INTERNATIONAL COURT OF JUSTICE

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

(CHILE v. BOLIVIA)

REJOINDER OF THE PLURINATIONAL STATE OF BOLIVIA

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VOLUME 5 OF 6

Annex 24

DHI, “Analysis and assessment of Chile’s reply to Bolivia’s counter claims on the Silala Case”, March 2019

(Original in English)

Single Product

Analysis and assessment of Chile's reply to Bolivia's counter claims on the Silala Case

Pluri-national State of Bolivia,
DIREMAR
18 March 2019

The expert in **WATER ENVIRONMENTS**

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Approved by
Oluf Zeilund Jessen Head of Project, Water Resource Department

Single Product –

Analysis and assessment of Chile’s reply to Bolivia’s counter claims on the Silala Case

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CONTENTS

1 Executive Summary

DHI has been requested by DIREMAR to provide a technical response to a subset of technical issues in of the document "International Court of Justice (Feb 2019): Dispute over the status and use of the waters of the Silala (Chile v. Bolivia). Reply of The Republic of Chile (Volumes 1-3)".

DHI has only commented on these issues. The absence of comments to other parts of the above-mentioned documents does not in any way imply that DHI agrees with them.

The structure the report is as follows:

Chapter 2: Background and structure

Chapter 3: The technical arguments and evidence in Chile's reply

Chapter 4: Assessment of the strengths and weaknesses

Chapter 5: Technical conclusions and recommendations

Under current conditions the water from the Silala Basin flows as both surface water and groundwater, however in the responses provided by Chile, there is an underlying presumption that the water resource supplying the Silala River basin is known. Groundwater is known as the "hidden" resource, which is generally more challenging to quantify. The spatial extent and volume of the groundwater aquifer discharging groundwater to the Silala springs remain unknown.

Radiometric data and estimated groundwater travel times for the inferred groundwater catchment indicate that a large part of present-day groundwater discharge at the Silala springs, was likely recharged under climatic conditions that prevailed thousands of years ago. Long-term declines in aquifer storage associated with reduced modern recharge, as is common throughout the Andes, cannot be eliminated with available data. Therefore, it cannot be claimed conclusively that the current inflows to and outflows to the aquifer supplying discharge to the Silala springs are balanced. As a result, the discharge to the Silala springs may well be decreasing with time, in which case it is a non-renewable groundwater resource.

The claim that the *"works do not have a significant impact on surface water flows"* is contradicted by the on-site field evidence, the scientific literature and by Chile's own experts.

DHI has emphasised that the impact assessment of removal of the canals is uncertain, as is also acknowledged by Chile's expert. We also agree that, under circumstances where the boundary is located close to the interventions and therefore may be affected by them, sensitivity analyses should be considered.

The validity of Chile's simplified impact calculations is questionable and therefore do not support the claim that DHI's impacts are exaggerated. The analysis is based on the one-dimensional Darcy equation, which is only valid under idealized conditions not satisfied at Silala. The groundwater aquifer is *not* homogeneous. The aquifer is both confined and unconfined. The groundwater flow is *not* one-dimensional but rather highly three-dimensional. In particular, the one-dimensional Darcy approach does not represent correctly the observed changes in groundwater gradients and therefore the flows towards the spring discharge zone and lacks reference to field data.

Chile emphasizes the importance of the highly complex and three-dimensional geology, yet they then ignore this complex geology in their simplified analysis. This is a clear inconsistency, which brings into question the validity of their assessments of the canalization impacts.

Regarding geology and the 3-D hydrogeological model developed by DHI, Chile finds no basis for incorporating a fault zone with high hydraulic conductivities. Chile claims that DHI's hydrogeological model does not account for vertical variability in permeability based on flowing conditions at a Chilean borehole. Chile also claims that DHI's model does not reflect Chile's interpretations and that differences in chemistry and isotopic compositions of groundwater are not reflected in the hydrogeological model. DHI agrees that geological and hydrogeological models involving many data sources are subject to interpretation. Nevertheless, the field data do support DHI's hydrogeological model and it is consistent with Chile's borehole information. Chile's claim that there is no basis for incorporating a fault or a highly fractured zone is not correct. Chile's statement that DHI's does not account for vertical variability is also incorrect since both the conceptual and numerical models account for both vertical anisotropy and changes in horizontal hydraulic conductivity with depth.

We do not oppose the statements made by Chile on the preference for water balance preserving groundwater models with fixed upstream boundaries and "known" recharge input. This concept was considered and rejected due to the lack of hydrogeological data in the Far Field and the inability, based on available data, to define correct catchment and aquifer boundaries. A groundwater calibration of the whole Far Field area to match the few data in the Near Field would have to be based on a lot of assumptions about the presently uncharacterised areas of the aquifer.

The technical approach employed was therefore to collect hydrogeological information within and in the vicinity of the Near Field. This allowed for the development of a numerical model that was calibrated to field characterisation data including hydraulic parameters and head distributions at various depths. The calibrated Near Field model reproduces the field data, which improves the reliability of the predictive capability of the model. In contrast, Chile has, repeatedly and strenuously, highlighted the importance of the geologic framework but then choose to ignore what they themselves consider important. Instead they chose to use a highly simplified, uncalibrated analytical solution that they agree does not capture the site hydrogeological conditions to critique model results.

A sensitivity and uncertainty analysis of the Near Field boundary conditions could be considered.

2 Introduction

2.1 Background for this report

Introduction to the contract and its objectives

On 6 June 2016, the Republic of Chile filed an application with the International Court of Justice against the Pluri-national State of Bolivia, concerning the dispute over the Status and Use of the Waters of the Silala (Chile v. Bolivia). In the framework of this legal case, Chile presented its Memorial on 3 July 2017 and Bolivia presented its Counter-memorial and Counterclaim on 31 August 2018. DHI has under a former contract for Bolivia's Strategic Office for the Maritime Claim, Silala and International Water Resources – DIREMAR carried out technical analyses and assessments of the surface water and groundwater flows in the Silala Springs System, analyses that were referenced in Bolivia's Counter Claim to Chile.

On 15 February 2019, Chile presented its response to Bolivia's counter claims1. DHI has been contracted by DIREMAR (through the product-based consultancy contract: CDP-I N° 07/2019) to make a technical assessment of the Chilean reply.

The present report describes the output of this assessment.

DHI is a technical water institution and our assessments reported in this document concerns only the technical arguments put forward in Chile's reply.

2.2 The structure of Chile's reply and this response

In this section, we introduce Chile's reply and its structure highlighting the parts we have analysed and evaluated in this report. The section also gives a short description of how our report is structured.

Chile's reply consists of three main chapters.

- Chapter 1 introduces the process and the structure of the reply. This chapter will not be commented on in this report.

- Chapter 2 presents Chile's legal arguments against Bolivia's second counter claim: "Bolivia has sovereignty over the artificial flow of Silala waters engineered, enhanced, or produced in its territory and Chile has no right to any part of that artificial flow". The arguments put forward in this chapter are of legal rather than technicalnature and DHI does not have the expertise to comment on these points.. DHI has, in previous reports, referred to a modified hydrological system affecting flow rates in surface water and groundwater. This terminology is understood to correspond to the 'artificially enhanced flows' described in Bolivia's counter claim.

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[1] International Court of Justice (Feb 2019): Dispute over the status and use of the waters of the Silala (Chile v. Bolivia). Reply of The Republic of Chile

- Chapter 3 describes Chile's comments to the technical arguments presented in Bolivia's Counter memorial and is the principal focus of this report.

  In Subsection A of Chapter 3, Chile lists the points they find the two parties agree upon. We have commented on these points in Section 3.1 below.

  In subsection B of Chapter 3, Chile explains the technical assessments and analyses to which they do not agree with Bolivia. The points made in the subsection is based on analyses and views as stated in two attached reports prepared by Chile's technical experts[2] [3](Drs. Wheater and Pearch). We analyse these points, in detail, in Section 3.2 of this report.

Furthermore, Section 4 of this report summarises Chile's arguments with our evaluation
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[2] Wheater, H.S. and Peach, D. W. (2019) Impacts of Channelization of the Silala River in Bolivia on the Hydrology of the Silala River Basin, Attachments to Reply of the Republic of Chile to ICJ on Dispute over the status and use of the waters of the Silala.

[3] Peach, D. W. and Wheater, H.S. (2019) Concerning the Geology, Hydrogeology and Hydrochemistry of the Silala River Basin, Attachments to Reply of the Republic of Chile to ICJ on Dispute over the status and use of the waters of the Silala

3 The technical arguments and evidence in Chile's reply

In this section, we comment on and discuss Chile's technical arguments regarding impacts of the canalisation on cross-border surface water flow.

3.1 Comments to Chile's assessment of the technical agreements on the hydrology of Silala

In Section A, Chile and Bolivia largely agree on the nature and functioning of Silala as an international watercourse.

In Section A[4] of the Chilean response, which is intended to summarise the points on which the Parties agree, Chile has introduced several claims to which DHI does not fully agree.

DHI can agree that water from the Silala System basin will flow from Bolivia, as surface water or groundwater. In many of the responses provided by Chile, there is an underlying presumption that the spatial extent, hydrogeologic properties and storage of this aquifer are precisely known and constant in time. The aquifer's extent, thickness, hydraulic properties and recharge rates to the aquifer are not known and thus, the volume of water stored in the aquifer supplying the Silala springs is not precisely known, (section 3.2.2, below). In addition, analyses of the groundwater residence times indicate the predominant source of groundwater discharging at the Silala springs, originated under climatic conditions that prevailed on the order of thousands of years ago. It cannot be claimed conclusively that the present-day conditions in the aquifer supply to the Silala springs are steady-state, as draining of the aquifer from periods of higher recharge and higher groundwater elevations may still be occurring.

DHI can agree "that the Silala River is a perennial flow that rises at two sets of springs in Bolivia and flows along the natural topographic gradient from Bolivia into Chile"[5] *under current conditions*. This, however, provides no evidence to the claim that "the direction of flow has been the same for thousands of years". In practice, it is likely that recharge rates, groundwater flow patterns and Silala spring discharge have varied through time in response to variations in climate that may have changed substantially at the scale of millennia.

Draining of the Silala wetlands has led to a reduction of the spatial extent of the inundated areas, not a "possible" reduction. This will result in, not "may" result in, a reduction in open water evaporation. The reduction in extent of inundated areas is also reflected in the presence of invasive grasses in soils that are now drained. Both sides can agree that evapotranspiration is a small component of the total water balance of the Silala River System.

While we agree that the influence of the wetland evaporation on the cross-border flows is minor, we do not agree with quantitative conclusions drawn by recent studies in Chile[6] because of several shortcomings in the study.

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[4] Vol 1. Section A Chile and Bolivia largely agree on the nature and functioning of the Silala River as an international watercourse

[5] Vol 1. Para 3.7

[6] Vol 1, Para 3.10

a) The study compares different wetlands with differing hydrogeologic properties, gradients and discharge relationships.

b) The study does not cover the pre-drainage period of the Bolivian Wetlands.

c) The evapotranspiration calculation is, unproven on the site, neglects evaporation from open water, that would be prevalent in an undisturbed wetland, and gives evapotranspiration values that are only 50% of (or lower) the potential or reference values, which are considered implausible for natural wetlands with a constant supply of water (i.e. not rate limited by water availability.)

