DE PALEORELIEVE	1.9 Ma
				ESTABILIDAD TECTONICA FORMACION DE PALEOSUELOS DISECTACION Y FORMACION DE VALLES PROCESOS DE EROSION	
			Superficie de erosión		5.3 Ma
		MIOCENO	LAVAS ANDESITICAS - DACITICAS (5.94 Ma)	VOLCAN INACALIRI (Fase I)	
			LAVAS ANDESITICAS (6.04 Ma)	DOMOS VOLCANICOS SILALA CHICO, VOLCAN NEGRO Y CERRO TORITO	
			IGNIMBRITAS SILALA (sumamente fracturadas) (7.8 Ma)		

Tabla 3.1 Columna estratigráfica del área de los manantiales del Silala

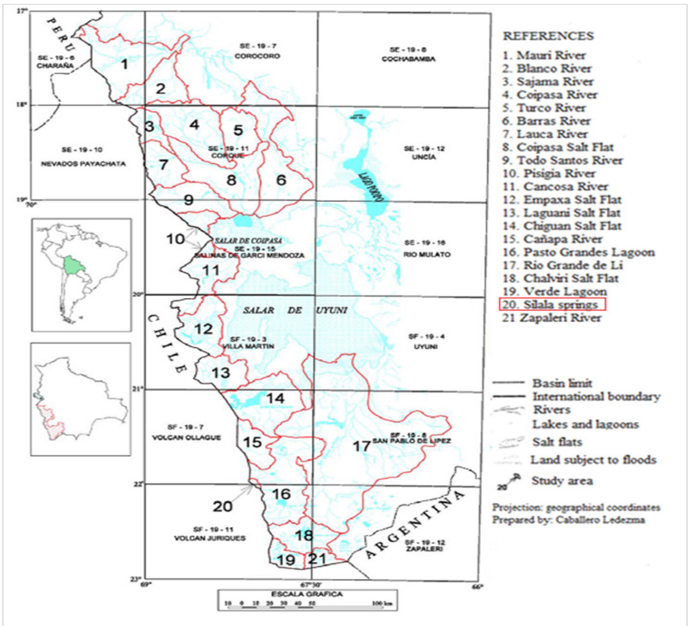


Figure 3.5 Geologic and hydrologic map, SERGEOMIN, 2003

ERA	AGE	PERIOD	LITHOLOGY	DESCRIPTION OF GEOMORPHIC PROCESSES	YEARS
CENOZOIC	QUATERNARY	HOLOCENE		STABILITY OF THE RELIEF DRY CLIMATE	
			ALLUVIAL DEPOSITS COLLUVIAL DEPOSITS FLUVIOAL-GLACIAL DEPOSITS	RELIEFS CHARACTERISTIC OF QUATERNARY SEDIMENTS WETLANDS EMERGENCE OF WETLANDS	10,000 years BP
		PLEISTOCENE	ALLUVIAL DEPOSITS COLLUVIAL DEPOSITS FLUVIOAL-GLACIAL DEPOSITS	FORMATION OF VALLEYS AND RAVINES ALLUVIAL RELIEFS MORAINIC RELIEFS GLACIATION	14,000 years BP 65,000 years BP
			BASIC ANDESITIC LAVA	FORMATION OF STRATOVOLCANOES SLIGHT MODIFICATIONS OF PALEORELIEFS	<10 Myr.
			Erosion surface		1,6 Myr.
	NEOGENE	PLIOCENE	ANDESITIC TO DACITIC LAVAS	FORMATION OF THE *INACALIRI* AND SILALA STRATOVOLCANOES	1,9 Myr.
				TECTONIC STABILITY FORMATION OF PALEOSOLS SEGMENTATION AND FORMATION OF VALLEYS EROSION PROCESSES	
			Erosion surface		5,3 Myr.
		MIOCENE	ANDESITIC-DACITIC LAVA (5.94Myr.) ADESITIC LAVA (6.04 Myr) SILALA IGNIMBRITES (highly fractured) (7.8 Myr)	*INACALIRI* VOLCANO (phase I) *SILALA CHICO* VOLCANIC DOMES, *NEGRO* VOLCANO, AND *TORITO* HILL	

Table 3.1. Stratigraphic column of the area of the Silala springs

3.3.3 Hidrología superficial

La hidrología superficial del sitio Ramsar se caracteriza por la presencia de pocos ríos intermitentes, algunos riachuelos y lagunas con déficits hídricos a escalas locales, regionales y probablemente globales (el conjunto del sitio Ramsar).

Una de las características hidrológicas más importantes del sitio Ramsar es la presencia de una gran cantidad de lagunas saladas que forman pequeñas unidades endorreicas, donde las lagunas ocupan la parte más baja de sus respectivas cuencas. En su mayoría, los ríos son de carácter temporal y de muy escaso caudal, producto de la extrema aridez del clima de la región. Sin embargo, existen manantiales que permiten que algunos cursos de agua tengan un caudal permanente. Como es frecuente en regiones de origen volcánico, existen afloramientos termales. La pérdida de agua se da principalmente a la evaporación producto de la intensa radiación solar.

La calidad del agua de esas lagunas es altamente variables, con un pH que va desde 7,9 hasta 10.8, son aguas cloruro-sódicas (las más frecuentes), sulfatadas-sódicas y carbonatadas-sódicas. Las aguas son predominantemente alcalinas, salobres e hipersalinas, con Na y Cl como iones dominantes, y en algunos casos Ca y K. Destacan también los niveles altos de sustancias tóxicas como As y algunos metales como Fe y Pb, una alta conductividad y valores altos de sólidos totales. La laguna que generalmente presenta mayor concentración de Sodio, Cloruros, sólidos totales y a su vez una mayor conductividad y alto valor en sólidos totales disueltos es Laguna Colorada y entre aquellas que presentan menor concentración en los mismos parámetros está Totoral (Rocha 2006).

Estas lagunas, generalmente poco profundas, son alimentadas por ríos y manantiales de agua subterránea. La ubicación geográfica y altura de las 37 lagunas inventariadas en el sitio Ramsar se enlistan en la tabla 3.2 (ver Anexo 1).

Existen tres factores que controlan la existencia de una laguna salada o de un salar (Eugster y Hardie, 1978):

- una cuenca cerrada,
- infiltraciones reducidas,
- evaporación superior a las lluvias.

Las cuencas cerradas pueden tener varios orígenes, entre los cuales se pueden citar:

- La tectónica: Graben, rift. Es el caso de la cuenca altiplánica, tomada globalmente;
- La actividad volcánica. Los flujos de lavas pueden cerrar pequeñas cuencas entre los volcanes (caso de Lípez);
- La acción del viento: la deflación. Puede ser la causa de algunos salares pequeños del Sur-Lípez (Laguna Kollpa, número 14 en la tabla 3.1); y
- La acción de los glaciares.

En cuanto a la evaporación superior a las lluvias, es evidente que si esto no fuese así se tendría un factor de dilución permanente debido a las lluvias. El clima y la tectónica son los dos factores que controlan la intensidad de la evaporación en relación con las lluvias.

Las principales zonas climáticas en las que la evaporación es superior a las lluvias son las zonas subtropicales y las zonas polares. En cuanto al control tectónico, son los altos relieves que pueden proteger ciertos terrenos de las lluvias, y almacenar las aguas que caen en las cumbres para después redistribuidas en cuencas áridas con fuerte evaporación como se muestra esquemáticamente en la figura 3.6. Este es probablemente el caso general del Altiplano Boliviano.

3.3.3. Surface Hydrology

The surface hydrology of the Ramsar site is characterized by the presence of intermittent rivers, streams, and lagoons that present water deficits at the local, regional, and probably global (the whole of the Ramsar site) scales.

One of the most important hydrological characteristics of the Ramsar site is the presence of a great amount of saline lagoons that form small endorheic units, where the lagoons occupy the lowest sections of their respective basins. Most of the rivers are ephemeral in nature and have a low volume of water owing to the extreme aridity of the region's climate. However, there are springs that allow some watercourses to have a permanent flow. As is common in volcanic-origin regions, there are thermal water outcrops. Water is lost mainly to evaporation, which caused by the intense solar radiation.

The water quality of these lagoons is highly variable, with a pH that ranges from 7.9 to 10.8; these are chloride-sodium (the most frequent ones), sulphate-sodium, and carbonate-sodium waters. The waters are predominantly alkaline, brackish, and hypersaline, with Na and Cl as the dominant ions, and Ca and K in some cases. There are also high levels of toxic substances, as A, and some metals, as Fe and Pb, with a high conductivity and high values of total solids. The lagoon that generally presents the highest concentration of sodium, chloride, total solids and, in turn, a higher conductivity and higher level of total dissolved solids is Laguna Colorada and among those that present an inferior concentration of these values is that of Totoral (Rocha, 2006).

These lagoons, which are generally shallow, are fed by rivers and groundwater springs. The geographical location and altitude of the 37 lagoons reported in the Ramsar site are both listed in table 3.2 (see Annex 1).

There are three factors that control the existence of a saline lagoon, or a salt flat (Eugster and Hardie, 1978):

- A closed basin
- Reduced infiltrations
- Evaporation that exceeds rainfall

The closed basins possibly have several origins, among which the following can be mentioned:

- Tectonic origin: Graben, rift. This is the case of the Altiplano basin, taken as a whole;
- Volcanic activity. Lava flows are likely to close small basins among the volcanos (this is the case of Lipez);
- Wind action: deflation. This is likely to be the cause for some small salt flats in Sur Lipez (Kollpa lagoon, No. 14 in table 3.1); and
- The action of glaciers.

In regard to evaporation exceeding rainfall, it is evident that if this were not the case, there would be a permanent dilution factor resulting from rainfall. The climate and tectonics are the two factors that control the intensity of evaporation in relation to rainfall.

The main climatic zones where evaporation exceeds rainfall are subtropical and polar areas. As for the tectonic control, high reliefs can protect certain lands from the rains, and store the waters that fall in the peaks to then redistribute them in dry basins characterized by strong evaporation, as shown schematically in Figure 3.6. This is probably the general case of the Bolivian Altiplano.

Una vez reunidos esos factores las aguas se van a concentrar por evaporación hasta precipitar las sales según el orden de sus solubilidades crecientes.

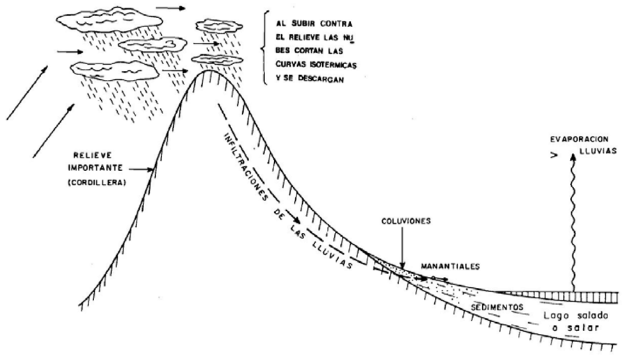


Figura 3.6 Representación esquemática del control morfo-climático en la formación de las lagunas saladas y salares.

El único rio permanente localizado en el sitio Ramsar es el rio Grande de Lípez. Este rio nace en el sitio Ramsar Lípez Sur y escurre esencialmente hacia el norte formando una cuenca importante mostrada en la figura 3.5 con la cuenca número 17. Este rio tiene una importancia mayor en la región pues representa el mayor aporte de aguas dulces al salar de Uyuni. Es un río permanente que desemboca en el Sureste del salar, infiltrándose en los sedimentos deltaico-lacustres de ese borde.

Finalmente, se puede afirmar que el origen de las aguas tanto superficiales como subterráneas (ver también sección 3.3.4) que entran en las cuencas pueden ser:

- Las lluvias por precipitación directa en las lagunas y/o salares;
- Por torrentes y ríos intermitentes. Una parte de las aguas de lluvia escurren en superficie hasta la laguna o el salar; y
- Por manantiales y ríos permanentes. Una parte de las aguas de lluvias al infiltrarse alimenta capas de aguas subterránea, que se descargan continuamente alimentando así directamente al salar por los manantiales o alimentando ríos cuando los manantiales están lejos de las orillas.

3.3.4 Hidrología subterránea

No existen datos sobre la disponibilidad de aguas subterráneas a la escala regional, pero las características geológicas y morfológicas de la región hacen suponer que son recursos de gran importancia.

A escalas intermediarias y locales, aunque no hay un acuífero dominante por su tamaño y/o volumen de almacenamiento, la región alberga un gran número de pequeños acuíferos los cuales en muchos casos representan las únicas fuentes de agua a las lagunas, salares, o ríos intermitentes, además del uso doméstico que se puede hacer de ellos.

Once these factors have been collected, the waters concentrate because of evaporation and then precipitate over the salts, according to the order of their increasing solubility.

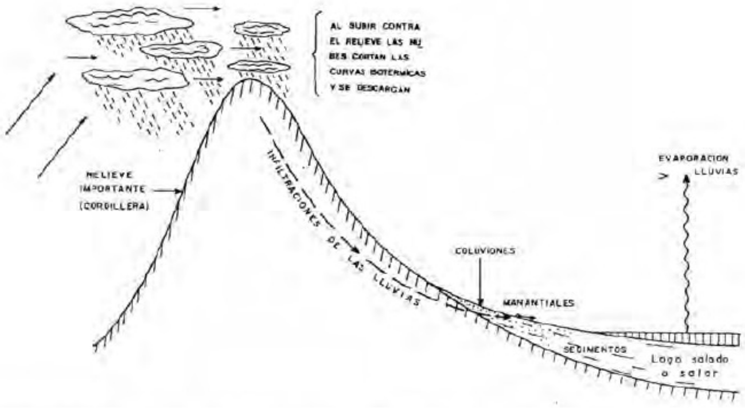


Figure 3.6. Schematic representation of morpho-climatic control in the formation of saline lagoons and salt flats.

The only permanent river found in the Ramsar Site is the Grande de Lipez River, which originates in the Sur Lipez Ramsar site and flows towards the north forming a very important basin—as shown in figure 3.5, basin Nº 17. This river has a higher importance in the region inasmuch as it provides the most freshwater to Uyuni salt flat. This is a permanent river that discharges in the southeast of the salt flat, infiltrating into the deltaic-lacustrine sediments of that edge.

Finally, it is possible to affirm that the surface waters and groundwater (see also, section 3.3.4) that enter the basins possibly constitute:

- Rainwaters, resulting from direct precipitation on the lagoons and/or salt flats;

- Waters originating from torrents and intermittent rivers. A part of the rainwaters flow on the surface until they reach the lagoon or salt flat; and

- Waters originating from springs and permanent rivers. When they infiltrate, a part of the rainwaters feeds groundwater layers, which are continuously discharged and feed directly the salt flat due to the springs formed, or feed rivers when the springs are far from the riverbanks.

3.3.4. Groundwater hydrology

There is no data on the availability of groundwater at the regional scale, but the geological and morphological characteristics of the region suggest that these are resources of high importance.