The study shows changed hydrological behaviour of the drained and undrained wetlands, contradicting Chile's own claims elsewhere, section 3.2.1.

3.2 Evaluation of the technical disagreements on the Silala hydrology

Chile claims the Bolivia's contentions on the impacts of the canalization are untenable as a matter of fact. We will in this section demonstrate that although our previous assessments are inherently uncertain, the impact assessment is valid, and the "facts" presented by Chile are disputable as described in Section 3.2.2.

Chile claims in their reply that DHI's impact assessment of the 1928 Canalization in Bolivia being up to 30-40% higher cross border surface flows is unrealistic and based on an unsuitable and fundamentally flawed numerical model. Chile's argumentation consists of two parts; the conceptualisation of the Near Field model together with the water balance and the interpretation of the local hydrogeology.

In section 3.2.1, and as a first step, we present international evidence that in general artificial drainage of wetlands is known for having the impacts shown by our model in Silala and some are also detected visually in the field. So, the model calculates the right types of impacts.

In section 3.2.2, we review the Far Field analyses and implications for the water balance.

In section 3.2.3, we address the interpretations of the local hydrogeology and how this is reflected in the model.

Finally, in section 3.2.4, we address Chile's criticism of the conceptualisation of the Near Field integrated groundwater surface water model.

3.2.1 The internationally agreed impacts of artificial wetland drainage

The section summarises and references through other cases generally accepted impacts of drainage networks. These include:

- *Lowering of groundwater table*
- *Drying out the top soils*
- *Increase of superficial discharge.*

There can be no doubt that the creation of artificial drainage canals in the Silala wetlands has created a change in the hydrological regime of Silala area. These changes have resulted in enhanced drainage or discharge from the aquifer resulting from a lowering of the groundwater table within the wetland areas. In turn, this has increased the surface water flows emerging from these wetlands. The claim[7] that the "*works do not have a significant impact on surface water flows*" is contradicted in the scientific literature as described below. Furthermore, it contradicts Chile's own experts who agree that the ": Construction of drainage channels and river channelization in the 1920s will have had some effect on the flow. An increase in flow due to these works is expected" [8].

Inspection of the current drained system and the remnants of the original wetland vegetation provide direct evidence of significant impact by the artificial drainage in the Silala wetlands (CR, p135, Figure 16).

General facts on artificial drainage

There is considerable evidence that drainage has a detrimental effect on wetlands. Globally, some 50% of wetlands have been lost since the 19th century as a result of drainage (Gibbons et al, 2006).

There is also considerable direct evidence that drainage changes the hydrological regime of wetlands, which is consistent with the physics of the wetland flow processes.

Outflows from wetlands are increased by the construction of drainage ditches, channels, and canals, or the removal of natural barriers such as vegetation and by straightening streams (US EPA, 2008). Artificial drainage networks remove water more rapidly, reducing the flooded area, as well as the duration and frequency of flooding (Erwin, 2009; Blann et al., 2009). The effect of the alteration of channels and canals can be two-fold—not only do the new excavations convey more water out of the wetland, the spoils may concentrate or otherwise alter the natural drainage through the wetland (Chabreck 1988). Ditches and tile drains increase the discharge of shallow groundwater, thus lowering water tables in the vicinity of the drains (Whiteley, 1979; US EPA, 2008). This produces drier conditions within the wetland and in turn can change the land cover (vegetation and open water) (South et al., 1998; Finlaysen et al., 2005; Kadlec and Wallace, 2009) and the evapotranspiration (ET). In natural undisturbed wetlands, water tables tend to remain close to the surface and water table fluctuations

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[7] Vol 1 para 1.7

[8] Wheater, H.S. and Peach, D. W. (2019) Impacts of Channelization of the Silala River in Bolivia on the Hydrology of the Silala River Basin, Attachments to Reply of the Republic of Chile to ICJ on Dispute over the status and use of the waters of the Silala., p101.

are generally limited (Evans et al., 1999; Lapen et al., 2000, Holden and Burt 2003; Holden et al., 2011).

In drained wetlands, the groundwater table is lowered at the drains and local groundwater gradients near the drains are altered. Groundwater discharge from the wetland is enhanced resulting in a lower average groundwater table in the wetland. This is consistent with the physics of hydrological processes in wetlands and with direct field evidence in monitored wetlands, (Luscombe et al, 2016, Holden et al., 2011). Holden et al (2006) observe significantly lower overland flow in the drained catchments and throughflow was more dominant. Chile's own experts agree "that there may have been some changes to river-groundwater interactions"[9].

In summary, the discharge will be increased by artificial drainage of a wetland area and the ratio between surface water and groundwater discharges will be changed. Where surface water and groundwater are closely linked (such as in the Silala Springs system) over-exploitation of surface and/or groundwater would be expected to result in declines in the spatial extent and health of the original type of wetland and lead to changed vegetation or degradation of the original ecosystem.

The above general effects of drainage are also reflected in the on-site physical evidence in Silala including:

- efficient drainage and conveyance via Chilean made canals that dissect and disturb the Silala wetlands;
- diffuse and scattered inflows concentrated by excavations and drain collection systems;
- dried out former wetland areas;
- declines in water table elevations;
- declines in soil water content;
- decrease in the flooded area when compared to natural bofedales; and,
- the presence of invasive grasses in the drained soils

The changes in Silala are consistent with the effects of drainage described in the above-mentioned literature and reports. Changes in flow regimes and flow rates from drainage must thus be expected from general experience.

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[9] Wheater, H.S. and Peach, D. W. (2019) Impacts of Channelization of the Silala River in Bolivia on the Hydrology of the Silala River Basin, Attachments to Reply of the Republic of Chile to ICJ on Dispute over the status and use of the waters of the Silala,, p 4

3.2.2 Regarding the Far Field model and basin water balance

In this section, we discuss the problem of quantifying the water resource in the Silala Basin and why this is important. We also explain our approach to the Far Field model, its rationale and limitations.

Chile states that: "independently of any modelling efforts, all water in the Silala River basin will flow from Bolivia into Chile, whether as surface water or groundwater "(CR.3.5 a).

Although this is true in a general sense (as confirmed by terrain and groundwater gradient in the wetlands and ravines[10]), the statement raises some critically important questions:

1) What is the correct Silala catchment and its area?

2) What is the quantity and sustainability of the basin's water resources?

In wetter basins where the discharge is dominated by surface water, these questions may be determined through surface flow observations, climate data and topography. This is not the case in Silala where the springs and canals are fed principally by groundwater from a Far Field much larger than the topographical catchment [11].

With the purpose of quantifying and understanding the basin's water resources, a water balance model of the plausible Far Field (also based on topographic divides) was established. The Far Field model is a distributed water balance model with a detailed infiltration model designed to assess the recharge to groundwater. The model is integrated with a coarse and simplified groundwater model based on the very sparse hydrogeological mapping information available on the Far Field area.

The model analysis of the Far Field led to an understanding of which components of the water balance can be estimated, the reliability of these estimates and the implications for making quantitative assessments in Silala. The method adopted also provided an independent estimate of groundwater residence time.

The Far Field analysis showed:

- Due to unknown hydrogeological aspects, it was not possible to delineate correctly the spatial extent of the aquifer supplying groundwater to the Silala springs. Therefore, the basin area and boundary; the hydraulic properties and thicknesses of aquifers; as well as the transient changes in groundwater volumes and heads are all unknown.
- A first order estimate of the recharge, using a plausible hydrological (Far Field) catchment was made (i.e. aquifer boundaries are equivalent to the hydrological catchment). The resulting recharge from this area was on the lower end of the estimated cross border flows (groundwater and surface water combined).
- Available data suggests that recharge rates in the Far Field range between 21 mm/year and 374 mm/year, which if the aquifer is steady-state would result in discharge rates of 151-374 l/s. Application of available hydro-geologic data to

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[10] Bolivian Contra Memorial (BCM), DHI 2018

[11] Bolivian Contra Memorial (BCM), DHI 2018, Annex A.

estimate combined cross border groundwater and surface flow results in calculated values of at least 260-440 l/s.

- The estimated recharge may explain a large proportion of the water supply to the Silala wetland but the uncertainty in the climatic conditions, the groundwater flows in the Far Field and transboundary groundwater flows mean we do not know with precision the magnitude of the groundwater resource providing water to Silala springs.
- It is also plausible that either the contributing area may be substantially different or that other sources of water, such as non-renewable water may contribute to the Silala springs.
- The underlying assumption in the first order recharge estimate is that there is a balance between inflows and outflows. The recharge estimates are based on recent climate conditions, whereas the parts of the water emerging in Silala now was recharged under the climatic conditions prevailing thousands of years ago, which were considerably different.

In their response, Chile refers to “all the water”[12] but do not recognise that this is, in fact, an unknown quantity.

Regarding the modelling approach taken by DHI

A number of idealisations and assumptions are made as the starting point for the later conclusions by Chile that DHI’s Near Field model produces erroneous results.

We do not oppose the statements made by Chile on the preference for water balance preserving groundwater models with fixed upstream boundaries and “known” recharge input (similar to the Far Field model). This concept was considered –and rejected due to the lack of hydrogeological data in the Far Field and the inability to define the vertical and lateral boundaries of the aquifer. Development of a groundwater model of the Far Field would have required many assumptions regarding the geologic framework, hydraulic conductivity, specific yield, specific storage, effects of faults on groundwater flow patterns, and recharge rates in areas that remain completely uncharacterized.

DHI determined that the available field data (none) did not justify detailed groundwater flow modelling in the Far Field. And that attempt to do so would have to be based on several assumptions that would be difficult to verify and would be highly uncertain.

Estimates of groundwater recharge using an aquifer extent equivalent to the topographic catchment results in aquifer discharge rates that are lower than those estimated from field data. As argued above it is also plausible that either the contributing area may be substantially different or that other sources of water, such as non-renewable water may contribute to the Silala springs. This introduces considerable uncertainty into the concept that the aquifer is in an equilibrium conditions within a catchment with closed upstream boundaries.

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[12] CR Vol 1, Para 1.10, Para 3.33

If, in theory, the surface water and aquifer are accurately mapped, and the recharge rate is constant in time, then the groundwater system will reach a steady-state condition in which the total recharge is equal to the total discharge.

However, the potential exists for inter-aquifer inflows into the Silala aquifer, as evidenced by high relative groundwater ages and discharge rates that are impossible to explain based on modern recharge. This suggests that either there are exchanges of groundwater with aquifers outside the assumed groundwater basin or there are long-terms trends in the subsurface storage associated with long-term climate trends that may contribute to discharge rates to the Silala.

The vast majority of the groundwater discharging to the springs and collected in the canals is much older than the canals themselves. The groundwater flow regime is therefore not necessarily in equilibrium or steady-state conditions. Chile provides no evidence that the aquifer is in a steady-state condition (aquifer inflows equals the outflows) and their assertion that the aquifer is in a steady-state condition is not supported by available site data or mass balance calculations.

Since the impacts to be assessed stem from the canals implemented in the wetlands and ravines, the largest impacts are assumed to be found closest to the wetlands. Therefore, the approach taken was to collect hydrogeological data within and in the vicinity of the Near Field and confine the Near Field model to the area over which the available hydrogeological data may reasonably be extrapolated. The downside of this approach is that the flow through the system is less well defined due to the open boundaries.

Comments regarding DHI table of results

DHI has emphasised that the impact assessment of removal of the canals is uncertain, as also acknowledged by Chile's expert. We also agree that, under circumstances where the model boundary conditions are located close to the hydraulic stress being simulated (i.e. draining of the system by canals), the results may be sensitive to boundary effects. A sensitivity analysis would improve our understanding of these effects and provide greater certainty in the range of potential wetland impacts relative to an undisturbed state.

3.2.3 The underlying interpretation of the geology and hydro-geology

Chile argues that: "the model is built on an incorrect interpretation of the geology and hydrogeology"

More specifically they argue "DHI assume in their model a distribution of high hydraulic conductivity in the region of this assumed fault system that has no basis." Pg. 201

Chile further claims that the model "does not represent the geology correctly either stratigraphically or structurally and invokes a fault system that is both unmapped and geometrically unlikely." Pg. 201.

This is not correct. The conceptual hydrogeological model implemented in the integrated Near Field model is based on detailed on-site mapping by Bolivian geologists who have identified a highly fractured zone along the ravines the Carones and Orientales wetlands and above the latter. Sergeomin (2017) geologic mapping indicates a relatively small displacement of 5 m at the border (Figure 1). This is not visible at the scale of the conceptual hydrogeologic cross section (Figure 36, Annex F), but a small displacement can be added to an updated figure to improve the conceptual aspects of the figure.

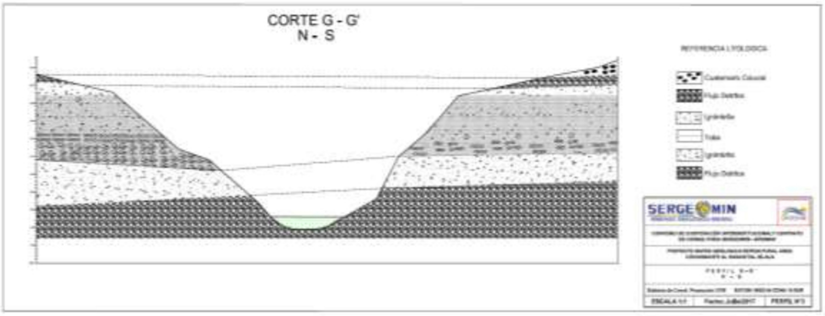

Figure 1 Geologic cross section near the Chilean border (Sergeomin, 2017)

As discussed in the report and as is routinely done in hydrogeology, the geologic units were lumped into hydrogeologic units based on hydraulic properties. The inclusion of HGU7 (Silala fault zone) as a unique hydrogeologic unit within the hydrogeologic framework model is supported by:

1. **Geologic maps** (Sergeomin, 2017) that includes a mapped fault along the main ravine near the border that splays to form the ravines that extend into the northern and southern wetland areas (Figure 1).

2. **Diamond core drilling** with highly fractured and brecciated ignimbrite in the areas near the mapped faults.

3. **Pumping test results from Bolivia** (DS-4P), located within the area of the mapped fault, that yielded hydraulic conductivity estimates between 14 m/d and 138 m/d. Late-time data results from this test which have hydraulic conductivity results that are 50% lower than early-time, suggesting decreases in hydraulic conductivity at greater lateral distances from the pumping well.

4. **Pumping test results from Chilean tests** near the border with an estimated hydraulic conductivity of 6.5 m/d.

5. Geometric mean value for **hydraulic conductivity from 19 slug tests** within the fault zone (HGU7) of about 7.5 m/d.

6. **Geophysical surveys** (COFADENA, 2017) measure low resistivity bedrock, interpreted as a zone of brecciated rock associated with faulting along the ravines and Sergeomin (2017) mapped faults.

The scientific evidence provided by points 2 – 5 above prove the existence of highly fractured ignimbrite with high hydraulic conductivity. This point cannot be credibly disputed.

The mapped fault is consistent with the observed displacement between units on either side of the ravine as shown in Figure 2 and the findings of points 2 – 6. However, DHI concedes that the precise geometry, transect and width of brecciated rock has not been perfectly determined. The width was approximated based on the geophysics and the ravine geometry, which is reasonable to capture groundwater flow patterns and fluxes through the Near Field.

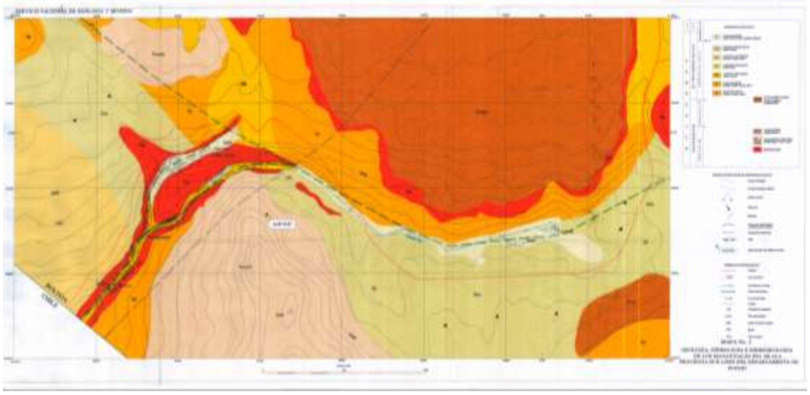

Figure 2 Geologic map of the Near Field area (Sergeomin, 2017)

Assuming (contrary to Bolivia's assessment) that these high hydraulic conductivity values should *not* be confined to a relative narrow highly fractured zone along the ravines would imply that they are representative for the ignimbrite layer as a whole. The implication of which, would be significantly greater transborder groundwater flow than estimated by DHI. Such transborder flows would be difficult to justify from the water balances using the delineated hydrological catchment as the aquifer boundaries. Higher transborder flows would require either a much larger aquifer extent, inter-aquifer flows and/or that the flow system is experiencing changes in subsurface storage associated with long-term declines in groundwater recharge.

Hence, there is strong technical basis for the hydraulic parameters used in this zone from both Chilean and Bolivian tests. To claim that its characteristics is unsupported by evidence is not accurate.

Chile further claims that the model "does not represent the geology correctly either stratigraphically or structurally…" Pg. 201

Regarding the stratigraphy, hydraulic testing has demonstrated that the hydro-stratigraphic layers of various ignimbrites have similar hydraulic conductivity values, varying over less than an order of magnitude, except when within the Silala fault zone. At the scale of the Near Field analysis and considering the objective of assessing groundwater flow patterns and flow rates, as well as groundwater - surface water interactions, the small-scale stratigraphy arguments are not relevant.

The concept of a Representative Elementary Volume (REV) is applied to capture the hydraulic behaviour of the rock mass. The REV is the smallest volume over which a measurement can be made that will yield a value representative of the whole and has to do with the well-known scale effects of hydraulic measurements in hydrogeology. Extensive hydraulic testing suggests that the ignimbrite REV is on the order of 100's of meters in the horizontal dimension or volumes greater than at least 10,000 m^3. As a result, small scale, laterally discontinuous stratigraphic features are unlikely to exert strong controls on groundwater flow patterns, or groundwater discharge relationships at the scale of the Silala Near Field analysis. The calibrated Near Field Model is evidence of this, in that it utilises an Equivalent Porous Media (EPM) approach and effectively captures the groundwater head distributions and discharges to various sectors of the Silala springs.

Chile claims that "DHI's modelling takes no account of the vertical variability of permeability, as demonstrated by the artesian flowing conditions at Chilean borehole SPW-DQN". Pg. 201.

Chile's statement is incorrect since both the conceptual and numerical models account for both vertical anisotropy and changes in horizontal hydraulic conductivity with depth. Interpretation of the hydraulic testing data led to vertical anisotropy estimates between 1:10 and 1:50 (Kv:Kh), as reported in the conceptual model. These values were initially used in the numerical model and calibrated vertical anisotropy was included for some units. Furthermore, the horizontal hydraulic conductivity decreases with depth by at least one order of magnitude.

Chile claims that "DHI, in their models, do not consider the downstream Chilean geology, including the controlling influence of the faulting or the presence of low permeability Pliocene dacitic lavas overlying the Cabana Ignimbrite and underlying the Chilean Silala Ignimbrite." Pg. 201

This may be a reasonable comment but the mandate given at the time of constructing the hydrogeological model was to stop it at the border. Although not proven with sufficient hydrogeologic data, it is plausible that both decreasing ignimbrite thickness and underlying low permeability lavas, as well as the hydrogeologic controls associated with the Cabana Fault, might serve to reduce down-gradient transmissivity of the ignimbrite aquifer.

However, the *transborder flows, groundwater flow patterns and groundwater-surface interactions in the Near Field are all calibrated to actual measurements* of:

- spring flows by spring sector;
- canal discharge measurements;
- groundwater heads; and,
- hydraulic conductivity and storage parameters.

This includes measurements made near the border with Chile. Because the calibrated values match measured values near the border and Near Field more generally, downgradient effects are implicitly incorporated in the Near Field Model. For example, examination of Figure 40 (Annex F) indicates that measured horizontal hydraulic gradients increase towards the border. This increase may be related to increases in ground surface slope or it may be associated with downgradient changes in transmissivity (as proposed by Chile), or both.

Therefore, downgradient hydrogeologic conditions that affect the border area would be reflected in the gradient boundary condition applied at the border.

Chile claims that the Bolivian stratigraphic column is incorrect based on their age dating and observed stratigraphic relationships. The principal implication of this disagreement is whether the Lavas Silala Chico and Inacaliri 1 are intruded ignimbrites or whether they intruded older dacitic and andesitic lavas. These relationships will exert controls over the spatial extent and anticipated depths of the ignimbrite aquifer.

DHI has not acted as Bolivia's geological expert on Silala and cannot comment on Chile's stratigraphic arguments. However, this discussion is not pertinent to the hydrogeological model as this narrow domain would have ignimbrite in both interpretations.

Chile states that "The thickness of these ignimbrite deposits is unknown but likely to be large, perhaps over 200 metres, but this has not been proven by drilling."

It remains true that the vertical extent of the ignimbrite aquifer remains unknown. However, if the Bolivian stratigraphic interpretation is correct it is reasonable to assume that the thickness of ignimbrites may be quite large and on the scale of the Near Field Model thickness of 400 m. If the thickness is less than assumed and the ignimbrite aquifer is underlain by lower permeability lavas, the implication of this would be smaller transborder groundwater flow. However, the hydraulic conductivity of these layers is already significantly reduced in the model (i.e. below 200 m) and the effects on simulated shallow groundwater-surface interactions would be negligible. Furthermore, analytical estimates of transborder flow are based on a very conservative ignimbrite aquifer thickness of 117 m (proven depth from drilling).

In summary, the stratigraphic discussion is not pertinent to the hydrogeological model where both interpretations coincide. As the conductivity of the model´s ignimbrite layers decreases with depth, the impact of a possible change is deemed not to be important for the canal impact assessment.

Chile finally claims that "the differences between the chemistry and isotopic compositions of Bolivia's Cajones and Orientales spring waters indicate different origins, which, though accepted by DHI in their report (BCM, Vol. 4, p.94), have not been represented in their modelling" Pg. 202

DHI acknowledges that local inflow from more local flow regime, including perched aquifers in the Cajones wetland is a possibility. However, hydrogeological characterization activities close to the wetlands have not detected perched aquifers. Furthermore, DHI clearly concluded that it is likely that there are two primary and distinct sources of groundwater discharging to the Silala springs.