At the intermediate and local scales, albeit there are no dominating aquifers, be for their size or/and their storage volume, the region comprises a great number of small aquifers, which are, in many cases, the only sources of water for lagoons, salt flats, or intermittent rivers, as well as for domestic use.

Los acuíferos, o pequeñas napas subterráneas que existen en la zona del sitio Ramsar pueden ser muy antiguos, y haberse establecido en una época en que los niveles de los lagos eran más altos. Aunque cabe hacer notar que también son las lluvias que las alimentaron, o que en muchos casos continúan alimentándolos. Esos acuíferos se manifiestan en ocasiones por manantiales que, por diferencia de presiones, hacen surgir las aguas subterráneas de las napas más someras.

En la zona existen dos tipos principales de manantiales:

- los manantiales francos, cuyas aguas escurren visiblemente. O sea sus salidas están bien determinadas (ese es el caso de los manantiales del Silala);
- Los manantiales difusos, es decir, el agua sale muy lentamente a todo lo largo de una orilla produciendo una zona pantanosa con vegetación (lo cual se manifiesta por la presencia de bofedales). En este segundo caso, no se nota el escurrimiento del agua subterránea. Esas aguas son generalmente más concentradas que las aguas de los manantiales francos, parque ya se han evaporado antes de salir a la superficie.

Con respecto al área del Silala, y en particular en la zona desértica de alta montaña nacen manantiales con un caudal estimado de alrededor de 200 l/s. El acuífero que origina esos manantiales está formado por ignimbritas bien fracturadas de edad miocénaica (16 a 12 Ma) que tienen una gran distribución al este de los manantiales. La figura 3.7 es un croquis esquemático propuesto por SERGEOTECMIN en 2004 para explicar este proceso en el sitio de las quebradas del Silala. La cuenca de captación superficial alcanza solamente 32 km^2, mientas la extensión de la cuenca subterránea, de acuerdo a la situación geológica y morfológica, se estima en 200 km^2. Sin embargo, esta área no es suficiente para explicar el caudal de las vertientes en una zona con una precipitación de apenas 60 mm/a. Estos aspectos y la ausencia de tritio en las aguas llevan a la conclusión, que las aguas son más antiguas y han sido recargadas probablemente en un tiempo pluvial más antiguo (Neumann-Redlin y Torres, 2003).

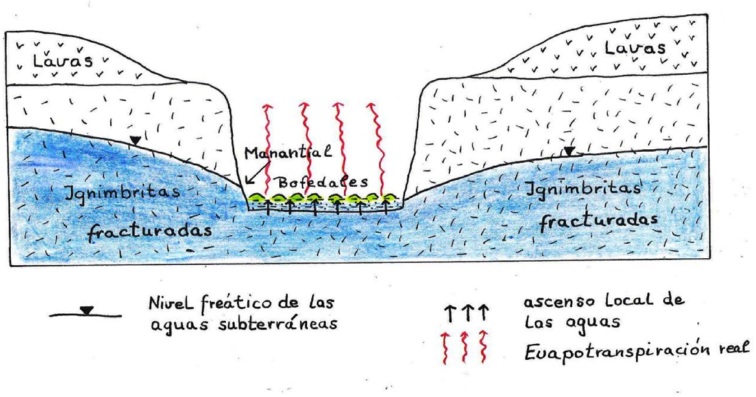


Figura 3.7 Situación hidrogeológica en el área del Silala. Según investigaciones en los Manantiales del Silala, SERGEOTECMIN (Diciembre 2004).

3.3.5 Suelos

The aquifers, or groundwater sources that exist in the area of the Ramsar site are possibly very old and are likely to have been established at a time when the lake levels were higher. Although it should be noted that it was also the rains that fed them, or in many cases continue to feed them. These aquifers sometimes manifest with the formation of springs that, depending on pressure differences, cause the groundwater of the shallower lagoons to emerge.

There are two kinds of springs in the area:

- Open springs, the waters of which flow visibly; i.e. their outflows are well determined (this is the case of Silala springs);

- Widespread springs, in which the water flows slowly covering a bank and producing a swampland with vegetation (which is manifested by the presence of highland wetlands). In this case, the flow of groundwater is not perceptible. These waters are generally more concentrated than the waters of open springs, because they evaporate before emerging to the surface.

In the Silala area, and particularly the high-mountain desert zone, the springs originate with an estimated flow of approximately 200 l/s. The aquifer that gives origin to these springs is formed by fractured ignimbrites of the Miocene (16 to 12 Myr), which are widespread to the east of the springs. Figure 3.7 presents a schematic sketch proposed by SERGEOTECMIN in 2004 to explain this process in the site of the Silala ravines. The surface intake basin has an extent of only 32 km^2, while the extent of the groundwater basin, based on its geological and morphological situation, is estimated at 200 km^2. However, this area is not sufficient to explain the flow rate of the springs, in a region characterized with a precipitation of barely 60 mm/a. These aspects and the absence of tritium in the waters lead to the conclusion that the waters are older and had probably been recharged in a more ancient pluvial period (Neumann-Redlin and Torres, 2003).

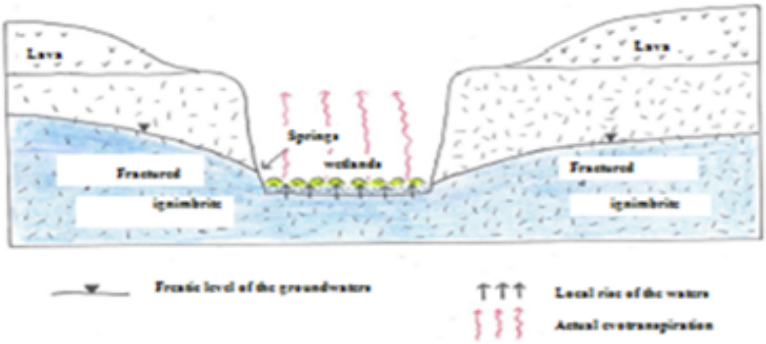


Figure 3.7. Hydrological situation of the Silala area. Based on research made on the Silala springs, SERGEOTECMIN (December, 2004)

3.3.5. Soils

23

Los suelos son de baja fertilidad y con un alto contenido de piedras, gravas y afloramientos rocosos, no aptos para la agricultura, exceptuando los suelos de la cuenca del río Quetena (Ergueta, 2002).

Los suelos presentan las siguientes características:

- Conos volcánicos, domos o volcanes en escudo y sobre flujos de lava andesítica y dacítica asociada con rocas piroclásticas.
- Mesetas de lavas ignimbríticas riodacíticas, disectadas por canales sub-paralelos con superficie irregular y pendientes variables.
- Materiales deposicionales de arena, arcilla y limo fluvio-lacustre del cuaternario en lugares planos o algo inclinados (pendientes de hasta de un 3%).

3.4 Uso del suelo

En el Sitio Ramsar Los Lípez, el uso del suelo está prácticamente ausente de la agricultura o el pecuario; las actividades agrícolas son mínimas o inexistentes. Muy cerca del sitio existe una importante producción de quinua. En el período 2014-2015 la producción de quinua llegó a 110,000 toneladas métricas. En los últimos 5 años, la superficie cultivada ha crecido y se estima actualmente en más de 170 mil hectáreas en el altiplano boliviano. La mayor parte de la producción del sector de la quinua se concentra alrededor del Salar de Uyuni al norte del sitio Ramsar, con aproximadamente 70,000 pequeños productores.

Otro aspecto relevante del uso del suelo es el hecho que durante milenios, la población de la región utiliza los bofedales para el pastoreo del ganado camélido teniendo el cuidado de no sobrecargar con unidades animales estas áreas de gran productividad pero muy frágiles en su equilibrio. Sin embargo el crecimiento de la población de camélidos y la creciente pérdida de áreas disponibles para el pastoreo –bofedales, hacen que estos lugares sean sobrecargados especialmente cuando se encuentran cerca de los poblados.

Actualmente, en algunos sectores como el bofedal del río Quetena se realiza el pastoreo extensivo de llamas (FIR, 2009).

En la zona no existe un sistema de tenencia de la tierra para usos agrícolas en lo que se refiere a las pocas familias que viven en el área. La actividad se reduce a la ganadería de camélidos y permite un uso de la tierra que es considerado, de modo genérico, como un bien comunitario, al cual es libre de acceso toda la población de la región.

En la región del SO de Potosí en los últimos años, se han desarrollados proyectos de ecoturismo en los que se ha involucrado activamente a las comunidades originarias y se ha desarrollado una interesante oferta de servicios turísticos, muchos de ellos asociados a las lagunas más atractivas de la región. (FIR, 2009).

Dentro y en los alrededores de la Reserva Eduardo Avaroa existen operaciones mineras principalmente de bórax, ulexita, azufre y carbonato de sodio (Tropico– Swedeforest 1998, Ergueta 2002).

4. **Estado actual del sitio (factores de deterioro naturales/antropogénicos pasados presentes)**

En el Sitio Ramsar de acuerdo a la FIR, 2009 se indican a continuación los principales factores de afectación:

The soils are of low fertility and present a high content of stones, gravel, and rock outcrops. These soils are not suitable for agriculture, with the exception those of the Quetena River basin (Ergueta, 2002).

The soils present the following characteristics:

- Volcanic cones, shield volcanoes, domes formed on flows of andesitic and dacitic lava associated with pyroclastic rocks.
- Plateaus of rhyodacitic ignimbrite lava, dissected by sub-parallel canals with an irregular surface and varying slopes.
- Pluvial-lacustrine sand, clay, and silt depositions from the quaternary found in plains and slopes (of up to 3% of inclination).

3.4. Land use

The use of the land for agricultural or farming purposes in the Los Lipez Ramsar site is practically nil; agricultural activities are either minimal, or inexistent. Close to the site, however, there is an important quinine production—which reached the 110,000 metric tons for the 2014-2015 period. The cultivated surface has increased in the past five years—it is estimated that it covers more than 170 hectares of the Bolivian High Plateau. Most of the quinine production is concentrated around the Uyuni salt flat, north of the Ramsar site, covering approximately 70,000 small producers.

Another relevant aspect connected with the use of the land is the fact that the inhabitants of the region have used the wetlands for camelid livestock grazing for thousands of years, taking the precaution of not overburdening these areas, which are highly productive but fragile also. This notwithstanding, the growing number of camelids and the recent loss of areas available for grazing—wetlands—have caused these zones to be overburdened, especially where these zones are found near populated areas.

Llama grazing, is currently carried out extensively at certain areas, as the wetland of Quetena River (RIS, 2009).

Land tenure systems for agricultural purposes for the few families that inhabit the area have not been implemented. Agricultural activities are limited to camelid raising, allowing for a use of the land that is regarded, in general, as a community asset, to which anyone can secure access.

In the past years, the southwestern part of Potosi has seen the implementation of ecotourism projects in which the indigenous communities have taken active part and an interesting tourist product offer has developed, much of which is connected with the most attractive lagoons of the region (RIS, 2009).

Within and in the surroundings of the Eduardo Avaroa Andean Fauna National Reserve, mining activities are carried out, particularly concerning borax, ulexite, sulfur, and sodium carbonate (Tropico–Swedeforest 1998, Ergueta 2002).

4. Current state of the site (past and present natural/anthropogenic factors of deterioration)

The following main affectation factors in the Ramsar site concerned here can be pointed out (based on the RIS, 2009):

Actividad minera. La actividad minera para la extracción de minerales no metálicos como ulexita, bórax, calizas marmóleras, sal y otros en algunas lagunas como Capina, Kollpa y Salar de Chalviri es considerable. Las cooperativas explotan los yacimientos de forma manual y rudimentaria a cielo abierto, luego el material extraído es secado al sol y transportado en camiones de mediano y alto tonelaje a puntos específicos para su exportación. El transporte de estos minerales no metálicos produce en la zona cercana a los caminos y a las lagunas contaminación atmosférica por la emisión de una importante cantidad de polvo producido. También es probable que se estén contaminando los cuerpos de agua, por derrame de aceites y combustibles.

Usos de aguas subterráneas. El uso de las aguas subterráneas en el Sitio Ramsar se da en la actividad minera y por los albergues para el turismo.

Proyecto geotérmico. En la FIR del 2009, se mencionaba la existencia de un proyecto de ley para impulsar el aprovechamiento de energía geotérmica en Sol de Mañana (dentro del sitio Ramsar), la cual se constituye en una de las estrategias del gobierno boliviano para el aprovechamiento de los recursos no renovables alternativos. La planta geotérmica de acuerdo a las prospecciones tiene un potencial de 280 MW y un periodo de vida de 40 años. A la fecha el Estado Plurinacional de Bolivia no ha previsto darle continuidad.

Se menciona igualmente que si bien esta alternativa pretende mejorar las características socioeconómicas de una de las regiones más pobres del país, los impactos ambientales también serán de gran escala, desde la modificación del paisaje - efecto sobre la actividad turística-, modificación de las lagunas –por utilización de agua de las cuencas y otras subterráneas de la región, efectos sobre la fauna silvestre –avifauna y otros vertebrados-, contaminación del aire y del agua de la región.

Durante la Misión se informó que El Ministerio de Hidrocarburos y Energía, junto a la Empresa Nacional de Electricidad (ENDE) hicieron posible el financiamiento del Proyecto Piloto Planta Geotérmica en la Laguna Colorada, con 5 (MW) de potencia.

Actividades turísticas. En los últimos años el turismo intensivo, más de 70.000 visitantes en el 2007, que llega a la RNFA Eduardo Avaroa y su área de influencia (www.bolivia-rea.com), originan ciertos impactos en la región y en particular en las lagunas, que son el principal hábitat para los flamencos. Por lo tanto, la presencia del turismo intensivo en algunas lagunas (Colorada, Hedionda Norte, Cañapa, Polques y Verde) puede ser un factor de alto riesgo para los humedales puesto que los turistas se aproximan demasiado a las orillas con el objeto de fotografiar a los flamencos, o realizan su “pic-nic” en lugares muy próximos a las orillas dejando basura o lavando los utensilios de cocina con detergentes en las lagunas.

La construcción de albergues o alojamientos para el turismo muy próximos a las lagunas como Colorada, Verde y Hedionda Norte, probablemente pueden estar contaminando los cuerpos de agua por carecer de sistemas adecuados de tratamiento de aguas servidas, asimismo estas infraestructuras no están acordes con el paisaje por no utilizar material local o estar mal ubicados.

Por otro lado, los servicios básicos para alojamiento demandan cada vez más agua en un área donde este elemento es muy escaso. El uso de vehículos “todo terreno” fuera de las rutas establecidas dejan huellas en el suelo arenoso modificando el paisaje y compactando el terreno. Por otro lado, el establecimiento de albergues improvisados como en el caso de Laguna Colorada, Huayllajara y Laguna Verde, que no tienen sistemas adecuados de evacuación de aguas servidas, las cuales pueden filtrarse contaminando las fuentes de agua o directamente los mismos cuerpos de agua, y finalmente el uso excesivo del agua de los manantiales, para servicios turísticos, que son los

Mining activities. Mining activities carried out to extract non-metallic minerals, such as ulexite, borax, limestones, salt, and others in some of the lagoons, as Capina, Kollpa, and Chalviri salt flat, are considerable. The cooperatives exploit the deposits manually and rudimentary in the open. The extracted materials are then dried in the sun and transported in trucks of medium and high tonnage to specific points for their exportation. The transport of these non-metallic minerals produces atmospheric pollution in the areas close to roads and lagoons due to the emission of a significant amount of dust. It is also probable that waterbodies are being contaminated by oil and fuel spills.

Uses of groundwater. The groundwater in the Ramsar Site is used in mining activities and to provide lodges for tourism.

Geothermal project. In the RIS of 2009, mention was made of a draft law to promote the utilization of geothermal energy in Sol de Mañana (found within the Ramsar site), which is one of the most strategic energy sources for the Government of Bolivia for the utilization of alternative, non-renewable resources. According to the projections for this initiative, the geothermal plant has a potential of 280 MW and a duration of 40 years. To date [however], the Plurinational State of Bolivia has not contemplated implementing this initiative.

Mention was also made of the fact that, whereas this alternative purports to improve the socioeconomic characteristics of one of the poorest regions of the country, the environmental impacts would also be of a great scale, ranging from modifications to the landscape (and their effect on tourist activities), to modifications of the lagoons (owing to the utilization of basins and groundwater of the region), effects on wildlife (avifauna and other vertebrae), and air and water contamination of the region.

During the mission, it was reported that the Ministry of Hydrocarbons and Energy, together with the National Electricity Company (ENDE) made possible the financing of the Pilot Project labelled Geothermal Plant in Laguna Colorada, with 5 (MW) of power.

Tourism activities. In recent years, intense tourism—more than 70,000 visitors in 2007—in the Eduardo Avaroa Andean Fauna National Reserve and its area of influence (www.bolivia-rea.com) has had certain impacts in the region and particularly in the lagoons, which are the main habitat for flamingoes. Therefore, the presence of intense tourism in some lagoons (Colorada, Hedionda Norte, Cañapa, Polques and Verde) is likely a high-risk factor for wetlands, as tourists approach the banks excessively to photograph flamingos, or perform picnics in places that are very close to the banks, and litter, or wash kitchen utensils with cleansing agents in the lagoons.

The construction of lodges, or hostels for tourism in areas that are too close to the lagoons, as Colorada, Hedionda Norte, Cañapa, Polques and Verde, are probably contaminating the bodies of water, inasmuch as these lack the proper systems to dispose of wastewater. Additionally, these infrastructures do not befit the landscape, insofar as they do not use local materials, or are wrongly located.

Furthermore, basic services for lodging increasingly demand more water in a region where this element is very scarce. The use of off-road vehicles outside of the established routes leaves tracks on the sandy soil, altering the landscape and downsizing the area. In addition, the establishment of improvised lodges—as it occurs in Colorada, Huayllajara, and Verde lagoons—, which lack adequate systems to dispose of wastewaters, and which might in turn leak out and contaminate water sources, or the bodies of water themselves, and the excessive use of water that upwells from the springs for touristic services might possibly be reducing the afluentes de los cuerpos de agua, pueden estar disminuyendo el caudal de recarga que necesitan, considerando que se trata de una zona semidesértica con muy poca precipitación.

Pastoreo de ganado camélido. En el área la actividad principal radica en el manejo de ganado camélido, particularmente de llamas. El pastoreo de llamas y ovinos se realiza mayormente al borde de las lagunas y en los bofedales, aunque en las lagunas no se pudo detectar un sobrepastoreo, pero si sobre los bofedales.

La vulnerabilidad de los humedales del altiplano es aún mayor si consideramos su variabilidad natural y la ocurrencia de ciclos secos-húmedos interanuales, el clima seco y las condiciones de alta evaporación contribuyen a grandes variaciones espaciales y temporales (Caziani et al. 2001).

Recolección de huevos de flamencos. Existe presión de las comunidades locales para hacer uso tradicional de los huevos de flamencos como se hacía antes de la implementación del área protegida. Se están analizando las posibilidades de hacer experiencias piloto de aprovechamiento de los huevos de flamencos para consumo local. No obstante hubo cosechas de huevos ilegales por parte de las comunidades locales, lo cual genera impacto sobre las colonias de reproducción en Laguna Colorada que no han sido cuantificables.

Cacería furtiva. Se presentan algunos hechos aislados sobre la cacería ilegal de vicuñas fuera de los límites del área protegida.

En la zona circundante del sitio Ramsar se producen las mismas actividades que generan efectos adversos a la salud de los humedales en la región, actividad minera poco controlada, actividades turísticas mal reguladas, impacto sobre el paisaje generándose caminos o huellas por todo lado producido por vehículos de empresas turísticas, actividades ganaderas poco eficientes.

Sin embargo, el uso de aguas subterráneas a una mayor escala es una de las principales amenazas para la conservación y permanencia del complejo de lagunas, puesto que en la región del suroeste de Potosí, actualmente se está emprendiendo la extracción a cielo abierto de yacimientos de plata, plomo y zinc a gran escala por la Empresa Minera San Cristóbal – la mayor inversión en este rubro en las últimas tres décadas-. Las actividades mineras de esta empresa están previstas para los siguientes doce años y demandarán 40 000 m3 agua/día durante la fase de operación, lo que equivale a 465 l/s de caudal continuo, aguas que sólo estarían disponibles de fuentes subterráneas (Molina 2007).

Registro de Montreux

Por la propuesta del Proyecto geotérmico el sitio ingreso al Registro de Montreux el 16 de Junio de 1993 y fue retirado del mismo el 7 de agosto de 1996.

Otros procesos de afectación.

Canalización de los bofedales del Silala. En 1908 la prefectura de Potosí otorga las aguas del Silala en concesión a la FCAB para el uso de locomotoras y aprueba el permiso de construcción de canales e infraestructura para surtir de agua a los ferrocarriles del FCAB.

A continuación se describen el estado de los componentes físicos y ecológicos del sitio Ramsar.

4.1 Componente físico

4.1.1 Geomorfología

recharge rate these bodies need, bearing in mind that this is a semi-desert region with very little rainfall.

Grazing camelid livestock. In the area, the main activity is the handling of camelid livestock, particularly llamas. Grazing of llamas and sheep occurs mostly at the edges of the lagoons and in the wetlands; although it was not possible to detect overgrazing in the lagoons, it was possible to identify it in the wetlands.

The vulnerability of the High Plateau wetlands is even higher if its natural variability and the existence of dry-humid interanual cycles are borne in mind. The dry climate and the high evaporation conditions contribute to high spatial and temporal variations (Caziani, et al, 2001).

Collection of flamingo eggs. There is pressure from local communities to make traditional use of flamingo eggs, as was done before the implementation of the protected area. The possibilities of pilot experiments on the use of flamingo eggs for local consumption are being analyzed. However, illegal egg harvests by local communities have been evidenced, resulting in an impact on the breeding colonies of Laguna Colorada that has not been quantified yet.

Poaching. Only isolated facts about illegal vicuña hunting outside the boundaries of the protected area are available.

In the area surrounding the Ramsar Site, the presence of the same activities that cause adverse effects on the wetland health of the region has been identified, i.e. poorly controlled mining activities, poorly regulated tourism activities with impacts on the landscape—the vehicles of tourist enterprises create roads or leave tracks on the soil—, and inefficient cattle-raising activities.

Nevertheless, the use of groundwater at a higher scale is one of the major threats to the preservation and permanence of the complex of lagoons, given that, in the southwest region of Potosi Department, extraction activities of silver, lead, and zinc are currently being undertaken at great scales in the open by San Cristobal mining enterprise—which is the greatest investment in this field in the last three decades. This enterprise's mining activities have been calculated for the coming twelve years and will demand 40,000 m3 of water per day in its operation phase, which is equivalent to a continuous flow rate of 465 l/s—these waters, however, would only be available from underground sources (Molina, 2007).

Montreux Record

Due to the Geothermal Project proposal, the site was registered into the Montreux Record on 16 June 1993 and it was then withdrawn from it on 7 August 1996.

Other processes of affectation

Canalization of the Silala Wetlands. On September 23, the Prefecture of Potosi Department awarded the waters of Silala in concession to the FCAB to power its locomotives and to this end also approved the permit for the construction of canals and infrastructure to channel the waters.

Below is a description of the state of the physical and ecological components of the Ramsar Site.

4.1 Physical component

4.1.1 Geomorphology

Geomorfológicamente, el área tiene variadas geoformas que corresponden a sectores donde existen depresiones (lagunas), planicies y zonas con imponentes elevaciones y temperaturas extremas; es ahí en donde se encuentra el mayor potencial hidrogeológico. Por todos estos aspectos, sumado a razones de tipo logístico y técnico como la distancias, vías de acceso deterioradas, dificultades en lo operatividad de los métodos de trabajo han impedido realizar estudios en detalle para cuantificar de manera precisa los cambios de deterioro naturales y/o antropogénicos pasados; hace cerca de dos décadas se inició la observación de cambios en el área por medio de la utilización de imágenes satelitales de LandSat.

4.1.2 Hidrología superficial

Una de las características básicas del sitio Ramsar Los Lipez son los déficits hídricos a escalas locales regionales y probablemente globales (el conjunto del sitio Ramsar). Los déficits hídricos son el resultado del deterioro natural desde el holoceno (miles de años) cuando el área era todavía más húmeda.

Aun con esas características desfavorables, la presencia de las lagunas es muy importante pues son ecosistemas clave para la presencia de flora y fauna en la región. Estas lagunas poco profundas son alimentadas por ríos y agua subterránea, por lo cual aun y cuando sean mínimas, las fuentes existentes de agua deben conservarse.

El drenaje superficial en la parte suroeste del sito Ramsar Los Lípez es de tipo radial en las cabeceras y en las partes bajas no se evidencian cursos de agua naturales definidos, a pesar de la amplia variación de altura. La red de drenaje principal se manifiesta a partir de manantiales, cuyas aguas han sido canalizadas generando un flujo artificial, con dirección oeste. Los aforos realizados por SERGEOTECMIN (2004) muestran flujos de entre 42 l/s y 129 l/s para un total de 164 l/s.

No obstante, estudios más recientes de geofísica e isotopía han demostrado que los flujos de drenaje del agua subterránea que surgen desde los manantiales en dirección oeste, ya se habían establecido desde tiempos geológicos dada la presencia de valles, vaguadas, talwegs, o *coulees*, los cuales se formaron por el derretimiento y drenaje glacial.

4.1.3 Hidrología subterránea

Desde inicio de los años 2000, SERGEOTECMIN realizó estudios de investigación de campo y de cálculo para establecer el origen y las características de flujo de las aguas en el Silala y continuar adquiriendo conocimientos sobre los acuíferos y las aguas subterráneas en la cordillera occidental.

Con esos estudios se concluyó que la ocurrencia del agua en el Silala se debe a la descarga natural de un acuífero constituido por ignimbritas fracturadas. La ocurrencia de las aguas es producto del flujo del agua a través de las fracturas de las ignimbritas por porosidad secundaria. Ese acuífero aflora en la zona y, por diferencias topográficas, crea manantiales que descargan en varias puntos de la zona y alimenta los bofedades localizados en la misma.

En diciembre de 2004 SERGEOTECMIN realizó estudios adicionales en el sitio del Silala con el objeto de cuantificar la descarga de los manantiales y establecer un balance hídrico de los bofedales.

El balance hídrico se elaboró como sigue:

- Superficie de los bofedales del Silala: 108,700 m^2
- Evapotranspiración real: 3,000 mm/a

Geomorphologically, the area has varied geoforms that correspond to sectors where there are depressions (lagoons), plains, and zones of imposing elevations and extreme temperatures; this is where the greatest hydrogeological potential is to be found. Owing to all these aspects, in addition to logistical and technical reasons, such as distances and deteriorated access routes, the difficulties in the operability of working methods have prevented the conduction of detailed studies to quantify precisely the natural deterioration and/or earlier anthropogenic changes; about two decades ago, the observation of natural deterioration changes began in the area through the use of LandSat satellite images.

4.1.2 Surface Hydrology

One of the basic characteristics of Los Lipez Ramsar site is the water deficits at local and probably global scales (at the whole Ramsar site). Water deficits are the result of natural deterioration from the Holocene (from thousands of years ago) when the area was still more humid.

Even with these unfavorable characteristics, the presence of lagoons is very important because they are key ecosystems for the presence of flora and fauna in the region. These shallow lagoons are fed by rivers and groundwater; as a result, even if they are minimal, existing water sources must be preserved.

The surface drainage in the southwestern part of Los Lipez Ramsar Site is radial in the headwaters and there is no evidence of defined natural watercourses in the lower parts, despite the wide altitude variations. The main drainage network manifests in the upwelling of springs, the waters of which have been channeled generating an artificial flow, in direction to the west. The measurements completed by SERGEOTECMIN (2004) show flow rates ranging between 42 l/s and 129 l/s for a total of 164 l/s.

However, more recent geophysical and isotopic studies have shown that the flows of drained groundwater from springs, which move in direction to the west, had already been established since geological times owing to the presence of valleys, troughs, thalwegs, or coulees, which were formed by melting and glacial drainage.

4.1.3 Groundwater hydrology

Since the beginning of the 2000s, SERGEOTECMIN has carried out field research and calculation studies to establish the origin and flow characteristics of the waters of the Silala and to continue acquiring knowledge on the aquifers and groundwater found in the western mountain range.

With these studies, the conclusion was reached that the occurrence of water in the Silala is the result of the natural discharge of an aquifer constituted by fractured ignimbrites. The occurrence of the water is the product of water that flows through the fractures of ignimbrites by secondary porosity. This aquifer upwells in the area and, due to topographical differences, creates springs that discharge at various points of the area and feed the wetlands located therein.

In December 2004, SERGEOTECMIN carried out additional studies in the Silala site in order to quantify the discharge of the springs and establish a water balance for the wetlands.

The water balance was elaborated as follows:

- Surface of the Silala wetlands: 108,700 m^2;
- Actual Evapotranspiration: 3,000 mm/a;

- Evapotranspiración real Silala : 326,100 m^3/a
- Oferta de aguas subterráneas Silala: 200 l/s = 6,307,200 m^3/a
- Oferta de agua menos evapotranspiración: 6,307,200 - 326,100 = 5,981,100 $m^3/a \approx 190$ l/s

Como resultado de ese análisis se concluyó que alrededor de 10 l/s, ó 5 % del agua subterránea que nace en Silala, evapotranspira, el resto de 190 l/s escurre superficialmente en dirección oeste.