However, the objective of the integrated Near Field Model is *not to* determine the source of the discharging water but the change in surface water / groundwater discharge from the wetlands due to the canalization (a near surface intervention).

Hence, it has not been the intention to represent the various sources of groundwater explicitly in the model as it would not reflect on the split between surface water and groundwater discharge from the Silala Wetlands.

3.2.4 Disputes regarding the Near Field numerical model

Chile claims that "DHI's modelling results are entirely dependent on magnifying the impact of the channels by modelling just 1% of the relevant area (the Near Field)" (3.5.c).

However, it must be recognised that the effects of canals occur primarily in the 1 % area and not the remaining 99 %. Furthermore, the information on hydrogeological characteristics in the remaining 99%, is almost non-existent, and inclusion of this large area would introduce other uncertainties as described previously. Hence, we maintain that a local scale model of the Near Field is the most appropriate and reliable method to assess the impacts of channelisation on the wetlands and local groundwater-surface water interactions.

The Near Field model was built to focus on the impact assessment of the canals with reference to available data. The Near Field model includes both a groundwater model based on field measurements and a detailed description of surface features including springs, wetland and canals. The integrated model considers the interaction between surface water and groundwater. The Near Field model boundaries are located in the area where the groundwater heads can be assessed from the borehole and spring observations.

- The model includes the entire drainage network and the springs which is the primary impact area with respect to removing canals
- Along the upstream boundaries of the model, head boundary conditions based on measured water table data were applied. While a constant gradient was applied along the model's downstream boundary (the international border).
- Applying boundaries located far from hydrogeological observations in the ungauged Far Field would also be inherently uncertain –if not speculative.

The Near Field model is, as opposed to the Far Field model, calibrated to measured groundwater heads and groundwater discharge to the various spring areas. Calibrating a Far Field model would require extensive speculation on hydrogeological properties, aquifer extent, aquifer thickness, inter-aquifer flow etc., for which we have almost no data. Instead, measured head and flow values were relied upon and the calibrated Near Field model robustly captures these measured values.

DHI's analysis has focused on impacts of the canals in an integrated hydrological context based on data collection in the Near Field. The catchment water balance remains poorly defined and may be affected by transient changes in head and storage associated with changes in long-term trends in climate over millennia.

The Near Field model and the Far field model are two separate models developed with different and distinct goals. Hence, the Near Field surface water- groundwater model is not linked to the Far Field water balance model and the Near Field model is not meant to close a larger scale catchment water balance.

We do not claim that the Near Field model includes the total groundwater flow across the border. The aquifer(s) are likely to extend into Chile in a cross section wider than the downstream model boundary and it does not include the aquifer conditions on the Chilean side of the border.

The groundwater table and flows at the near field, control the flow to the wetlands and the spring discharge. A closed water balance approach would be an idealisation that cannot be supported with respect to groundwater as groundwater flow divides cannot be delineated without more information on aquifers and water tables in the Far Field.

It is evident that groundwater inflows feed and maintain the spring and canal flows. In the Near Field model groundwater flows are closely tied to groundwater boundary conditions. DHI acknowledges that the model results, including the impacts of the drainage network, are most likely sensitive to boundary conditions. Sensitivity and uncertainty analysis have not been conducted as part of the Near Field modelling work, but such analyses could be beneficial in improving our understanding of these effects and provide greater certainty in the range of potential wetland impacts relative to an undisturbed state.

Any groundwater model is an approximation both with respect to its resolution, its process description, its parameters and its boundary conditions. This also applies to the Near Field model. The model area extent, the boundary type and the data used to describe the horizontal and vertical distribution are based on interpolation, assumptions and generalisations which introduces uncertainty. With the boundary conditions applied the hydrogeological parameters are adjusted with the objective of simulating the canal flows collecting upstream spring discharges and diffuse seepage inflows. Expanding the model area implies formulating another boundary condition approximation and covering an area for which no data exists. This does not resolve the uncertainty issue.

Chile's comments on DHI's table of model scenario results.

Chile says that the scenario comparison shows nothing.

We will maintain that it does but do also emphasise that the results are uncertain and that a sensitivity analysis should be used to quantify the uncertainty and may help to reduce it.

The major water balance components of the Near Field model runs are presented. The baseline model (with canals), the 'no canal' scenario and the 'restored wetlands scenario' have different inflows.

Chile argues that with a closed water balance and constant recharge in equilibrium with groundwater the inflow to the Near Field area should be the same in all three scenarios.

Based on field data DHI does not find basis for assuming that the recharge and inflow should necessarily be the same in all scenarios. On the contrary, feedback from removing canals on the groundwater flow changes the total inflow and rate of groundwater discharge to surface water. Only under the assumption that all upstream water must run through the Near Field Model will this be the case but this assumption is unlikely and is not verified from by the available field data. However, the same inflow in all scenarios would definitely simplify the scenario comparison and this could be further analysed through a sensitivity analysis.

While the physical aquifer and surface water system represented in the Near Field Model cannot be considered a closed system, for each of the model runs, conservation of mass, in the model itself, should apply. The Near Field model is run as a dynamic model but with steady state boundaries. Storage end error terms are negligible (0 - 5 % of the total inflow) for the model runs. Consequently, the effects predicted by the numerical model are not to any appreciable degree influenced by the numerical imbalances or errors. Adding the water balance components applying the correct sign (inflows versus outflows or losses) shows that the water balance adds up within a deviation of 3 % of inflow on the Baseline model and 1 % on the scenarios without canals. Unaccounted flow is considered well within uncertainty bounds and does not to any significant degree change the impact assessment.

DHI does not claim that the Near Field model represents a closed water balance system and flow conditions are not transferred from the coarser Far Field model to the Near Field model. That would be incorrect, given the uncertainties, especially in subsurface conditions. A head boundary is an open boundary with inflows depending on internal model groundwater heads and it does not close the flow system. With higher groundwater heads internally in the Near Field model less water enters the model domain through the fixed head boundaries as the gradient changes.

With no canals, less water enters the surface water system and more enters the groundwater inside or outside the Near Field model domain. The differences in inflow between the scenarios reflect changes in total inflow caused by changed groundwater gradients and flows. Groundwater entering the Near Field or flowing past the Near Field domain will likely flow into Chile.

DHI has emphasised that the impact assessment of removal of the canals is uncertain, as also acknowledged by Chile's expert. We also agree that under circumstances where the boundary is located close to the interventions and therefore may be affected by them. Sensitivity analyses may improve the uncertainty assessment of the impacts, and they may be reduced.

Why Chile's simplified impact calculations are not valid

When Chile claims to have proven the surface flow impacts from the canals to be small - it is simply not correct.

Differences in flow between two 1-D Darcy profiles located within the Near Field and Far Field model area are used to suggest that effects of removing canals are exaggerated. A ratio between Darcy profiles flow estimates is carried forward by Chile as a quantitative measure of overestimation by the Near Field model.

For a number of reasons this approach is not valid:

On page 51 Chile writes, "Hence, both Chile's and Bolivia's experts confirm the complex nature of the Silala River and groundwater flow systems." and yet an idealised hillslope element is considered suitable for flow calculation. This is inconsistent.

The one-dimensional Darcy equation is valid only under idealised conditions which are not satisfied at Silala:

1) The groundwater aquifer is not homogeneous.
2) The groundwater flow is not one-dimensional rather it is highly three-dimensional.
3) The aquifer is both confined and unconfined.

To calculate plausible water levels and water level gradients under the conditions in Silala, the Darcy equation has to be solved in three dimensions for a large number of elements each of which can be assumed to be homogeneous and to which realistic properties can be assigned. This cannot be done in a simplified hand calculation. This is, however, exactly what is done in the mathematical models, used by DHI.

Furthermore,

- Chile's Darcy profiles lack reference to observed field data.
- Chile has used the Far Field model for extracting groundwater table gradients in comparison to the Near Field model which is a misunderstanding and incorrect. The Far Field model, as described by DHI, is developed and used for overall water balance and recharge calculations only and it is based on very limited field data, no hydrogeological data, uncertain catchment boundaries. Since it has not been calibrated against any groundwater data, the simulated groundwater heads cannot be used for quantitative assessments and were only included in the report to illustrate possible gradient and flow directions. Consequently, the groundwater levels extracted from a figure are not a reliable measure to be used in this context.
- It is also clear that profiles could have been picked in other locations which each would have different gradients, hydraulic conductivities, flows and impacts of canals.

Comparing two single, random transects based on an overly simplified, idealised method can under no circumstances be translated, directly nor relatively, to outputs of the 3-D integrated Near Field model results.

Figure A5 (CR Vol.1. page 149), although overly simplified, illustrates the inconsistency in Chile's proposed Darcy profile approach. At the Near Field multiple layers and combined horizontal and vertical gradients and flow directions are depicted. They are not considered by a Darcy hillslope transect.

It is noted that Chile, despite the inadequacies of this approach, calculate an effect of the canals on groundwater inflow. The effect is, however, much lower than the estimates derived from DHI's Near Field model. The Darcy profile flow estimates are presented in the unit (discharge per unit width, (m3/day/m). The width along the Far Field outer boundary is much larger than the Near Field model boundary meaning that the 1-D profile results cannot be carried forward as a measure to explain the responses of a 3-D model. This important fact is left uncommented.

Highly calibrated fully integrated three-dimensional groundwater models cannot be replaced by idealised hill slope estimates, and we can for the many reasons described above not accept Chile's estimate of changes in groundwater discharge.

The integrated Near Field model is based on field data and includes both groundwater and surface water. Despite data limitations, it is the most comprehensive and calibrated tool for assessing canal impacts, and it is considered the best tool for providing technically sounds estimates to changes in groundwater discharge. As with all models, its predictions are subject to uncertainty associated with model construction and parameterisation. However, the limitations associated with the vastly simplified cross section Darcy flux calculations (as proposed by Chile) are unquestionably greater.

Additional model sensitivity analysis will improve our understanding about the range of likely impacts, as constrained by the measured field values.

3.2.5 Analysis of Chile's comparative studies of the Silala wetlands

Chile questions some conclusions of the 2018 report from the Ramsar Convention:

- *In 3.37, it is questioned: "That the groundwater system is classified as a non-renewable aquifer"*.

  We agree that such statement cannot be based solely on the high age of water detected in the springs and that DHI's assessment is that a large part of the cross-border water flow may currently be recharged under the present climate. Although our sensitivity analyses indicate an aquifer recharge rate of the same order of magnitude as surface water and groundwater discharge at the border, there nevertheless remains a discrepancy between the two values.

  In other words, it is not proven that the aquifer is in a steady-state condition. Given the long residence times, it may well be experiencing transient declines in aquifer storage associated with millennial scale climate changes.

- *In 3.39, it is questioned: "That there are only vestiges of the original wetlands that used to cover 14.1 Ha The current surface area covers only 0.6 Ha*".

  We agree that the latter area seems small, but it is not clear to us if it refers to the remaining undisturbed parts of the wetland, which as indicated by Chile's Figure 12 (from BCM, Vol 2 p. 333) is much smaller than the canalised area.