Convertida en volumen, la evapotranspiración real en el Silala, es mucho menor con respecto a la oferta del agua descargada por el acuífero. Por eso existe un escurrimiento superficial en dirección al oeste.

A la escala local (bofedales y manantiales del Silala) esos datos de balance hídrico parecen ser los únicos que existen. No se sabe si el volumen total de los manantiales, de 200 l/s, ha cambiado con el tiempo, pero dadas las características hidrogeológicas del sitio, y como primera hipótesis conceptual, se puede concluir que se trata de manantiales, u ojos de agua de origen subterráneo con un volumen relativamente estable. La Mision fue informada que el Estado Plurinacional de Bolivia está realizando estudios a fin de contar con datos actuales.

Por otro lado, según estudios más o menos recientes (Neumann-Redlin y Torres, J., 2003) de las aguas de los manantiales del Silala realizados con isótopos estables ($\delta^{18}O$, $\delta^{2}H$, ^{3}H y ^{14}C), las aguas que afloran en esos manantiales son aguas fósiles de más de 10,000 años. Es decir son aguas que no se renuevan por recarga natural de aguas meteóricas en el acuífero local. Bajo las condiciones climáticas actuales, esto significa que esos recursos hídricos están almacenados en el acuífero ignimbritico bien fracturado desde hace miles de años, el cual se vacía natural y paulatinamente a través de los siglos.

4.1.4 Suelos

Los factores de deterioro más adversos que afecten a las características del sitio son los cambios en el uso del suelo (incluyendo el aprovechamiento del agua) y de proyectos de desarrollo, son principalmente las concesiones para la minería.

La actividad minera para la extracción de minerales no metálicos como ulexita, bórax, calizas marmóleras, sal y otros en algunas lagunas como Capina, Kollpa y Salar de Chalviri es considerable.

Estas actividades de extracción son realizadas por una empresa privada y por varias pequeñas cooperativas constituidas por los pobladores de la región. Estas cooperativas explotan los yacimientos de forma manual y rudimentaria a cielo abierto, luego el material extraído es secado al sol y transportado en camiones de mediano y alto tonelaje a puntos específicos para su exportación. Además de impactos directos sobre las lagunas –por presencia humana y cambios en las orillas y espejo de agua; el transporte de estos minerales no metálicos produce en la zona cercana a los caminos y a las lagunas contaminación atmosférica por la emisión de una importante cantidad de polvo producido. La extracción de material es de forma artesanal por las cooperativas y con maquinaria pesada por parte de la empresa privada, por lo cual existe la probabilidad que se contaminen los cuerpos de agua, principalmente en el segundo caso por derrame de aceites y combustibles. Este aspecto no ha sido estudiado en detalle (FIR, 2009).

4.2 Componente ecosistémico

4.2.1 Flora y vegetación

- Actual Evapotranspiration Silala: 326,100 m^3/a;
- Supply of Silala groundwater: 200 l/s = 6,307,200 m^3/a;
- Water supply excepting evapotranspiration: 6,307,200 - 326,100 = 5,981,100 m^3/a = 190 l/s

As a result of this analysis, it was estimated that about 10 l/s, or 5% of the groundwater that originates in Silala evapotranspires, while the remainder, amounting to 190 l/s flows superficially to the west.

Converted to volume, the actual evapotranspiration in the Silala is much smaller with respect to the supply of water discharged by the aquifer. That is why there is a surface runoff in direction to the west.

At the local scale (Silala springs and wetlands), these water balance data seem to be the only ones available. It is not known if the total volume of the springs, amounting to 200 l/s, has changed over time, but due to the hydrogeological characteristics of the site, and as the first conceptual hypothesis, it can be concluded that these springs or water outflows originate from groundwater and have a relatively stable volume. The Ramsar Mission has been informed that the Plurinational State of Bolivia is carrying out surveys in order to obtain updated data.

On the other hand, according to relatively recent studies (Neumann-Redlin and Torres, J., 2003) of the waters of the Silala springs, which were carried out with stable isotopes ($\delta^{18}O$, $\delta^{2}H$, ^{3}H and ^{14}C), the waters that surface in those springs are fossil waters dating back to more than 10,000 years. In other words, these are waters that are not renewed by natural recharges of meteoric waters in the local aquifer. Under the current climatic conditions, this means that these water resources are stored in the well-fractured ignimbrite aquifer for thousands of years, emptying naturally and gradually over the centuries.

4.1.4 Soils

The most adverse deterioration factors that affect the characteristics of the site are changes in the use of the soil (including the utilization of water) and development projects, mainly mining concessions.

Mining activities to extract non-metallic minerals, as ulexite, borax, limestones, salts, and others in Capina and Kollpa lagoons, and in the Chaviri salt flat is significant.

These extraction activities are carried out by a private company and by several small cooperatives set up by the inhabitants of the region. These cooperatives exploit the reservoirs manually and rudimentarily in the open. The extracted materials are then dried in the sun and transported in trucks of medium and high tonnage to specific points for their exportation. In addition to direct impacts on the lagoons—caused by human presence and changes in the banks and water mirrors—the transport of these non-metallic minerals produces atmospheric pollution in the area that is close to the roads and lagoons due to the emission of a significant amount of dust produced. The extraction of material is handmade by cooperatives and with heavy machinery by the private company, which is why it is likely that the water bodies will be contaminated, mainly by the latter company due to spillage of oils and fuels. This aspect has not been studied in detail, though (RIS of 2009).

4.2 Ecosystem component

4.2.1 Flora and vegetation

Varias especies vegetales están sometidas a explotación a gran escala por su carácter combustible como la yareta, las tholas, la tara y otras más. La mayor presión proviene de las minas de ulexita, campamentos mineros y caleras. En el caso de la yareta (*Azorella compacta)*, se produce una explotación en gran escala, extracción histórica de cojines completos, disminuyendo grandemente las posibilidades de producción de semillas. Es la especie considerada más vulnerable en la zona sobre todo por su uso en minería (FIR, 2009).

4.2.2 Fauna

De las especies presentes en el Sitio Ramsar, los flamencos son especies altamente especializadas cuya capacidad para adaptarse a condiciones cambiantes es limitada y cuya vulnerabilidad a interferencias por humanos es especialmente alta, particularmente debido a que los ambientes salinos que habitan son explotados para la extracción de sal, sulfatos y boratos (del Hoyo 1992).

5. Evaluación del cambio en las características ecológicas

De acuerdo a la información suministrada por el gobierno de Bolivia, como parte de solicitud de la Misión se indicó que en el Sitio Ramsar Los Lipez (bofedal Silala y areas conexas), se están presentando cambios en sus características ecológicas debido a la canalización artificial de sus manantiales. En este sentido se mencionó que las aguas no renovables del Silala se han visto disminuidas, que los suelos se han dañado y que el sistema de aguas y de vida interconectado a dicho bofedal se han visto negativamente afectados.

En el marco de la Convención, el carácter ecológico de un sitio Ramsar es la combinación de los componentes, procesos y beneficios/servicios que caracterizan al humedal en un punto dado del tiempo.

En el contexto de implementación del Artículo 3.2 cambio en el carácter ecológico, son las alteraciones humanas adversas de cualquier componente, proceso y o beneficio/servicio del ecosistema.

De acuerdo a lo anterior a continuación se realiza una evaluación del estado del carácter ecológico del Sitio Ramsar Los Lipez como un todo en base a la información suministrada y la visita de campo al sitio.

5.1 Aspectos físicos

5.1.1 Hidrología superficial

Se describen brevemente algunos cambios considerados como importantes, producidos en las características hidrológicas superficiales y subterráneas a las escalas regional, intermediaria y local del sito Ramsar Los Lípez.

A la escala del sitio Ramsar Los Lípez, con un área total de 14,277 km^2, no se observan cambios hidrológicos notables desde la denominación del toda el área como sito Ramsar.

A la escala intermediaria y local, se observa un desarrollo intensivo del turismo en el Sitio, con el establecimiento de infraestructura para alojamientos en lugares poco adecuados y próximos a los cuerpos de agua (lagunas, bofedales), lo que origina cierta contaminación por no contar con sistemas adecuados de evacuación de aguas servidas. Asimismo, se está utilizando cada vez más agua de los afluentes que llegan a Laguna Colorada. Otros albergues se han establecido cerca de los

Several plant species are subject to large-scale exploitation because they can be used as fuels; this is the case of the yareta, the tholas, the tara and others. These are predominantly exploited in ulexite mines, mining camps, and lime fields. The yareta (*Azorella compacta*) is exploited at a large scale; whole yareta cushions have been historically extracted, greatly diminishing the possibilities of seed production. This species is considered the most vulnerable in the area, mainly because of its use in mining (RIS of 2009).

4.2.2 Fauna

From among the species present in this Ramsar Site, flamingoes are a highly specialized genus. Their capacity to adapt to changing conditions is limited and their vulnerability to human interferences is remarkably high, particularly due to the exploitation of salt, sulphate, and borates in the saline environments they inhabit (del Hoyo, 1992).

5. Assessment of changes in ecological characteristics

According to the information provided by the Bolivian Government, as part of the Mission's request, it was indicated that the Los Lipez Ramsar Site (Silala wetland and related areas) are showing changes in their ecological characteristics due to the artificial channeling. In this sense, it was mentioned that the non-renewable waters of the Silala have decreased, that the soils have been damaged, and that the system of waters and life interconnected to said wetland have been adversely affected.

Within the framework of the Convention, the ecological character of a Ramsar site is the combination of the components, processes, and benefits/services that characterize the wetland at a given point in time.

In the context of implementing Article 3.2, changes in the ecological character occur when there have been adverse human alterations of any component, process, and/or ecosystem benefit/service.

In light of the foregoing, an evaluation of the ecological status of the Los Lipez Ramsar Site as a whole is carried out on basis of the information provided and the field visit to the site.

5.1. Physical aspects

5.1.1. Surface hydrology

Some important changes occurring in the surface and underground hydrological characteristics are described briefly at the regional, intermediate, and local scales of the Los Lipez Ramsar site.

At the scale of the Los Lipez Ramsar site, covering a total area of 14,277 km^2, no noticeable hydrological changes are observed since its inclusion as a Ramsar site.

At the intermediate and local level, there is a concentrated development of tourism activities in the site, with the establishment of infrastructures for accommodations in places that are not suitable and that are close to the waterbodies (lagoons, wetlands), which causes a certain degree of contamination resulting from the lack of adequate wastewater disposal systems. Similarly, waters from the tributaries that reach Laguna Colorada are increasingly being used. Other lodging sites have been established near other cuerpos de agua como en Laguna Verde y laguna Hedionda Norte y el impacto de la infraestructura que rompe el paisaje, basura y otros aspectos es cada vez más evidente.

A la escala de los bofedales del Silala, no existen cuerpos de agua superficial, excepto aquellas que afloran de los manantiales en los bofedales descritos antes. Las denominadas Laguna Blanca y Laguna Chica son depresiones topográficas secas sin agua. La Laguna Blanca está cubierta en su superficie por clastos de 2 a 20 cm de chert o cuarzo amorfo, que dan lugar a ese tono blanquecino que se observa en la imagen satelital y fotografías aéreas

El cuerpo de agua superficial más cercano a los bofedales del Silala es la Laguna Khara que se encuentra a 5.5 Km al NE y la Laguna Colorada, localizada a 38 Km al sur del área de Silala.

Por último, no existe ningún efluente contaminante en toda el área de estudio.

5.1.2 Hidrología subterránea

La zona está conformada por numerosas cuencas endorreicas constituidas por subcuencas, lagunas, corrientes de agua superficial y afloramientos de agua subterránea. Esta zona es considerada muy árida con escasas precipitaciones (<100 mm anuales en Laguna Colorada) y un alto nivel de evaporación (> 500 mm), produciéndose un déficit hídrico permanente que contrasta con la presencia de numerosas lagunas que, como oasis en el desierto son ecosistemas clave para la presencia de flora y fauna en la región. Estas lagunas poco profundas son alimentadas por ríos y manantiales de agua subterránea (Alurralde 2006).

No obstante, el agua subterránea tiene un valor inestimable sobre los humedales locales (bofedales) pues los desniveles de la presión del agua subterránea permiten a la vez la resurgencia de manantiales quienes escurren de manera superficial y alimentan los bofedales; al mismo tiempo estos desniveles alimentan los bofedales directamente por emergencia vertical sobre los mismos (ver croquis en la figura 3.7). De hecho, los bofedales deben su existencia al agua subterránea.

Estudios realizados por el SERGEOMIN (2001) revelan la íntima relación entre las aguas superficiales y subterráneas que definen las características hidrológicas de la región; es decir, que la formación de lagunas y bofedales en la superficie terrestre dependen del aporte de las aguas subterráneas, y estas son bastante antiguas (Alurralde 2006). El sistema de aguas subterráneas constituye un tejido interno regulador que sostiene la humedad en el suelo externo con la manifestación de manantiales, vertientes, ríos, cuencas y formación de humedales que sirven de hábitat de poblaciones de avifauna y poblaciones humanas asentadas en la región (SERGEOMIN 2001, citado en Alurralde 2006).

Estudios realizados en la zona coinciden en que la recarga de acuíferos en la región es muy débil o casi inexistente. La recarga de los acuíferos pudo haberse producido entre algunos cientos y varios miles de años, cuando las característica climáticas eran diferentes a las actuales. Por lo tanto, se puede considerar al agua como un recurso no renovable fósil y bastante limitado del que dependen las actividades antrópicas realizadas en la región.

El uso de las aguas subterráneas en el Sitio Ramsar se da en la actividad minera y por los albergues para el turismo. En el primer caso las aguas de los manantiales del Silala se desvían hacia Chile para su uso en las mineras y la empresa Tierra Ltda también hace uso de agua subterránea de un pozo de energía geotérmica para el procesamiento de ácido bórico. Los albergues de turismo utilizan agua de los manantiales de agua subterránea y aguas termales (FIR, 2009).

waterbodies as the Verde and northern Hedionda Lagoons, and the impact of these infrastructures—disrupting the landscape—, garbage, and other components is increasingly evident.

At the scale of the silala wetlands, there are no surface water bodies, with the exception of those that well up from the springs located in the wetlands described above. The so-called Laguna Blanca and Laguna Chica are dry topographic depressions. The surface of Laguna Blanca is covered by clasts of chert, or amorphous quartz of 2 to 20 cm, which give place to that whitish tone that can be observed in satellite images and aerial photographs.

The surface waterbody that is closest to the Silala wetlands is Khara lagoon, which is found at 5.5 Km to the northeast, and Laguna Colorada, found at 38 km to the south of the Silala area.

Finally, there is no polluting effluent in the whole of the area studied.

5.1.2 Groundwater hydrology

The area is formed by numerous endorheic basins constituted by sub-basins, lagoons, surface water currents, and outcrops of groundwater. This area is considered very arid with little rainfall (<100 mm per year in Laguna Colorada) and a high level of evaporation (> 500 mm), resulting in a permanent water deficit that contrasts with the presence of numerous lagoons which, like oases in the desert, are key ecosystems for the presence of flora and fauna in the region. These shallow lagoons are fed by rivers and groundwater springs (Alurralde, 2006).