Chile, in their argumentation (3.34), seems to use the vegetated area as a measure of the wetlands not being degraded by the canalisation. The newer satellite studies[13],[14] (as also recognised by Chile) cannot be expected to capture a deterioration originating from the artificial drainage implemented around 50 years before the start of the analysis period. Both studies show a large seasonal variation in the evaporating surface of the Bolivian drained wetlands while this seasonality was not found in the undisturbed Quebrada Negra wetland in Chile. Castel correctly associated the seasonality with the fact that large parts of the drained wetlands are now dominated by invasive grasses growing on the drained soils and that this vegetation depend on the soil moisture storage after the wet winter season and dries out during summer. This indicates another biological and hydrological regime than that the original undrained wetland with ponding stagnant water all year round.

Hence, Chile's quoted satellite studies support that the drained wetlands have changed (and potentially biologically deteriorated) as a consequence of the drainage.

We cannot agree with Muños and Suarez' conclusion that" the canalisation activities in Bolivia's wetlands, has not significantly affected the area of the active wetlands in the valley floors".

On the contrary, they detect a larger evapotranspiration seasonality in the Bolivian wetlands, grasses occupy a larger proportion of the former fully saturated and flooded

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[13] Castel A. (DIREMAR 2017), CR Vol 2 Annex 98

[14] CR Vol 3 Annex XIII Muñoz and Suárez, 2019, Quebrada Negra Wetland Study

wetland. Furthermore, in the Orientales (Southern Wetland), photographs e.g. (CR, p135, Figure 16) shows signs of old dead wetland vegetation indicating a formerly more extensive wetland.

Chile's Experts conclude with reference to Muñoz and Suarez that the evaporation rates from the two Bolivian wetlands should be higher than those of the undisturbed Quebrada Negra and that the drainage should therefore not have any impact on the evaporation (CR p. 141).

We do not agree with this conclusion. The methodology leading to it is based on an evaporation formula (unproven on the site) that neglects open water evaporation, which will not be correct for the undisturbed wetland, and which gives actual evapotranspiration rates only 50% or lower than the potential ones (CR p137 Table 3). This is considered implausible for wetlands with abundant supply of water and shallow depth-to-groundwater.

In spite of our disagreements with Chile's conclusions on the wetland areas, state of degradation and evaporation rates, we do emphasise that basically the two parties agree on the influence of the wetland evaporation on the cross-border flows being minor.

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4 Assessment

The following table contains a long list of arguments from Chile.

It is divided into two parts: first a part on the points Chile states that the two parties agree upon, which has been included since we feel that this contains some statements from Chile that are open to dispute.

The second part concerns the argument that the parties (according to Chile) does not agree upon. In addition to DHI's comments, this part also includes our evaluated strengths and weaknesses in Chile's argumentation.

In both parts, the first column is a reference to the statement in the main part of CR while the second column references statement in the Experts reports. The following table summarises the key arguments presented by Chile. For each subject or item, we have highlighted if it can be viewed as an agreement or a disagreement to be contested. DHI's evaluation of items on which we disagree is evaluated shown in the right two columns.

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Reference	Expert's report page number	Chile´s response	DHI Comments
3.7		Chile and Bolivia agree that the Silala River is a perennial flow that rises at two sets of springs in Bolivia and flows along the natural topographic gradient from Bolivia into Chile	Agreed
3.7		The Parties also agree that the channelization in Bolivian territory did not alter or divert the natural direction of the flow of the water from Bolivia towards Chile	Agreed
3.7		Thus, the direction of the flow of Silala waters has been the same for thousands of years.	Perhaps, but this conclusion cannot be derived from the former two statements. Flows and rivers change in time over thousands of years and the drainage directions may well have changed in parts of the catchment. What matters is the natural and affected flow situation at present.
3.8		The Parties agree that surface water runoff contributes a very minor proportion of the average daily flow of the Silala River, which is groundwater dominated.	Correct. This is about the surface runoff from the catchment *into* the Silala wetlands. NOT to be mistaken for the trans-border surface water flow in the canal.
3.8		They also agree that the Silala stream interacts with groundwater throughout its course and that the direction of the subsurface water (as of the surface water) is westward towards and into Chile. Bolivia's expert DHI estimates that the groundwater flow is at least of the same order of magnitude as the surface flow.	Agreed.
3.9		Chile and Bolivia agree that the channelization undertaken in 1928 may have resulted in reduced direct loss of water to evaporation, due to a possible reduction of the extent of surface water in the Bolivian wetlands	Correct.

Reference	Expert's report page number	Chile´s response	DHI Comments
3.9		Both sides agree that this reduction of evaporation is a small component of the total water balance of the Silala River system.	Correct.
3.10		The conclusions as to evaporation have been reinforced by recent studies by Chile, in which estimates of evaporation from Bolivia's wetlands (with channelization) are very similar to evaporation from a similar wetland in the Silala River basin in Chile (which has no channelization). This suggests that the effects of channelization on the water balance, if any, are very limited.	Disagree. Any changes in evapotranspiration are important for documentation of changes in the wetland and for preservation of the wetland and wetland habitats. In terms of the overall water balance and water sharing the changes in evapotranspiration are small. However it cannot be concluded from this, that the effects of channelization on the water balance are limited, . Finally, *we do not agree* to the conclusions drawn from the studies. We do not agree that quantitative conclusions can be drawn from this since: A. The study compares different wetlands B. The study does not cover the pre-drainage period of The Bolivian wetlands. C. The formula used disregards open water evaporation and gives evapotranspiration values far below the potential ones, which is not to be expected for localised areas well supplied with water. The study actually shows changed hydrological behaviour of the drained and undrained wetlands
3.11		Chile's and Bolivia's experts agree that the springs in the Orientales and Cajones wetlands in Bolivia have different isotopic and chemical compositions, implying different origins and different recharge areas	Correct.

Reference	**Expert's report page number**	**Chile´s response**	**DHI Comments**
3.11		Chile's and Bolivia's experts confirm the complex nature of the Silala River and groundwater flow systems	Correct
3.12		Despite these important convergences between Chile's and Bolivia's experts, they maintain different interpretations of the geology and hydrogeology of the Silala River basin	This is not surprising given the sparse data availability. DHI's assessment of hydrogeology is based on SERGEOMIN's field surveys, and extensive drilling and testing in crucial parts of the basin
3.13		Bolivia's proposed succession and dates of (permeable) ignimbrite and lava deposits in the Silala River valley cannot be reconciled with Chile's recent geological mapping, radiometric dating results, drilling evidence and pumping test results	The layers used in Bolivia's hydrogeological model are based on Bolivia's geological field surveys on site, Chile's own geological interpretation from (CM) and extensive hydrogeological drilling and pump test results including Chilean one. Obviously new interpretations made by Chile after the model establishment is not included.
3.13		This means that the aquifer system in the ignimbrites identified in Chile has not been recognized by Bolivia	This means that the *recent* Chilean *interpretation* of the hydrogeology may be subject to dispute between the parties
3.13		Bolivia infers a massive geological fault system that would run from the Orientales wetland to the Cajones wetland in Bolivia, bending around and following the line of the Silala River into Chile, that Chile's experts consider highly implausible.	The intensively fractured zones identified in the Bolivian parts of the basin is supported by: • Intensive geological field surveys • High hydraulic conductivities by field testing both in Bolivia and in Chile • The lone existence of the ravines with distinctly different weathering and fracturing that the surroundings.
3.13		This inferred fault is not evidenced by any displacement of rocks on either side of the river valley, as would necessarily occur in a major fault	This statement is not sufficiently documented by Chile.

Reference	Expert's report page number	Chile´s response	DHI Comments
		These differences in interpretation do not affect Chile's and Bolivia's common understanding of the Silala River as an international watercourse. However, they do affect the reliability of the DHI Near Field model, which is the only source of support for Bolivia's claims for the large effects of channelization, as discussed in more detail in section B below.	Uncertainty does not mean unreliability. A second source of support is also clearly cited in DHI's analysis. The discharge measurement by Fox before canalisation compared to the current flow indicate an effect in the same order as the model. The differences also affect the reliability of Chile's interpretation.
3.5.a		Independently of any modelling efforts, all water in the Silala river basin will flow from Bolivia into Chile, whether as surface water or groundwater;	Yes. The questions are: what is the basin extent? How much water is there and when will it flow into Chile.
	RC,p101,1	The Silala River flows naturally from Bolivia to Chile. The river rises in two sets of springs in Bolivia, which maintain the Cajones and Orientales wetlands.	Agreed. However, in spite of serious efforts, the larger hydrological basin still remains poorly defined and there is uncertainty about the boundaries, parts of the assumed basin draining to other areas or other areas draining to Silala. Since the water balance (if partly fossil /or fully renewable) has still not be finally determined any increase of the discharge may be unsustainable and irreversible.
	RC, p101,2	The river is primarily fed by groundwater and interacts with groundwater along its course to the border and beyond.	Correct.
	RC, p101,3	In addition, there are substantial groundwater flows from Bolivia to Chile, likely of an equivalent magnitude to the surface water flows.	Yes, but the total cross border groundwater flow has not been quantified.
	RC, p101,4	Construction of drainage channels and river channelization in the 1920s will have had some effect on the flow. An increase in flow due to these works is expected.	This statement by Chile recognizes that the effect of drainage is an increase in flow and therefore can be neglected.
	RC, p101,4	The impact of drainage on evaporation from the wetlands is small.	Changes in ET losses should not be ignored. See previous comments for reference 3.10. 'Small' as compared to what?

Reference	Expert's report page number	Chile´s response	DHI Comments
	RC, p101,5	The Silala is an international watercourse	
	p. 102	We have shown that the model is based on incorrect geology,	The Near Field model is based on geological and hydrogeological interpretations of the best information available at the time and combines the geological mapping with facts from hydrogeological boreholes and testing. I.e. evidence from the field.
	p. 140	Bolivian estimates of a 30-40% effect on flows are implausible. Calculations show that incorrect assumptions of the model's boundary conditions lead to an overestimate of the impacts, by a factor of approximately 20. DHI has stated the large uncertainty in the results	Uncertainties in general and in the boundary conditions in particular affect the estimates. The 30-40 % range is range of the results but not indicative of the full uncertainty range. The factor referred to is derived from idealised Darcy profile approximations cannot be used for any absolute or relative measure of impact or accuracy of the Near Field model.
3.5.b		The inflow in each scenario modelled by DHI is different, causing the outflow in each scenario to be different as well, proving nothing about the impact of channelization;	The attempt to argue that a closed water balance can be adopted is not valid for the Silala catchment. Such generalised and invalid assumptions will conceal the actual uncertainties with respect to catchment delineation, groundwater flow and recharge.
3.5.c		DHI's modelling results are entirely dependent on magnifying the impact of the channels by modelling just 1% of the relevant area (the Near Field);	The effects of canals occur primarily in the 1 % area and not the remaining 99 %. Including larger areas introduces other uncertainties.
		On the wetland changes and deterioration	
3.5.c		Bolivia relies on a 2018 Report of the Ramsar Convention Secretariat and its contentions that the wetlands in Bolivia are severely deteriorated,	It seems that the areas in the Ramsar report are not reflecting the full wetland – can it be the undisturbed wetland?

Reference	Expert's report page number	Chile´s response	DHI Comments
		however this is contradicted by Bolivia's own 2017 Castel study and a Ministerial report	
	p. 102	New studies based on detailed monitoring of an undisturbed Chilean wetland within the Silala basin, coupled with high resolution remote sensing data, show that Bolivian and Chilean wetlands continue to fully occupy the valley floor, and seasonally extend up the base of adjacent hillslopes.	The satellite remote sensing studies referred to commence around 50 years after the implementation of drains, hence they do not reflect the change in wetland area due to drainage.
	p. 102	The condition of the wetland vegetation, as indicated by remote sensing, is similar in all three wetlands. Associated estimates of actual evaporation suggest that the higher evaporation rates are observed from the Cajones and Orientales wetlands, some 10% greater than that of the undisturbed Quebrada Negra wetland.	The evaporation formula used a) Neglects open water evaporation b) Results in actual evaporation around 50% of the potential values. Not to be expected in wetlands fully supplied with water. c) Local wind conditions are important
	p. 102	At least from the satellite data, it appears that there has been no significant change in evaporation associated with the channelization of the Bolivian wetlands, and hence no effect of evaporation changes on river flows.	Disagree. Impact from evapotranspiration approximately 2% of the cross-boundary flows. There are effects in the evapotranspiration shown in the satellite data. The seasonality of the plant cover is higher (factor 3) in the drained wetlands than in the undisturbed wetland (factor 1.6). Invasive grasses dominate the drained not the undisturbed wetland.

5 Technical conclusions

The groundwater discharging at the Silala Near Field (covering springs and canals) is associated with an ignimbrite aquifer of unknown spatial and vertical extent, with uncertain hydraulic properties and an unquantified volume of water in storage.

The groundwater water emerging in the Silala springs has high relative ages indicative of long residence times in the aquifer, potentially up to many millennia. As a result, changes in aquifer storage over time cannot be ruled out. By extension, this means that the inflows and outflows to the aquifer may not be equivalent and that a portion of the discharging waters may be non-renewable or fossil water.

Chile recognises that the drainage network and canals have increased surface flows but downplay their significance as ‘negligible’. The claim that the “works do not have a significant impact on surface water flows” is contradicted by the on-site field evidence, the scientific literature and by Chile’s own experts. The exact magnitude of impacts remains an unresolved issue, but it is clearly greater than the 1.2% Chile purports.

DHI acknowledges that the Near Field Model lateral boundaries are close to the interventions and therefore may be affected by them. Sensitivity analyses could be considered to address these uncertainties.

The validity of Chile’s simplified impact calculations is questionable and therefore does not support the claim that DHI’s impacts are exaggerated. The analysis is based on the one-dimensional Darcy equation, which is valid only under idealised conditions not satisfied at Silala. The groundwater aquifer is not homogeneous but heterogeneous and anisotropic, as suggested by Chile in other sections of the response. Groundwater flow is not one-dimensional but highly three-dimensional and the aquifer is both confined and unconfined. The one-dimensional Darcy approach, in particular, fails to account for the three-dimensional groundwater flow pattern towards the Silala springs and the change in groundwater gradients towards the discharge zone.

Regarding the geology and the three-dimensional hydrogeological framework model developed by DHI, Chile finds no basis for incorporating a fault zone and further claims that the model does not account for vertical anisotropy. This is not correct. Chile claims DHI’s hydrogeological framework model does not reflect Chile’s latest geological interpretations. However, these are generally distant from the area of interest of the model and unlikely to affect the hydraulic properties at the REV[15] scale or model results regarding groundwater discharge to the springs and canals or transborder flows.

DHI’s conceptual model proposes that groundwater discharging to the Southern and Northern wetlands have differing residence times, general chemistry and isotopic compositions associated with different flow paths within the aquifer. Both

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[15] Representative Elementary Volume, the smallest volume of a porous media over which a measurement can be made that will yield a value representative of the whole

a shorter more local flow path and a longer, more regional flow path were conceptualised. Chile's interpretation is largely similar, with the exception that they conclude the shorter flow path is associated with a perched aquifer system that has not been encountered in the Bolivian territory.

Chile's assertion that the numerical model does not include the two differing sources of water, stems from the assertion that both the local and regional flow regimes are conceptualised to have origins outside of the Near Field. Furthermore, the intent of the Near Field model was to simulate effects associated with canalization and Chile's modifications to the natural system – not the origin of the spring waters.

We do not oppose the statements made by Chile on the preference for water balance preserving groundwater models with fixed upstream boundaries and "known" recharge input. This concept was considered and rejected due to the lack of hydrogeological data in the Far Field and the inability, based on available data, to define correct catchment and aquifer boundaries. A groundwater calibration of the whole Far Field area to match the few data in the Near Field would have to be based on a large number of assumptions about the presently uncharacterised areas of the aquifer.

The approach taken was therefore to collect hydrogeological information within and in the vicinity of the Near Field and confine the Near Field model to the area where hydrogeological information is available. The downside of this approach is that the model area does not include groundwater in the full width of the aquifer and the inflow to the system is not fixed but a function of the boundary condition.

6 References

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Annex 25

DHI, “Updating of the mathematical hydrological model scenarios of the Silala spring waters with: Sensitivity analysis of the model boundaries”, April 2019

(Original in English)

Single Product

Updating of the mathematical hydrological model scenarios of the Silala spring waters with:

Sensitivity analysis of the model boundaries

Pluri-national State of Bolivia, DIREMAR
April 26, 2019

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Management System Certification
BUREAU VERITAS
Certification Denmark A/S

Approved by

Oluf Zeilund Jessen
Head of Project, Water Resources Department

Single Product

Updating of the mathematical hydrological model scenarios of the Silala Spring waters with:

Sensitivity analysis of the model boundaries

Prepared for	Pluri-national State of Bolivia, DIREMAR
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1 Executive Summary

This report documents the sensitivity analyses of the boundary conditions of the numerical integrated surface water – groundwater model of the Silala Springs focusing on the impacts of the model boundaries on the model results.

Due to the absence of surveyed hydrogeological data further away from the wetlands and the specific purpose of assessing canal impacts, the model is confined to an area quite close to the Silala springs. Observed groundwater levels have been used as boundary conditions to the model. It has been found, however, that the model boundaries are affected by the changes introduced by the removal of the canals and that the chosen boundary conditions will therefore also have a bearing on the produced results for a situation in which the canals have been removed. When considering the baseline model and the 'no canal"/"Undisturbed" scenario results, the sensitivity and uncertainty should therefore be taken into account.

This project has produced sensitivity analyses of the model boundaries focusing on their impacts on the distribution between groundwater and surface water in a situation without the canals. Through a number of boundary condition sensitivity simulations, the study has identified ranges of canal impact, which are measured by changes in surface water and groundwater flows relative to the present canalised conditions.

The analyses have been carried out as two separate parts.

- A sensitivity analysis of the upstream boundaries and
- An analysis of the sensitivity of the results to changes in the downstream outflow boundary along the border to Chile.

Regarding the upstream boundaries, our approach has been to frame the possible range of model results between two sets of assumptions – each considered to represent either the lower or the upper bound of the flow changes, relative to the present baseline situation, assuming that the canals are dismantled and wetlands are restored.

Assuming that no changes will occur on the boundary will lead to the largest impacts on the surface water flows and, hence, such analysis will represent the upper bound. This corresponds to the simulations already reported in the original study (DHI, 2018).

To assess the boundary conditions that would represent the smallest impact of removing the canals (the lower bound), it is assumed that the discharge through the Near Field without the canals will be the same as with the canals.

The downstream model boundary controls the flow across the border and affects the ratio between surface water and groundwater flow. This boundary assumes a fixed groundwater gradient (a fixed slope of the groundwater heads) The sensitivity of model results to this boundary was analysed by varying the gradient with +/- 20% of the calibrated value of 0.05.

Findings

The sensitivity analysis of the upstream boundary conditions resulted in the following ranges of the transborder flow in the scenario without the canals:

- For the boundary sensitivity cases tested the simulated range of decrease in transborder surface flow when removing the canals is 11% - 33 %.
- The groundwater flow will increase between 4% and 10% of the modelled groundwater flow in the present situation.
- The evapotranspiration from the wetlands is much better defined and will increase between 28% and 24% of the baseline values or between 3 and 3.4 l/s.

The values do not add up to zero as only one of the analysed boundary conditions assume the same amount of flow through the Near Field with and without the canals while the other assumes that a part of the original flow bypasses the Near Field in the surrounding groundwater layers.

The sensitivity range of assessed surface water flow crossing the border in the “No canal” scenario is quite large and it is not possible to quantify the most likely surface water flow value within this interval from this analysis.

However, the only field observations of the pre canal situation (Fox, 1922) is 131 l/s or 18% lower than the 160 l/s measured at the de-siltation tank (the assumed same location) during 2017. A reduction of 18% is quite close to the centre of the sensitivity range.

The downstream gradient does influence the ratio of groundwater versus surface water out flow.

In the “No canal” situation, applying a 20% higher head gradient along the lower boundary increases the groundwater fraction across the border at the expense of the surface water fraction. More specifically, it results in 7% less overland flow and 8% more groundwater flow across the border. Evapotranspiration is almost unchanged (decreasing less than 1 percent). Application of a 20% lower downstream gradient has the opposite effects.

While the flow through the model increases with the downstream gradient, both in the present baseline situation (with the canals) and in the situation without the canals, the impact from the gradient on the model inflow in these two situations is small (less than 1 percent).

2 Introduction

2.1 Background for this report

Introduction to the contract and its objectives

On 6 June 2016, the Republic of Chile filed an application with the International Court of Justice against the Pluri-national State of Bolivia, concerning the dispute over the status and use of the waters of the Silala (Chile v. Bolivia). In the framework of this legal case, Chile presented its Memorial on 3 July 2017 and Bolivia presented its Counter-memorial and Counterclaim on 31 August 2018. Under a former contract for Bolivia's Strategic Office for the Maritime Claim, Silala and International Water Resources – DIREMAR, DHI carried out technical analyses and assessments of the surface water and groundwater flows in the Silala Springs System with and without the implemented drainage canals, analyses that were referenced in Bolivia's Counter Claim to Chile.

On 15 February 2019, Chile presented its response to Bolivia's counter claims[1]. in which Chile questions the findings of DHI, particularly the boundary conditions of DHI's numerical model used for the assessment of the possible hydrological impacts of the drainage canals implemented in the wetlands early last century. DHI supports the need for a sensitivity analysis considering that the database for the modelling is quite sparse.

DHI has been contracted by DIREMAR (through the product-based consultancy contract: CDP-I N° 16/2019) to carry out a sensitivity analysis of how these boundaries affects the assessed hydrological impacts of the canalisation.

2.2 Scope of this study

According to the Terms of Reference, the scope of the study is:

a) Sensitivity analysis of the established Near Field model boundary condition's influence on the modelled canal impacts, with the aim of strengthening the impact assessments made in 2018

b) Description of the analyses made and their rationale

c) Discussion of the results

2.3 About the content of this report

The overall contents of the report are given in the contract and the report therefore follows the structure given.