However, groundwater has an invaluable importance on local wetlands, inasmuch as the unevenness of the groundwater pressure allows the resurgence of springs that runoff on the surface and feed the wetlands, and, at the same time, feeds the wetlands directly by vertical emergence over them (see diagram in figure 3.7). In fact, the wetlands owe their existence to groundwater.

Studies carried out by SERGEOMIN (2001) reveal the intimate relationship between surface and groundwater, which defines the hydrological characteristics of the region; that is, the formation of lagoons and wetlands on the surface depends on the inputs of groundwater, and these are quite old (Alurralde 2006). The groundwater system is an internal regulating tissue that maintains the humidity in the external soil with the manifestation of springs, slopes, rivers, basins, and the formation of wetlands that serve as the habitat for bird and human populations settled in the region (SERGEOMIN 2001, quoted in Alurralde 2006).

Studies carried out in the area agree that the recharge of aquifers in the region is very weak, or almost inexistent. The recharge of the aquifers might have occurred between several hundred and several thousand years, when the climatic characteristics were different to the present ones. Therefore, water can be considered as a rather limited and non-renewable fossil resource on which anthropic activities in the region depend.

The groundwater in the Ramsar Site is mainly used in mining activities and lodging for tourism. In regard to the former, the waters of the Silala springs are diverted to Chile and are used by mining companies. Tierra Ltd. Company also makes use of groundwater obtained from a geothermal well to process boric acid. Tourist lodges, on the other hand, use waters from groundwater springs and thermal waters (RIS of 2009).

Otro uso de aguas subterráneas en la región del suroeste de Potosí, es la extracción a cielo abierto de yacimientos de plata, plomo y zinc a gran escala por la Empresa Minera San Cristóbal – la mayor inversión en este rubro en las últimas tres décadas. Las actividades mineras de esta empresa están previstas para los siguientes doce años y demandarán 40 000 m^3 agua/día durante la fase de operación, lo que equivale a 465 l/s de caudal continuo, aguas que sólo estarían disponibles de fuentes subterráneas (Molina 2007).

Independientemente de la utilización de este recurso para actividades mineras de gran escala, el uso de estos recursos en esta frágil región puede causar impactos como la disminución de los niveles de agua subterránea y el volumen de agua almacenados en los acuíferos, degradación y/o desecación de bofedales, la desecación de lagunas alto-andinas, efectos negativos sobre la avifauna que depende de estas lagunas (flamencos), reducción de los hatos de camélidos, impactos socioeconómicos y culturales en las poblaciones humanas, la desaparición o degradación de fuentes de agua utilizadas para consumo humano (Molina 2007).

La totalidad de los manantiales que afloran en forma artesiana en el área de Silala son descargas del acuífero de las Ignimbritas Silala. En muchos casos se observan manantiales surgentes directamente de las diaclasas y fisuras. Los sedimentos finos Cuaternarios y Recientes que cubren las ignimbritas son alimentados y saturados por el agua del acuífero ignimbrítico subyacente formando bofedales.

El acuífero de Silala es de escala intermediaria cuya área se estima a aproximadamente 320 km^2, el acuífero puede ser confinado o de condición freática dependiendo de la cobertura de materiales del Cuaternario. Se requerirían la perforación de por lo menos dos pozos exploratorios para definir su real origen, el espesor de las ignimbritas y las rocas infrayacentes. Así como la determinación del nivel o niveles de los acuíferos y el bombeo necesario para determinar los niveles de descarga permisibles.

Según la hidro-química y los parámetros físicos de las aguas, se deduce la existencia de dos niveles de acuíferos ignimbríticos. Uno superior que forma el bofedal del Sur con afloramientos a los 4450 msnm y conductividad promedio de 257 µS/cm, y mayor contenido de Ca, Li y S04. El segundo nivel acuífero inferior, aflora a los 4400 msnm y tiene una conductividad promedio de 109 µS/cm, y mayor contenido de Na. Este nivel es el que aflora en el Bofedal Norte o Cajones.

No se ha detectado ningún tipo de contaminación en las aguas surgentes del acuífero.

Desde el punto de vista de la recarga natural al acuífero por medio de la infiltración de la precipitación en el área, se observa que esta es de menor importancia pues corresponde a los aportes de la precipitación, que en promedio, son menores de 100 mm/año, además, es muy variable de un año a otro: hay años en que ha superado los 250 mm, mientras que en otros está por debajo de los 50 mm.

De esas observaciones se puede deducir que la recarga neta al acuífero es casi nula, debido o pérdidas por evaporación y sublimación. Eso lo ubica en un acuífero de tipo no-renovable a la escala geológica. El origen y cantidad de esas aguas es únicamente el volumen almacenado en el acuífero, el cual se vacía natural y paulatinamente a través de los siglos.

Para tener una idea de los tiempos de escurrimiento naturales así como de los volúmenes potenciales almacenados en el acuífero, en las secciones siguientes se presenta un análisis cuantitativo, conceptual, basado en los conocimientos y datos actuales de los que se dispone, recabados por la misión Ramsar (noviembre 2016- marzo 2017).

Another use of groundwater in the southwest region of Potosi Department is the open-pit large-scale extraction of silver, lead, and zinc deposits by the San Cristobal Mining Company—the largest investment in this area in the last three decades. Mining activities of this company are planned for the next twelve years and will demand 40,000 m^3 water/day during its operation phase, which is equivalent to a continuous flow-rate of 465 1/s; these waters would only be available from underground sources (Molina, 2007).

Irrespective of the use of this resource for large-scale mining activities, the use of these resources in this fragile region can cause impacts such as reductions of the groundwater levels and the volume of water stored in the aquifers, degradation, and/or desiccation of high-Andean lagoons, negative effects on the avifauna—which depends on these lagoons (flamingoes)—, declines of camelidae herds, socioeconomic and cultural impacts on human populations, and disappearance or degradation of the water used for human consumption (Molina 2007).

The whole of the springs that appear artesianly in the area of Silala results from discharges of the aquifer of the Silala ignimbrites. In many cases, springs arising directly from the joints and fissures can be observed. The Quaternary and Recent thin sediments that cover the ignimbrites are fed and saturated by the water of the underlying ignimbrite aquifer, forming wetlands.

The Silala aquifer is of intermediate scale. Its area is estimated at approximately 320 km2. This aquifer might be a confined, or phreatic one depending on the coverage of materials from the Quaternary. The drilling of at least two exploratory wells was required to define its true origin, the thickness of the ignimbrites, and the underwater rocks, together with the determination of the level, or levels, of the aquifers and the necessary pumping to determine permissible discharge levels.

According to the hydro-chemistry and the physical parameters of the waters, the existence of two levels of ignimbrite aquifers is deduced. A superior one that forms the south wetland with emergences of water at 4450 m.a.s.l and an average conductivity of 257 µS/cm, and higher content of Ca, Li, and S04.; and a lower one that emerges at 4400 m.a.s.l and has an average conductivity of 109 µS/cm, and a higher Na content. This aquifer level is the one that emerges in the north wetland or Cajones.

No contamination has been detected in the waters that emerge from the aquifer.

As far as the aquifer's natural recharge through the infiltration of precipitation in the area is concerned, it is observed that this infiltration is of minor importance because it corresponds to the contributions of precipitation, which on average amount to less than 100 mm/year and varies from year to year: there are years when it has exceeded the 250 mm, while in others it was below the 50 mm.

From these observations it can be deduced that the aquifer's net recharge is almost nil, due to losses resulting from evaporation and sublimation. This leads to its classification as a non-renewable aquifer on the geological scale. The origin and quantity of these waters comprises only the volume stored in the aquifer, which empties naturally and gradually over the centuries.

To get an idea of the natural runoff times, as well as of the potential volumes stored in the aquifer, the following sections present a quantitative, conceptual analysis, based on current knowledge and data collected by the Ramsar Mission (November 2016–March 2017).

Escurrimientos naturales

Para evaluar los escurrimientos naturales del agua subterránea contenida en el acuífero de ignimbritas del Silala, se consideraron los límites del mismo propuestos por SERGEOTECMIN (2002). La carta geológica mostrada de la figura 5.1 indica en color rojo los límites del acuífero; mientras que la figura 5.2 es un corte transversal suroeste-noreste del sitio del Silala con énfasis en la hidrogeología, según SERGEOTECMIN (2002). De igual manera se utilizó la figura 5.3 también propuesta por SERGEOTECMIN (2002) mostrando las direcciones del flujo subterráneo en 2D horizontal.

Con el uso esas figuras se aplicó la ley de Darcy para estimar los flujos de agua subterránea que ocurren el acuífero desde sus límites noreste hasta los límites suroeste.

La formulación de Darcy para medios porosos o porosos equivalentes (el caso de este acuífero) es:

$Q = A \cdot K \cdot i$

En donde: Q es el flujo volumétrico, en m^3/s; K es la conductividad hidráulica del acuífero en m/s; e i es el gradiente hidráulico, sin dimensiones.

Dada la falta de datos de parámetros precisos del acuífero, se hizo una búsqueda en la literatura para materiales similares al acuífero del Silala el cual está compuesto esencialmente de ignimbritas fracturadas y se encontraron valores distintos de conductividad de hasta tres órdenes de magnitud, entre 1E-5 m/s y 1E-7 m/s (Huang et al., 2014).

El área del acuífero se estimó de la delimitación propuesta en la figura 5.1; mientras que el gradiente hidráulico se estimó del corte transversal de la figura 5.2, los valores estimados son:

$A=320\ km^2$
$i=0.02$

Con esos valores y utilizando la gama de las tres conductividades, se obtienen gastos de escurrimiento de entre 64’000 l/s para K=1E-5 m/s, y 640 l/s para K=1E-7 m/s. El valor dado para K=1E-7 m/s es el que más se acerca al volumen total de los caudales que emergen en los manantiales del Silala (200 l/s). Dadas las incertidumbres en el área y en las conductividades propuestas, se puede concluir que un valor de K= 1E-7 m/s sería el más representante del acuífero pues es el que reproduce el mismo orden de magnitud de los volúmenes que emergen en los manantiales.

Estas estimaciones son muy preliminares, los cálculos pueden ser refinados y disminuir así las incertidumbres, con la obtención de datos más precisos.

Natural runoff

To assess the natural runoff of the groundwater contained in the ignimbrite aquifer of Silala, the limits set by SERGEOTECMIN (2002) were taken into account. The geological map of figure 5.1 depicts the aquifer's limits in red; while figure 5.2 depicts a southwest– northeast cross-section of the Silala site, placing emphasis on hydrogeology, as per SERGEOTECMIN (2002). Similarly, figure 5.3—proposed by SERGEOTECMIN also (2002)—was used to depict the directions of groundwater flow in a 2D horizontal plane.

With the use of these figures, the Darcy law was applied to estimate the groundwater flows that occur in the aquifer, stretching from its northeast limits to its southwest limits.

The Darcy formula for porous media, or equivalent porous (in the case of this aquifer) is:

$Q = A \bullet K \bullet i$

Where: Q is the volumetric flow, in m^3/s; K is the hydraulic conductivity of the aquifer in m/s; and i is the hydraulic gradient, without dimensions.

Owing to the lack of precise parameters for the aquifer, the literature was examined to search for materials that are similar to those of the Silala aquifer, which is essentially composed of fractured ignimbrites. Different conductivity values of up to three magnitude orders were found, between 1E-5 m/s and 1E-7 m/s (Huang et al, 2014).

The area of the aquifer was estimated on basis of the delimitation proposed in figure 5.1; while the hydraulic gradient was estimated on basis of the cross-section presented in figure 5.2, the values estimated are:

$A = 320\ km^2$

i: 0.02

With these values and using the range of the three conductivities, the result of runoff rates obtained is between 64'000 l/s for K = 1E-5 m/s and 640 l/s for K = lE-7 m/s. The value given for K = lE-7 m/s is the one closest to the total volume of the flows that emerge in the Silala springs (200 l/s). Due to the uncertainties in the area and the proposed conductivities, it can be concluded that a value of K = lE-7 m/s would be the most representative for the aquifer because it reproduces the same order of magnitude as the volumes that emerge in the springs.

These estimates are preliminary; the calculations can be improved and thus reduce the uncertainties—once more precise data is obtained.

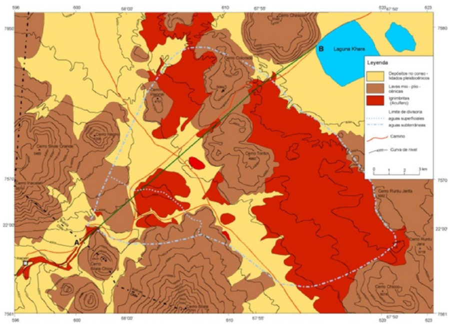


Figura 5.1 Mapa geológico del área del Silala con énfasis en la hidrogeología, según SERGEOTECMIN (2002).

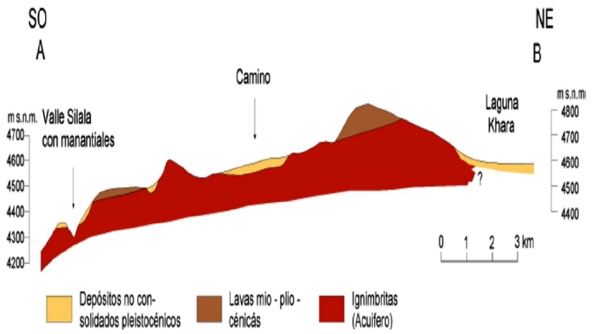


Figura 5.2 Corte transversal suroeste-noreste del área del Silala con énfasis en la hidrogeología, según SERGEOTECMIN (2002).

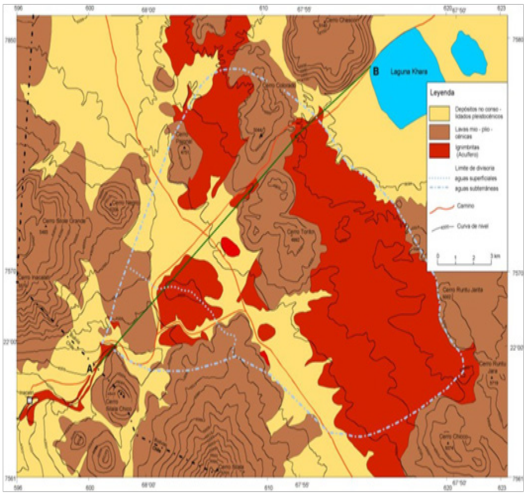


Figure 5.1. Geological map of the Silala area with an emphasis on hydrogeology. Based on SERGEOTECMIN (2002)

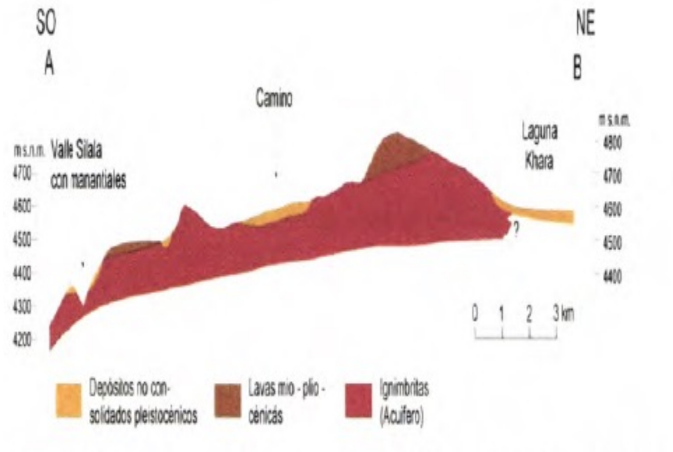


Figure 5.2. Transversal Southwest–Northeast cut of the Silala with an emphasis on hydrology. Based on SERGEOTECMIN (2002)

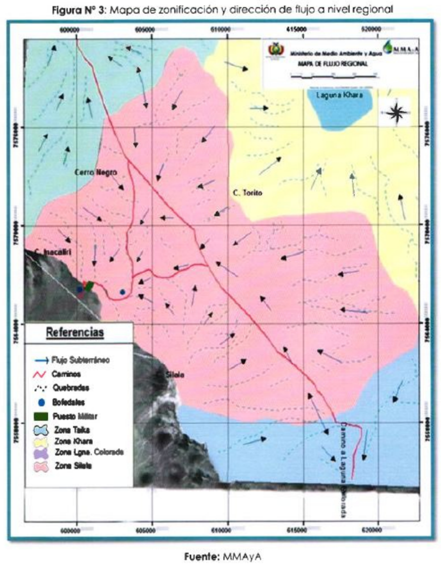


Figura 5.3 Direcciones del flujo subterráneo con vista en 2D horizontal, según SERGEOTECMIN (2002).

Volúmenes almacenados y tiempos asociados al escurrimiento

Una de las hipótesis más importantes en el área del Silala es el modelo conceptual adoptado del acuífero ignimbrítico descrito en las secciones 3.3.4 y 4.1.3. Por ende, además de los escurrimientos naturales estimados en la sección precedente, es imperativo cuantificar los volúmenes almacenados y los tiempos asociados al escurrimiento natural, lo cual permitirá evaluar los cambios en las características ecológicas (bofedales localizados en el sitio Silala), así como cualquier otro evento natural o antropogénico.

Los caudales de los manantiales del Silala han sido monitoreados desde los años noventa, contando a la fecha con 20 años de datos cumulados con una frecuencia de una vez y hasta cuatro veces por año. El total de los caudales de todos los manantiales del sitio del Silalal se ha mantenido relativamente constante. Los caudales medidos desde junio de 1996 muestran un valor promedio anual de 187.5 l/s con un valor mínimo de 155 l/s en junio de 1996, y un máximo de 280 l/s en abril de 1999; la desviación estándar es de 43 l/s. La figura 5.4 es una representación gráfica de los caudales de los manantiales del Silala, se observa que los caudales aumentan ligeramente en el periodo de verano, entre diciembre y abril.

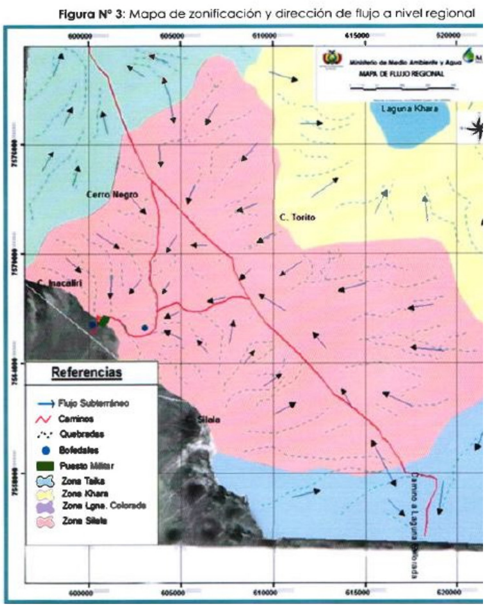


Figure 5.3. Directions of the groundwater flows in a 2D horizontal plane. Based on SERGEOTECMIN (2002)

Stored volumes and times associated with runoff

One of the most important hypotheses concerning the Silala area is the conceptual model adopted for the ignimbrite aquifer described in Sections 3.3.4 and 4.1.3. Therefore, in addition to the natural runoff estimated in the preceding section, it is imperative to quantify the volumes stored and the time associated with natural runoff, which will allow assessing the changes in the ecological characteristics (wetlands located in the Silala site), as well as any another natural, or anthropogenic event.

The flows of the Silala springs have been monitored since the 90s. To date, 20 years of data, accumulated with a frequency of one to four times per year, is available. The total flow of all the springs of the Silala site has remained relatively constant. Flowrates measured since June 1996 show an annual average value of 187.5 1/s with a minimum value of 155 1/s in June 1996, and a maximum value of 280 1/s in April 1999. The standard deviation is of 43 1/s. Figure 5.4 is a graphical representation of the flows of the Silala springs, which shows that the flows increase slightly in summer, between December and April.

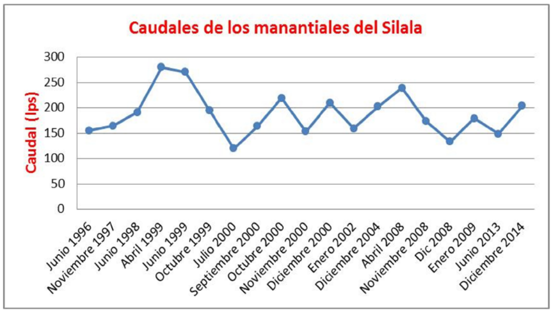


Figura 5.4 Caudales totales aforados en los manantiales del Silala; tomados del reporte de SERGEOTECMIN (2002).

Siguiendo con la hipótesis de acuífero con recarga ínfima, o nula, conteniendo aguas fósiles no-renovables a escala humana (secciones .3.4 y 4.1.3), se puede entonces deducir la importancia de los manantiales como la única fuente de agua del sitio del Silala con un volumen permanente pero no-renovable.

Es por ello que resulta muy interesante hacer un análisis cuantitativo de los volúmenes potencialmente almacenados en el acuífero y de los tiempos asociados al escurrimiento subterráneo que emerge en los manantiales.

Una manera de estimar esos volúmenes es utilizando la ecuación hidrogeológica:

$V = S \cdot A \cdot b$

En donde V es el volumen almacenado en m^3; A es el área del acuífero en m^2; S representa el coeficiente de almacenamiento del acuífero para el caso de acuífero confinado, o rendimiento especifico S_y (conocido también como porosidad de drenaje, n_d) si el acuífero es no-confinado; b representa el espesor del acuífero, o el nivel de agua subterránea medido desde el fondo del acuífero.

Una vez más, utilizando las figuras 5.1 y 5.2 se deducen los valores del área y del espesor del acuífero de manera aproximativa:
$A= 2.22 \cdot 10^8$ m^2
B= 100 to 175 m
S, or S_y, or n_d = variable

Los valores del coeficiente de almacenamiento para ese acuífero no son conocidos pero se pueden estimar en un rango de entre 5% y 25% para ese tipo de roca de origen volcánico. Tomando el valor más bajo del ese rango, de 5%, se obtiene un volumen almacenado de $1.77 \cdot 10^9$ m^3; y de $8.83 \cdot 10^9$ m^3 para el valor más alto del coeficiente de almacenamiento, 25%. La figura 5.5 muestra los volúmenes potencialmente almacenado en el acuífero ignimbritico del Silala con un rango aun mayor de coeficientes de almacenamiento.

Figure 5.4. Total estimated flow of the Silala springs, taken from SERGEOTECMIN report (2002)

Following the hypothesis that this aquifer has very little, or no recharge, and that it contains non-renewable fossil water on a human scale (Sections 3.4 and 4.1.3), the importance of the springs as the only water source in the Silala site, with a permanent yet non-renewable natural volume, can be deduced.

That is why it is quite interesting to make a quantitative analysis of the volumes potentially stored in the aquifer and the times associated with the underground runoff that emerges in the springs.

One way to estimate these volumes is to use the hydrogeological equation:

$V = S \cdot A \cdot b$

Where V is the volume stored in m^3; A is the area of the aquifer in m^2; S represents the aquifer's storage coefficient for the confined aquifer, or specific output S_y (also known as drainage porosity, nd) in case the aquifer is unconfined; b represents the thickness of the aquifer, or the level of groundwater measured from the bottom of the aquifer.

Again, using figures 5.1 and 5.2 the values of the area and the thickness of the aquifer are deduced on an approximate basis:

$A = 2.22 \cdot 108\ m^2$
B = 100 to 175m
S, or S_y, or n_d = variable

The values of the storage coefficient for this aquifer are not known, but can be estimated in a range between 5% and 25% for that type of volcanic origin rock. A stored volume of $1.77 \cdot 10^9\ m^3$ is obtained for the lowest value of that range, 5%, and one of $8.83 \cdot 10^9\ m^3$ for the highest value of storage coefficient, 25%. Figure 5.5 shows the volumes potentially stored in the Silala ignimbrite aquifer with an even greater range of storage coefficients.

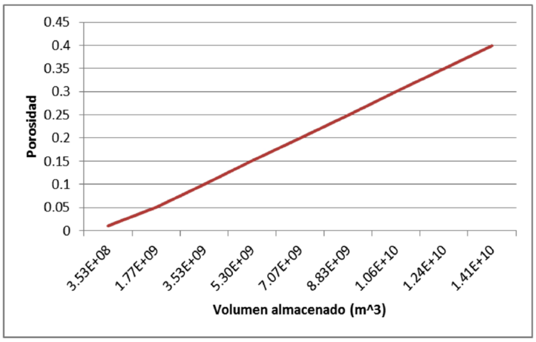


Figura 5.5 Agua subterránea almacenada en el acuífero del Silala.

5.1.3 Suelos

Potencialmente, la actividad minera es la que más puede producir cambios en las características naturales de los suelos; por otro lado, el incremento del turismo aunque tiene efectos menores sobre los suelos, el uso de vehículos "todo terreno" fuera de las rutas establecidas dejan huellas en el suelo arenoso modificando el paisaje y compactando el terreno; sin embrago hasta ahora no se han observado cambios substanciales en el mismo.

5.1.4 Geomorfología

El análisis detallado y a escala fina de las fotografías satelitales de alta resolución, tomadas entre 2001 y 2011 (imagen 1 de noviembre 2001; imagen 2 de junio, 2004; imagen 3 de marzo, 2011), no revelan ningún cambio geomorfológico notable durante ese periodo. No se detectan modificaciones en la configuración geomórfica del sitio que pudiesen ser atribuidas a orden antropogénico.

El uso de vehículos "todo terreno" fuera de las rutas establecidas dejan huellas en el suelo arenoso modificando el paisaje y compactando el terreno; sin embrago esto conlleva a un efecto mínimo sobre la geomorfología del sitio. Desde el punto de vista geomorfológico, la huella del impacto, magnitud y forma de las modificaciones humanas es muy reciente y difícil de cuantificar. La geomorfológica de la región fue modificada durante miles de años (holoceno, ver sección 3.3.1), mientras que los efectos antropogénicos solo son visibles a escala décadal.

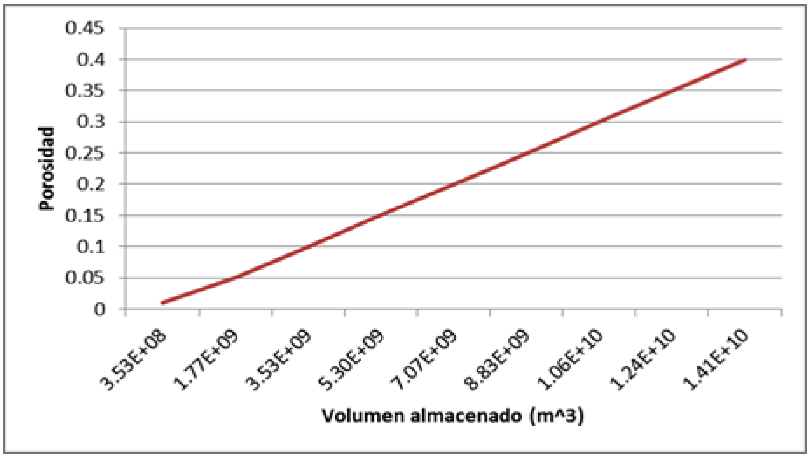


Figure 5.5. Groundwater stored in the Silala aquifer

5.1.3. Soils

Potentially, mining activity is the most likely to produce changes in the natural features of the soils; on the other hand, the increase in tourism—albeit it has minor effects on the soils—the use of "all-terrain" vehicles outside the established routes leave tracks on the sandy soil, altering the landscape and diminishing the extent of the land; nevertheless, substantial changes on the soil have yet not been detected.

5.1.4. Geomorphology

The detailed analysis, and at a fine-scale, of the high resolution satellite images, taken between 2001 and 2011 (image No. 1, November 2001; image No. 2, June 2004; image No. 3, March 2011) do not reveal any notorious geomorphological change in this period. Modifications in the geomorphological configuration of the site can be attributed to anthropogenic activities.

The use of "all-terrain" vehicles outside the established roads leave tracks on the sandy soil, altering the landscape and diminishing the area of the land; this, however, has minimal effects on the geomorphology of the site. From the geomorphological viewpoint, the traces of the impacts, magnitude, and types of human alterations are quite recent (Holocene, see section 3.3.1), while the anthropogenic effects are only visible at decadal time scales.

2001

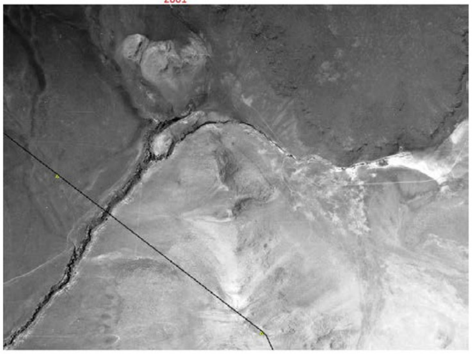


Imagen 1 satelital tomada en noviembre de 2001.

2004

Imagen 2 satelital tomada en junio de 2004.