This report is to be seen as an extension to the former modelling reports by DHI (DHI, 2018) which, in its annexes, includes detailed descriptions of the applied modelling

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[1] International Court of Justice (Feb 2019): Dispute over the status and use of the waters of the Silala (Chile v. Bolivia). Reply of The Republic of Chile.

approach, its calibration and its results). To make it easier to read, the introductions to the applied models are repeated in section 3 of this report as follows:

- Section 3.1 describes the hydrogeological conceptual model.

- Section 3.2 introduces the configuration and components of the integrated model.

Section 4 describes and discusses the model boundary conditions.

Section 5 describes and discusses the scenarios previously analysed

Section 6 describes the approach to the sensitivity analyses carried out and

Section 7 describes the results and conclusions of these analyses.

Summary and conclusions are included as section 8.

2.4 The overall hydrology of Silala Springs

This sub-section gives a brief introduction of the hydrology of Silala Springs System. Please refer to (DHI 2018) for more detailed information.

The Silala Springs are located at altitudes from 4300 to 4400 m above sea level in the arid Western part of the Potosi Department of Bolivia, a few kilometres from the border with Chile (see Figure 2-1).

The Silala Springs System is fed by groundwater from sources further inside Bolivia and constitutes the only flowing surface water resource on the Bolivian side of the border within a distance of 20 kilometres.

Today, the Silala Springs System in Bolivia is a modified flow system in which a fine network of pipes and stone-lined canals drains the Silala wetlands and conveys the water efficiently from the large number of individual springs in the Northern and Southern wetlands in Bolivia to a water intake on the Chilean side of the international border around 4 km downstream (see Figure 2-2).

Figure 2-1 Location of the Silala Springs System

Contributions from superficial catchment runoff are small in comparison to the stationary or slowly varying groundwater inflow to the wetlands which is in the order of 160-210 l/s.

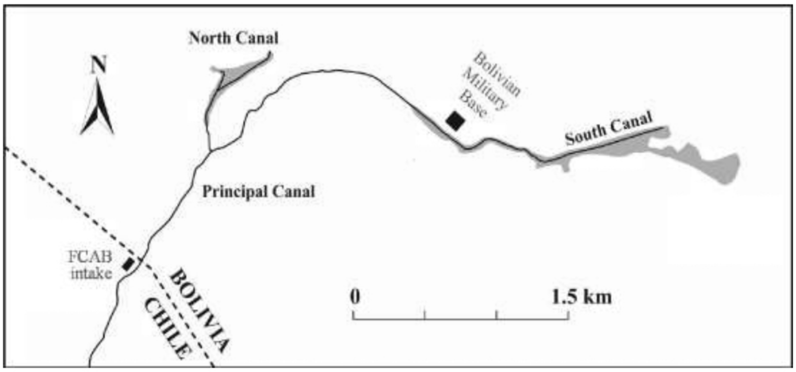

Figure 2-2 Approximate extent of the Silala Near Field. (Mulligan & Eckstein, 2011)

Figure 2-3 Approximate extents of the Silala Far Field (the groundwater catchments likely to contribute to Silala Springs System)

Silala has a desert climate with low precipitation, low temperatures but high potential evaporation. Outside the wetlands, the vegetation is very sparse and top soils are coarse and sandy, originating from weathered or glacier-eroded lava and ignimbrite formations.

The base rock formation consists of ignimbrite layers with a general inclination towards the West and the valley in which the Silala springs, wetlands and canals coincides with major faults in the ignimbrites (SERGEOMIN, 2001).

The ignimbrites are porous and fractured and have been found to have significant hydraulic conductivities. In some areas, the ignimbrites are found directly under the top soils, while in other parts of the area, they are superimposed by layers of lavas which have been deposited during later eruptions.

The potential groundwater heads observed in the piezometer wells, established by DIREMAR during 2017 in the area around the Silala springs, indicate a groundwater flow from higher Eastern grounds towards the Silala Springs and further on towards the international border.

Although the spatial extent and volume of the groundwater aquifer discharging groundwater to the Silala springs remain unknown (as indicated in Figure 2-3), both the observed groundwater levels (sloping towards the Chilean border) and the high hydraulic conductivities of the aquifer show that water from the Silala River basin will flow from Bolivia as surface water or groundwater (DIREMAR's Hydrogeological field survey program, 2017, Figure 2-4).

It is noted that the terrain gradients are very small along the road to Laguna Colorada crossing the upper parts of the Far Field. It is therefore likely that the underlying groundwater head gradients along the road are also small, and that modest changes in the groundwater heads along the road might influence the location of the groundwater divide towards the Laguna Colorada Basin, potentially affecting the flow to that basin. It is however not deemed likely that the back water impacts from removal of the canal should travel so far upstream.

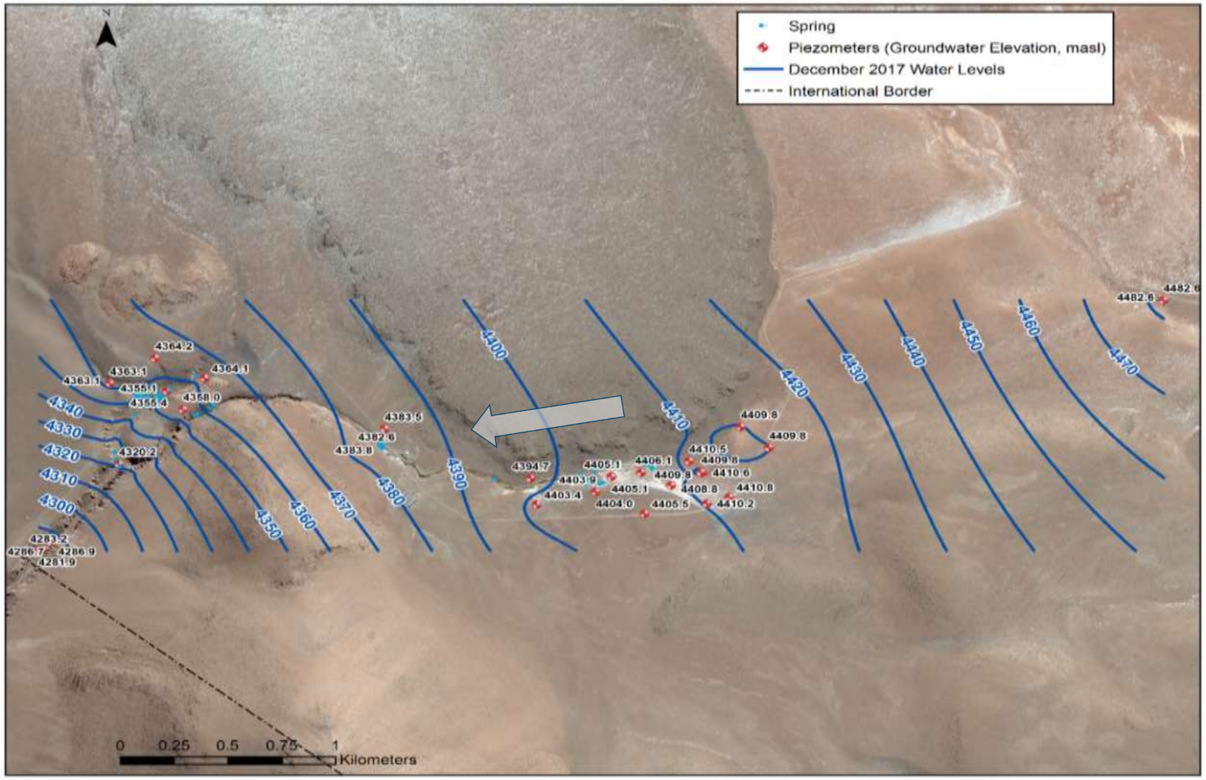

Figure 2-4 Borehole locations and groundwater level contours in the Silala Near field, interpolated form Piezometer wells spring elevations and wetland excavations for soil sampling. N.B. the contouring away from the wetlands and the boreholes are uncertain (DHI, 2018)

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3 The modelling approach and the applied models

The section describes the components and configuration of the applied model

3.1 The conceptual hydrogeological model

A conceptual hydrogeological model has been used to establish the integrated numerical model and ensures that the latter corresponds reasonably well to the hydrogeological conditions observed in the field. For more detailed information on the conceptual hydrogeological model, please refer to (DHI, 2018)

The conceptual hydrogeological model was established by combining the surface geological mapping with topographies and the extensive hydrogeological borehole program (launched by DIREMAR during 2017).

The data from hydrogeological characterisation program (the borehole data, the hydrogeological borehole test results, and electro resistivity transects) has been combined with previous Bolivian data (surface geological mapping, water quality and surface water flow rates) along with Chilean borehole data and pumping test results (Arcadis 2017). The combined data has been used to develop a Hydrogeological Model (HCM) of the Silala Near Field and, to a lesser extent, the Silala Far Field areas.

The conclusions of the combined data analyses regarding the conceptual groundwater flow system of the Silala Near Field include:

- Groundwater discharge is the principal source of water to the Silala Spring System. Dominant sources of groundwater to the springs are:
  - Northeast trending structures including several large faults. These fault zones are brecciated and have elevated hydraulic conductivity relative to the surrounding materials and are interpreted to be transmitting groundwater over large distances (i.e. Silala Far Field or beyond).
  - A network of small apertures, Northwest trending fractures act as conduits transmitting groundwater along strike.
- Pumping tests completed in the Southern Wetland indicate a transmissive ignimbrite aquifer with large-scale hydraulic conductivity estimated to be about 18 m/d and locally higher conductivity within the Silala Fault Zone (up to 54 m/d). These are higher than the 6.5 m/d estimated from the pumping tests in Chile near the border;
- Hydraulic test data indicates that:
  - Fractures in the ignimbrites are well connected over a large scale and appear to control the flow characteristics of the aquifer.
  - The aquifers approximate a porous media.
- Groundwater head measurements indicate that groundwater is discharging to the Southern and Northern wetlands (gaining) but much

further downstream the groundwater may be hydraulically disconnected from the Silala Canal at the Chilean-Bolivian border (disconnected losing stream);

- The hydrochemistry and age of the groundwater discharging into the Northern wetlands is significantly different from that of the Southern wetland. Water in the Southern wetland was found to be considerably older than water in the Northern wetland. Isotope analyses indicate the apparent average age to be up to 1,000 years in the Northern and 11,000 years in the Southern wetland, respectively. Although such analyses may over-estimate the real water age (DHI, 2018, Annex F), the age of the spring water is indeed very old. A likely interpretation of the difference in water chemistry and age is that this older water is derived from flow within the Silala Fault Zone from a sub-regional to regional flow regime (i.e. the Silala Far Field), while the younger water in the Northern wetland is more likely to be derived from localised flow closer to the Silala Near Field.

It is found that water from the Silala River basin will flow from Bolivia, as surface water or groundwater. However, the spatial extent and volume of the groundwater aquifer discharging groundwater to the Silala Springs remain unknown.