2011

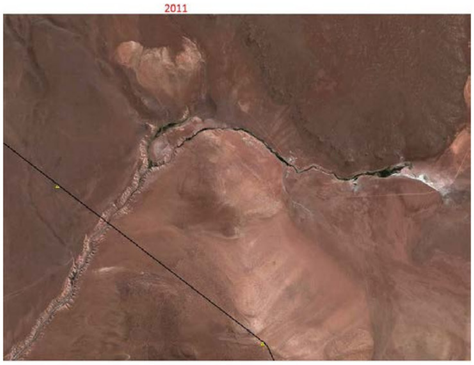
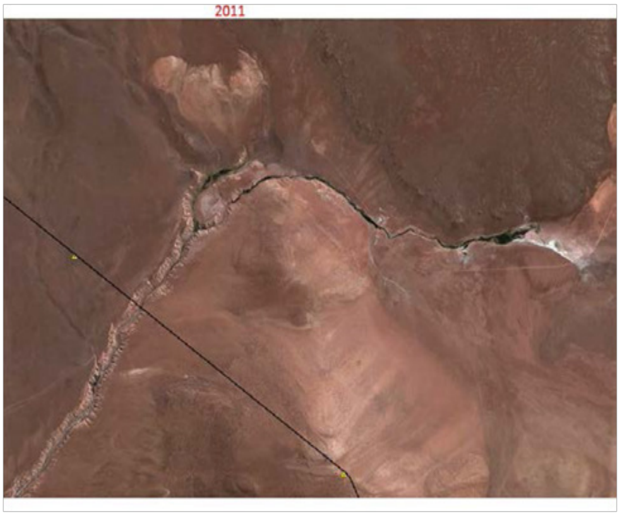


Imagen 3 satelital tomada en marzo de 2011.

Satellite image No. 1, taken in November 2001

Satellite image No. 2, taken in June 2004



Satellite image No. 3, taken in March 2011

5.1.5 Salinidad

En términos generales no se detectan cambios en la salinidad con respecto a las concentraciones de base, las cuales son consecuencia de las condiciones climáticas, geológicas e hidrológicas, tal y como se describe en la sección 3.3.3.

No obstante lo anterior, la disminución del agua en los bofedales, especialmente en época seca hace que las sales disueltas tengan mayor concentración, por lo tanto se presentan afloramientos salinos en los suelos de estos bofedales (principalmente en el bofedal sur) (Ministerio de Medio Ambiente y Agua, 2016)

5.1.6 Calidad del agua

Como se indicó en la sección 4, el efecto más evidente de cambios en la calidad del agua son las actividades turísticas, aunque cabe decir que su impacto es difícil de cuantificar de manera objetiva a escalas intermediarias y locales. En los últimos años el turismo intensivo, de más de 70,000 visitantes en 2007, que llega a la RNFA Eduardo Avaroa y su área de influencia, originan ciertos impactos en la región y en particular en las lagunas, que son el principal hábitat para los flamencos.

También es un hecho que todavía existen algunas lagunas que por su ubicación o difícil acceso, no tienen ningún impacto o presencia de actividad antrópica hasta el presente y mantienen sus características ecológicas bien conservadas, entre ellas destacan Laguna Khara, Kalina, Guayaques y Pelada.

Las muestras tomadas en los bofedales del Silala, por su pureza y bajísimo contenido de sales, están consideradas de muy alta calidad fisicoquímica (Ministerio de Medio Ambiente y Agua, 2016)

5.2 Componentes ecológicos

Respecto a los cambios en los componentes ecológicos, de acuerdo a los estudios realizados en 28 lagunas de 1990 a 2009 (Rocha, comms personal), se presenta una retracción en el área del complejo de lagunas en un 34.5%, lo cual implica la pérdida de hábitat para las especies que dependen de estos sistemas especialmente aves acuáticas así como para el suministro de agua.

Los bofedales de la región de Silala han sido altamente afectados con la construcción de los canales recolectores de agua iniciada en 1908. En la actualidad quedan tan solo relictos de los bofedales originales que cubrían un área de cerca de 141,200 m2 ó 14.1 hectáreas. La superficie actual de bofedales es tan sólo de alrededor de 6,000 m2 ó 0.6 Ha. que se ubican en el entorno de las captaciones de agua y canales artificiales (SERGEOMIN,2003). Este proceso de degradación progresiva se pudo constatar durante la visita al sitio Ramsar donde los bofedales sur y norte presentan fuertes procesos de deterioro.

Igualmente, el Ministerio de Medio Ambiente y Agua (2016) realizo un análisis de los cambios en la vegetación en los bofedales del Silala utilizando imágenes de satélite (Land Sat TMs) en el cual se encontró una disminución de 1.08 ha en bofedales entre los periodos 1986 y 2010. De esto resultados también se pudo observar la presencia de afloramientos de sales en la superficie del suelo. Así, la disminución de lo cobertura vegetal predispone a la pérdida de suelo por los frecuentes vientos característicos de la zona, especialmente en la época seca.

Respecto a la vegetación, tal vez las que presentan la mayor degradación son las praderas nativas.

5.1.5 Salinity

In general terms, no changes in the salinity are detected with respect to the basic concentrations, which are a consequence of the climatic, geological, and hydrological conditions, as described in section 3.3.3.

Nevertheless, the reduction of water found in the wetlands, especially in dry season, causes the dissolved salts to have a higher concentration; therefore, saline outflows occur in the soils of these wetlands (mainly in the south wetland) (Ministry of Environment and Water, 2016).

5.1.6 Water quality

As indicated in section 4, the most obvious effect of the changes in water quality concerns tourism activities, although it is difficult to quantify it objectively at the intermediate and local scales. In recent years, concentrated tourism—amounting to more than 70,000 visitors at the Eduardo Avaroa Andean Fauna National Reserve and its area of influence in 2007—causes certain impacts on the region and particularly on the lagoons, which are the main habitat for flamingoes.

It is also a fact that there are still some lagoons which, due to their location, or difficult access, have received no impact, or influence of anthropic activities up to the present and have preserved their ecological characteristics—among them, Khara, Kalina, Guayaques and Pelada lagoons.

Due to their purity and low content of salts, the samples taken from the Silala wetlands are regarded as having a very high physic-chemical quality (Ministry of Environment and Water, 2016).

5.2 Environment components

Regarding changes in the environment components, according to the studies carried out in 28 lagoons from 1990 to 2009 (Rocha, personal commission), there is a reduction by the 34.5% in the lagoon complex area which implies a habitat loss for species that depend on these systems, particularly waterbirds, as well as a loss of water provision.

The wetlands found in the Silala area have been highly affected by the construction of the water-catchment canals started in 1908. At present, there are only vestiges of the original wetlands that used to cover an area of about 141,200 m^2, or 14.1 hectares. The current surface area of the wetlands covers only about 6,000 m^2, or 0.6 ha., which are surrounded by the water catchment works and artificial canals (SERGEOMIN, 2003). This process of progressive degradation was verified during the visit made to this Ramsar site, where the south and north wetlands have been affected by strong deterioration processes.

Likewise, the Ministry of Environment and Water (2016) carried out an analysis of the changes in vegetation in the Silala wetlands using satellite images (Land Sat TMs) and found a reduction by 1.08 ha. in the wetlands between 1986 and 2010. From these results, it was also possible to observe the presence of salt outcrops on the soil surface. As such, this reduction in the vegetation leads to soil losses, owing to the frequent winds that are typical of the area, especially during dry seasons.

As regards vegetation, native prairies are likely the ones that present the most severe degradation.

Su potencial forrajero está en peligro de perderse como consecuencia de la combinación de la falta de un manejo adecuado y las condiciones climáticas y edáficas. El desequilibrio del ecosistema produce la pérdida de las especies forrajeras más aceptadas por alpacas y llamas, y en muchos casos, pérdidas de agua por evaporación y de suelo por erosión hídrica y eólica, con la formación de arenales. Extensas superficies de comunidades vegetales son sometidas a extracción drástica, sobrepastoreo y extensión de la frontera agrícola, las cuales están provocando una desertificación paulatina (García, 2006).

Varias especies están sometidas a explotación a gran escala por su carácter combustible como la yareta, las tholas, la tara y otras más. La mayor presión proviene de las minas, ulexita, campamentos mineros y caleras. Asimismo se identifica a *Parastrephia lepidophylla* como la especie combustible con mayor cobertura en la zona.

En el caso de la yareta (*Azorella compacta*), se produce una explotación en gran escala, extracción histórica de cojines completos, disminuyendo grandemente las posibilidades de producción de semillas. Es la especie considerada más vulnerable en la zona sobre todo por su uso en minería.

Respecta a la fauna de acuerdo al Plan de Manejo de la Reserva Nacional de Fauna Andina Eduardo Avaroa (2010), algunas especies silvestres de fauna consideradas como recurso potencial se estarían recuperando satisfactoriamente gracias a los procesos de protección (flamencos, vicuña, suri, yareta). Según los datos de los censos de flamencos y la observación de los guardaparques, las poblaciones de especies silvestres se estarían recuperando por la presencia del área protegida en la región por lo que no se presentan cambios de fondo en este componente pero se requiere la continuidad en las medidas de conservación implementadas así como en los monitoreos de las poblaciones de las tres especies presentes en el sitio.

6. Conclusiones

1. En el sitio Ramsar Los Lípez, con un área total de 14,277 Km^2 se presentan factores de deterioro de carácter antropogénico que amenazan sus características ecológicas.

2. Los principales cambios en las características ecológicas se presentan en la reducción en el 34.5 % del área de 28 de sus lagunas así como en el deterioro de los bofedales del Valle del Silala por la construcción de los canales recolectores de agua iniciada en 1908.

3. Existen algunos factores adversos que afectan, o que pueden afectar en el futuro, las características ecológicas del sitio Ramsar en particular los suelos y el agua. Estos son principalmente las concesiones para la minería y otros proyectos de desarrollo, e.g., proyecto piloto geotérmico en la Laguna Colorada.

4. El proyecto piloto geotérmico en la Laguna Colorada así como propuestas futuras de explotación y/o aprovechamiento de los recursos hídricos incluyendo aguas subterráneas requieren de enfoques integrales teniendo en cuenta el estado de las características ecológicas del sitio Ramsar y el mantenimiento de las mismas.

5. Los déficits hídricos son el resultado del deterioro natural desde la época del Cuaternario (miles de años) cuando el área era todavía más húmeda.

6. El agua subterránea tiene un valor inestimable sobre los humedales locales (bofedales) pues los desniveles de la presión del agua subterránea permiten a la vez la resurgencia de manantiales que escurren de manera superficial y alimentan los bofedales; y, al mismo

Their forage potential is in danger of being lost owing to a combination of the lack of proper management and the climatic and edaphic conditions. This imbalance in the ecosystem results in losses of the forage species that are most accepted by alpacas and llamas, and in many cases, also entails water losses to evaporation and soil losses to water and wind erosion, resulting in the formation of sandbanks. Extensive areas of plant communities are subject to drastic extraction, overgrazing, and extensions of the agricultural frontier, which are causing gradual desertification (Garcia, 2006).

Several species are subject to large-scale exploitation because they can be used as fuels, i.e. yareta, tholas, tara, and others. These are predominantly exploited in ulexite mines, mining camps, and lime fields. The *Parastrephia lepidophylla* has been identified as the ignitable plant species that is most present in the area.

The yareta (*Azorella compacta*) is exploited at a large scale; whole yareta cushions have been historically extracted, greatly diminishing the possibilities of seed production. This species is considered the most vulnerable in the area, mainly because of its use in mining.

As far as fauna is concerned, according to the Management Plan of the Eduardo Avaroa Andean Fauna National Reserve (2010), some wild species of fauna considered potential resources are apparently recovering satisfactorily due to protection processes (flamingoes, vicuna, suri, and yareta). According to the data obtained from flamingo censuses and from observations made by park rangers, it appears that the populations of wild species are recovering as a result of the region's insertion into the protected area. There seemingly are no fundamental changes in this component, but the preservation measures implemented must continue, as well as population monitoring for the three species present on the site.

6. Conclusions

1. The presence of anthropogenic deterioration factors has been confirmed in the Los Lipez Ramsar site—which covers an area of 1,427,717 ha. This anthropogenic deterioration threatens the site's ecological characteristics.

2. The main changes in the ecological characteristics entail a reduction of 34.5% of the area of 28 of the site's lagoons, as well as in the deterioration of the wetlands of Silala valley derived from the construction of abstraction canals begun in 1908.

3. There are some adverse factors affecting, or likely to affect in the future, the ecological characteristics of this Ramsar site, particularly its soils and water; these factors are related to mining concessions and other development projects, e.g., a geothermal pilot project in Laguna Colorada.

4. The geothermal pilot project in Laguna Colorada, as well as the future prospects for exploitation and/or utilization of the water resources of this site—including groundwater—requires integral approaches that take into account the state of the ecological characteristics in this Ramsar site and their preservation.

5. The water deficits are the result of natural deterioration occurring since the Quaternary (thousands of years ago), when the area was even more humid.

6. Groundwater is of inestimable value to local wetlands inasmuch as the unevenness of groundwater pressure allows the resurgence of springs that run off on the surface and directly feed the wetlands,

tiempo, estos desniveles alimentan los bofedales directamente por emergencia vertical. Los bofedales deben su existencia al agua subterránea.

7. La formación de lagunas y bofedales en la superficie terrestre dependen del aporte de las aguas subterráneas. El sistema de aguas subterráneas constituye un tejido interno regulador que sostiene la humedad en el suelo externo con la manifestación de manantiales, vertientes, ríos, cuencas y formación de humedales que sirven de hábitat de poblaciones de avifauna y poblaciones humanas asentadas en la región

8. A la escala local (bofedales y manantiales del Silala) el volumen total de los manantiales es de 200 l/s, este volumen tiene variaciones menores, y no ha cambiado con el tiempo desde que se iniciaron los aforos en 1996. Dadas las características hidrogeológicas del sitio, y como primera hipótesis conceptual, se puede teorizar que se trata de un volumen permanente.

9. Estudios con isótopos estables han mostrado que las aguas que afloran en los manantiales del Silala son aguas fósiles de más de 10,000 años. Es decir son aguas que no se renuevan por recarga natural de aguas meteóricas en el acuífero local. Bajo las condiciones climáticas actuales, esto significa que esos recursos hídricos están almacenados en el acuífero ignimbritico desde hace miles de años, el cual se vacía natural y paulatinamente a través de los siglos.

10. No existe ningún efluente contaminante superficial en el área del sitio del Silala.

11. Aún existen algunas lagunas que por su ubicación o difícil acceso, no tienen ningún impacto o presencia de actividad antrópica hasta el presente y mantienen sus características ecológicas bien conservadas, entre ellas destacan Laguna Khara, Kalina, Guayaques y Pelada.

12. La presencia de *coulees* establecidos desde tiempos geológicos por el derretimiento y drenaje glacial en el sitio del Silala han causado un drenaje de agua subterránea en dirección oeste.

7. Recomendaciones

1- Es importante que se prepare un Plan de Manejo para todo el Sitio Ramsar de manera integral que incluya al área protegida de la Reserva Nacional de Fauna Andina Eduardo Avaroa y en el que se especifiquen medidas concretas para el uso sostenible de las actividades turísticas y actividades mineras.

2. Dado los fuertes factores de cambio en las características ecológicas de los bofedales norte y sur del SIlala, es de carácter prioritario realizar acciones inmediatas para la mitigación de los impactos y la preparación de un programa para su restauración.

3. Es prioritario continuar con el monitoreo de los caudales de los manantiales, tanto por separado (este y norte),

4. Sería de una muy gran utilidad realizar estudios adicionales de campo específicos, con el propósito de obtener valores reales de parámetros hidrogeológicos del acuífero ignimbrítico del Silala, tales como la conductividad hidráulica y la porosidad.

owing to vertical emergence over them. The wetlands owe their existence to groundwater.

7. The formation of lagoons and wetlands on the surface depends on the inputs of groundwater. The groundwater system is an internal regulating tissue that sustains the moisture in the external soil with the manifestation of springs, slopes, rivers, basins, and the formation of wetlands that serve as the habitat for bird and human populations settled in the region.

8. At the local level (Silala springs and wetlands), the total volume of the springs is 200 l/s; this volume has minor variations and has not changed over the time since the appraisals began in 1996. Given the hydrogeological characteristics of the site, and as the first conceptual hypothesis, it can be theorized that this is a permanent volume.

9. Studies with stable isotopes have shown that the waters that emerge in the Silala springs are fossil waters dating back to more than 10,000 years. In other words, these are waters that are not renewed by natural recharges of meteoric waters in the local aquifer. Under the current climatic conditions, this means that these water resources have been stored in the well-fractured ignimbrite aquifer for thousands of years, emptying naturally and gradually over centuries.

10. No superficial polluting effluent has been detected in the whole of the area studied.

11. There are still some lagoons which, due to their location or difficult access, have received no impact or presence of anthropic activities up to the present, and have preserved their ecological characteristics—among them, Khara, Kalina, Guayaques and Pelada lagoons.

12. The presence of coulees established since geological times by the melting and glacial drainage at the site of Silala have caused a drainage of groundwater to the west.

7. Recommendations

1. It is essential that a comprehensive Management Plan for this Ramsar site be prepared; this ought to include the protected area of the Eduardo Avaroa Andean Fauna National Reserve and detail specific measures for the sustainable use of tourism and mining activities.

2. Given the strong factors of change in the ecological characteristics of the north and south wetlands of Silala, it is essential that immediate actions be implemented to mitigate the impacts and that a restoration program be prepared.

3. Priority should be given to the monitoring of the springs' flow rates, both separately (east and north), [sic].

4. It would be highly advantageous to carry out additional specific field studies to obtain real values of hydrological parameters of the Silala ignimbrite aquifer, such as hydraulic conductivity and porosity.

5. Se recomienda construir un modelo numérico hidrogeológico a la escala local en dos dimensiones vertical para simular los escurrimientos y las reservas de aguas subterráneas del acuífero ignimbrítico del Silala, así como para examinar diversos parámetros e hipótesis, y simular escenarios diferentes.

5. It is advisable that a hydrological numerical model, at the local scale and in two vertical dimensions, be prepared to simulate the outflows and reserves of groundwater of the Silala ignimbrite aquifer, as well as to examine different parameters and hypotheses, and to simulate different scenarios.

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Anexo 1.

Tabla 3.2 Ubicación geográfica y altura de las principales lagunas del sitio Ramsar Los Lípez en el Suroeste de Potosí, Bolivia (Rocha 2006).

No.	Laguna	Ubicación geográfica		Altura msnm
		19K	UTM	
1	Chulluncani	615833	7617362	4525
2	Pastos Grandes	627463	7598966	4458
3	Cachi	608268	7597239	4368
4	Khara Grande	615313	7578131	4526
5	Capina	647867	7574630	4260
6	Cañapa	602493	7622072	4164
7	Hedionda Norte	597702	7612517	4166
8	Chiar Khota	597261	7608598	4111
9	Honda Norte	598141	7613026	4216
10	Ramaditas	595520	7605313	4160
11	Colorada	624832	7547943	4232
12	Chalviri Norte	647443	7516928	4445
13	Hedionda Sur	665123	7515515	4638
14	Kollpa	663106	7514095	4525
15	Salada o L. Polkes	639170	7507802	4487
16	Puripica Chico	653913	7510418	4479
17	Totoral	676137	7506164	4584
18	Catalcito	681117	7502573	4640
19	Herrera	653167	7504535	4449
20	Calina	680526	7498129	4575
21	Puripica Grande	652523	7487005	4742
22	Guayaques	652398	7484676	4767
23	Verde	623863	7477042	4425
24	Pelada	687368	7483614	4738
25	Cristal	684528	7523916	4520
26	Chojllas	697316	7526035	4577
27	Loromayu	682397	7521913	4468
28	Corante	710235	7543474	4381
29	Morejón	699914	7562594	4617
30	Coruto	704483	7516197	4550
31	Mama Khumo	696538	7537006	4589
32	Sombrerito	697282	7547754	4716
33	Chipapas	695217	7544817	4519
34	Peñas Blancas	666192	7519018	4604
35	Luriqui	689140	7522958	4726
36	Celeste	695456	7541362	4500
37	Khastor	707636	7536798	4499

Annex 1.

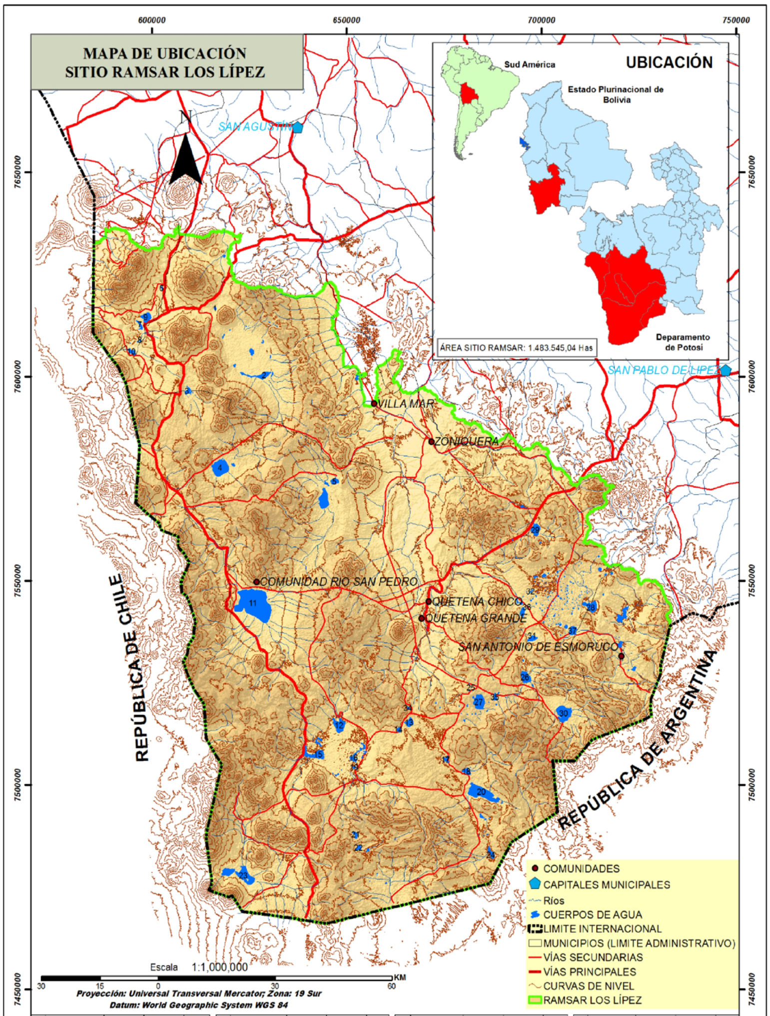
Table 3.2. Geographical location and altitude of the main lagoons of the Los Lipez Ramsar site in the southeast of Potosi (Rocha, 2006).

No.	Lagoon	Geographical location		Altitude in m.a.s.l
		19K	UTM	
1	Chulluncani	615833	7617362	4525
2	Pastos Grandes	627463	7598966	4458
3	Cachi	608268	7597239	4368
4	Khara Grande	615313	7578131	4526
5	Capina	647867	7574630	4260
6	Cañapa	602493	7622072	4164
7	Hedionda Norte	597702	7612517	4166
8	Chiar Khota	597261	7608598	4111
9	Honda Norte	598141	7613026	4216
10	Ramaditas	595520	7605313	4160
11	Colorada	624832	7547943	4232
12	Chalviri Norte	647443	7516928	4445
13	Hedionda Sur	665123	7515515	4638
14	Kollpa	663106	7514095	4525
15	Salada o L. Polkes	639170	7507802	4487
16	Puripica Chico	653913	7510418	4479
17	Totoral	676137	7506164	4584
18	Catalcito	681117	7502573	4640
19	Herrera	653167	7504535	4449
20	Calina	680526	7498129	4575
21	Puripica Grande	652523	7487005	4742
22	Guayaques	652398	7484676	4767
23	Verde	623863	7477042	4425
24	Pelada	687368	7483614	4738
25	Cristal	684528	7523916	4520
26	Chojllas	697316	7526035	4577
27	Loromayu	682397	7521913	4468
28	Corante	710235	7543474	4381
29	Morejón	699914	7562594	4617
30	Coruto	704483	7516197	4550
31	Mama Khumo	696538	7537006	4589
32	Sombrerito	697282	7547754	4716
33	Chipapas	695217	7544817	4519
34	Peñas Blancas	666192	7519018	4604
35	Luriqui	689140	7522958	4726
36	Celeste	695456	7541362	4500
37	Khastor	707636	7536798	4499

Translation prepared on basis of the Spanish source-text original by the Strategic Office for the Maritime Claim, Silala, and International Water Resources

Anexo 2.

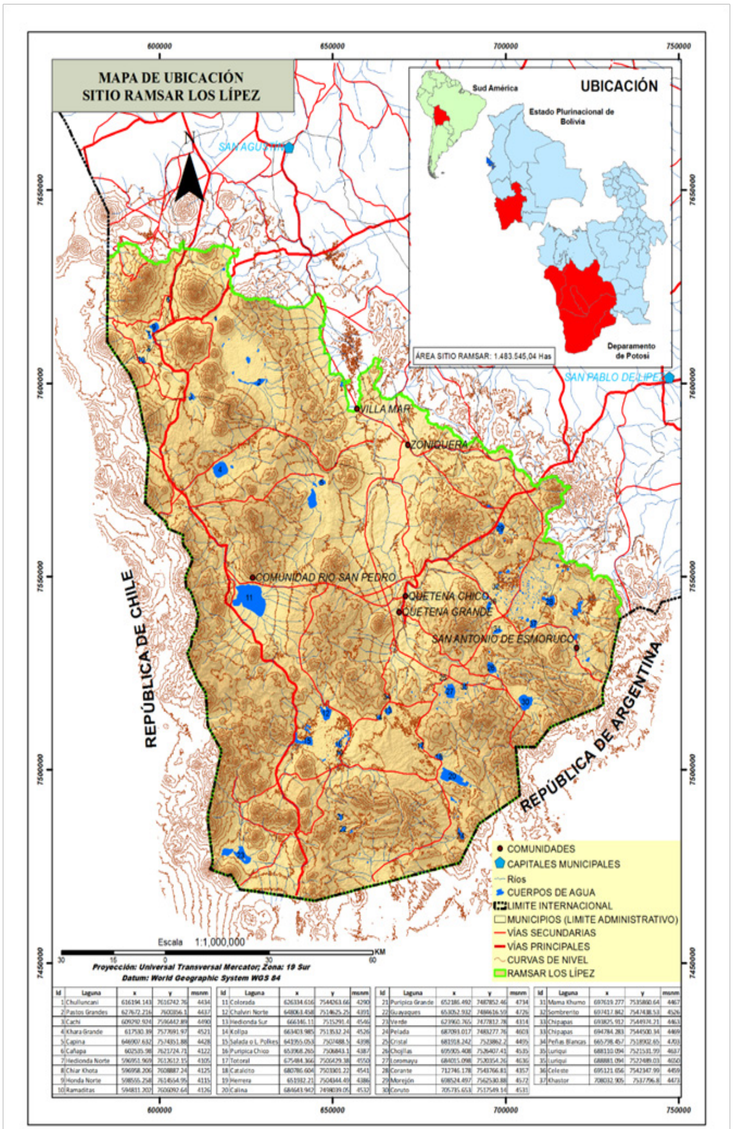
Mapa de ubicación Sitio Ramsar Los Lipez



Id	Laguna	x	y	msnm	Id	Laguna	x	y	msnm	Id	Laguna	x	y	msnm	Id	Laguna	x	y	msnm
1	Chulluncani	616194.143	7616742.76	4434	11	Colorada	626334.616	7544263.66	4290	21	Puripica Grande	652186.492	7487852.46	4734	31	Mama Khumo	697619.277	7535860.64	4467
2	Pastos Grandes	627672.216	7600356.1	4437	12	Chalviri Norte	648063.458	7514625.25	4391	22	Guayaques	653052.932	7484616.59	4726	32	Sombrerito	697417.842	7547438.53	4526
3	Cachi	609292.924	7596442.89	4490	13	Hedionda Sur	666146.11	7515291.4	4546	23	Verde	623960.765	7477812.78	4314	33	Chipapas	693825.912	7544974.21	4463
4	Khara Grande	617530.39	7577691.97	4521	14	Kollpa	663403.985	7513532.24	4526	24	Pelada	687093.017	7483277.76	4603	33	Chipapas	694784.283	7544500.34	4469
5	Capina	646907.632	7574351.88	4428	15	Salada o L. Polkes	641955.053	7507488.5	4398	25	Cristal	681918.242	7523862.2	4495	34	Peñas Blancas	665798.457	7518902.65	4703
6	Cañapa	602535.98	7621724.71	4122	16	Puripica Chico	653968.265	7506843.1	4387	26	Chojllas	695905.408	7526407.41	4535	35	Luriqui	688110.094	7521531.99	4637
7	Hedionda Norte	596951.969	7612612.15	4105	17	Totoral	675484.366	7506429.38	4550	27	Loromayu	684015.098	7520354.26	4636	35	Luriqui	688881.094	7522489.03	4650
8	Chiar Khota	596958.206	7608887.24	4125	18	Catalcito	680786.604	7503301.22	4541	28	Corante	712746.178	7543766.81	4357	36	Celeste	695121.656	7542347.99	4459
9	Honda Norte	598555.258	7614554.95	4115	19	Herrera	651932.21	7504344.49	4386	29	Morejón	698524.497	7562530.88	4572	37	Khastor	708032.905	7537796.8	4473
10	Ramaditas	594811.202	7606092.64	4126	20	Calina	684643.942	7498039.05	4532	30	Coruto	705735.653	7517549.14	4531					

45

Annex 2
Location map of the Los Lipez Ramsar site



45