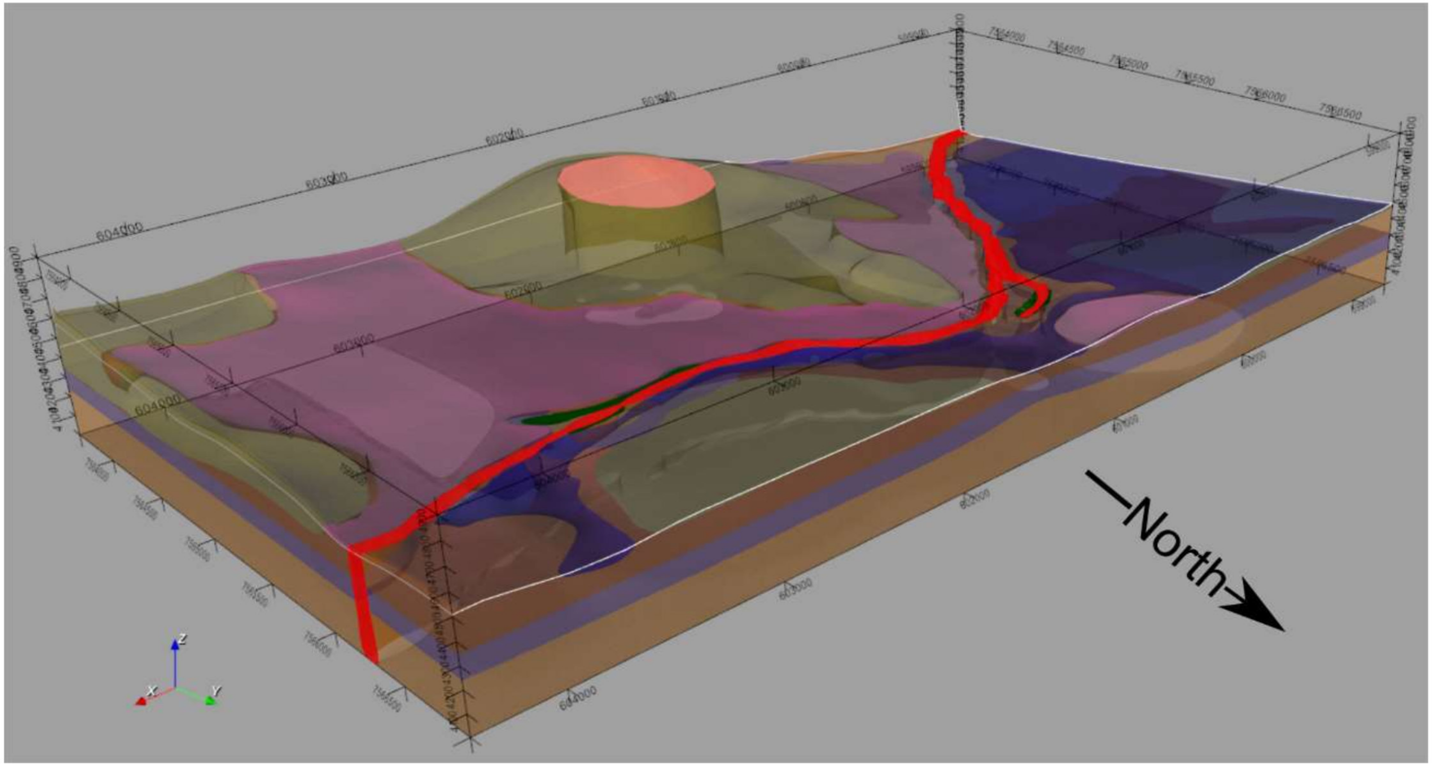

Figure 3-1 Hydrogeologic Framework Model rendered in 3D. The Silala Fault (HGU7) is highlighted in red. Remaining units are displayed with transparency for easier viewing of modelled subsurface

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3.2 Components and configuration of the applied numerical model

The section describes the modelling approach taken, why it was chosen along with the strengths and weaknesses and alternatives. Furthermore, it contains a brief description of the implementation of the field data and the hydrogeological conceptual model into the numerical integrated model and introduction to the calibration of the model and the results on the baseline simulation of the present situation. The descriptions are included here to comply with the Terms of Reference and ease the reading. For more details please refer to the original modelling reports ((DHI, 2018)*, Annex F, G and H).*

3.2.1 Modelling approach

Although we acknowledge the preference for closed water balance groundwater models with fixed upstream boundaries and “known” recharge input, we rejected the approach due to the lack of hydrogeological data in the Far Field, uncertainty in climate data and recharge rates and the inability based on available data, to accurately define catchment and aquifer boundaries. A groundwater calibration of the whole Far Field area to match the few data in the Near Field would inevitably be based on a lot of assumptions about the presently un-characterised areas of the aquifer.

The technical approach employed was therefore to collect hydrogeological information within and in the vicinity of the Near Field. This allowed for the development of a numerical model that was calibrated to an extensive field characterisation database including hydraulic parameters and head distributions at various depths.

We do also acknowledge that the downside of the chosen approach is that the model boundaries may affect the model results. The present report aims at quantifying model sensitivities in this respect.

To cope with all the important hydrological processes playing a role in the Silala wetlands, a proven integrated physically based hydrological modelling system (MIKE SHE) has been applied.

3.2.2 Implementation of the conceptual models

The total model area of the Silala Near Field is 2.7 km2 and the main elements of the model were established in accordance with the conceptual models described in the previous sections.

All canals are represented in a hydrodynamic one-dimensional model in terms of cross sections and levels as surveyed in the field. Canal modifications as observed in the field have been included.

Flow and water ponding on terrain are described in the two-dimensional overland flow component in a 10 m by 10 m grid of the whole Near Field. The terrain levels of the overland flow model have been interpolated from the detailed drone survey of the area.

The unsaturated zone model calculates the evapotranspiration from the wetlands and all upland areas and have been established using standard parameters for the soil types found in the wetlands during the soil survey. This model uses the same grid resolution as the overland flow model.

The 3-D hydrogeological conceptual model (described in Section 3.1) is implemented in the numerical groundwater model. The hydrogeological units and their spatial extents defined in the hydrogeological conceptual model are represented. The numerical groundwater model applies three layers. The top layer has varying thickness and hydrogeological properties as it incorporates all surficial deposits. The second layer includes the upper Silala ignimbrite and the third layer represents the deep ignimbrite layer. The fault line defined from the surface to a depth of 400 m cuts across the layers and introduces a high permeable flow zone along the canals. The same horizontal grid resolution of 10 m by 10 m as in the above models is used.

The input data to the model are data in terms of precipitation, potential evaporation and temperature. The boundary conditions for the groundwater model are based on ground water levels (as determined by the field observations) and assigned along the upper groundwater boundaries controlling inflow and a constant groundwater gradient along the downstream boundary controlling outflow.

3.2.3 Model calibration and performance

Model parameters have been adjusted iteratively in a calibration process to demonstrate that the model qualitatively describes the Silala Near Field hydrology in accordance with conceptual understanding and that the model results produced quantitatively match the measured values, in particular the canal flows at the gauging sites.

It has been found that the overall results of the integrated model reproduce the important characteristics from the 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 feeding surface water by discharges to the springs, canal and drainage network
- Upstream gaining canal reaches versus the downstream neutral or loosing 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 shows that:

- 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. The width of the downstream model boundary is 450 m (with the ravine in the centre). For comparison, the rough hand calculation in (DHI, 2018) Annex F assessed 230 l/s (or more), but over a much larger cross section and using less information.
- 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.

In summary:

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 this cannot be confirmed by measurements and is therefore more uncertain than surface water flows. However, the model results confirm a coupled groundwater – surface water system within the Silala Near Field area. This coupled system extends across the border.

The calibrated model is in reasonable agreement with the current conditions and therefore a sound basis for estimating the impacts of the canals.

4 The boundary conditions in the Near Field groundwater model

This section describes the various types of boundary conditions applied in the Near Field model, their characteristics strengths and weaknesses. It also describes the observed groundwater conditions in the area.

4.1 Fixed head boundaries (along upper inflow boundaries)

In order to compute the groundwater flow and water level conditions at the outer model boundaries, boundary conditions must be assigned. Different types of groundwater boundary conditions are available and they are all approximations based on assumptions on the prevailing flow or water table condition. The Silala Near Field area receives groundwater inflows from a larger catchment along parts of the model boundaries. A prescribed head boundary is used along those sections of the boundary where groundwater flows from outside the model area enter the Silala Near Field 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 will propagate to the boundary decreasing the flow gradients and the inflow.

This fact complicates the comparison of scenarios. In (Chile R. , 2019), there were questions about the boundaries of the model changing its inflow in the modelled scenario.

The changes in inflow between scenarios is an indication of the boundaries being affected by the intervention. In the next section, we analyse the sensitivity of the main model results to variations in the groundwater heads along the model boundaries.

4.2 Closed boundaries (where groundwater flows parallel with the boundary)

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). Model report reference ((DHI, 2018) Annex G).

4.3 Fixed groundwater table gradient (along the lower model outflow boundary)

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 (m/m) 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.

4.4 The observed groundwater levels in the Silala Springs

Water level data available for the Silala Near Field area includes 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 (Figure 2-4). 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 has been used as direct input for describing both the initial groundwater head map for the integrated model simulation and the boundary groundwater head values at the model boundaries of all groundwater layers (Figure 4-1). 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,

In the model, 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.

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.

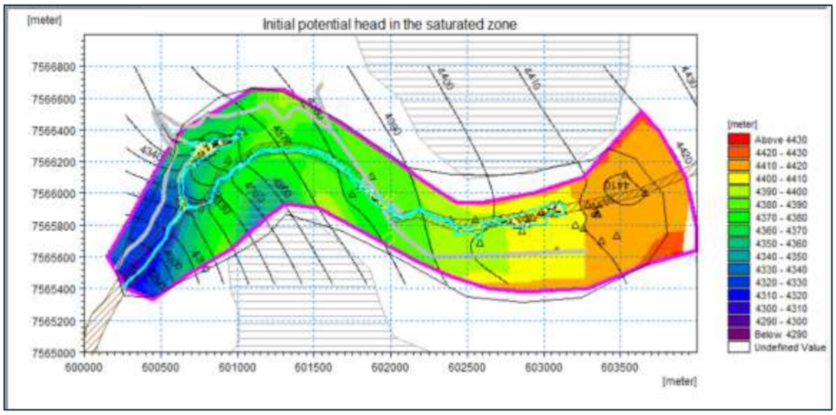

Figure 4-1 Groundwater level maps used in definition of groundwater component boundary conditions

Figure 4-2 below illustrates groundwater tables, cross sectional flow and discharge from an upstream head boundary towards a downstream surface water body.

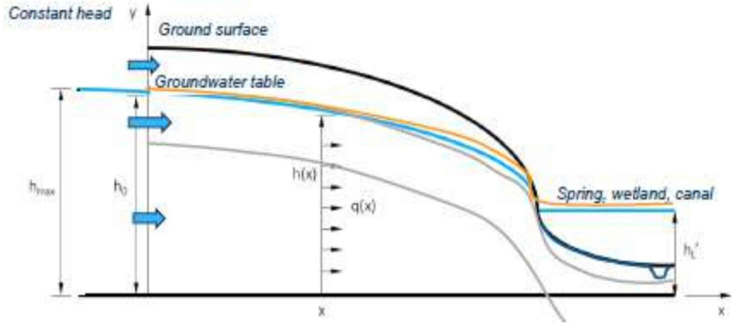

Figure 4-2 Illustration of groundwater boundary condition

5 The scenarios previously analysed

In this section, we describe the scenarios investigated in the previous assessment (DHI, 2018) *and the main findings.*

To address the main objective of this project, the following baseline and scenario models have been run as follows:

1) **Baseline model**. Represents the (2018) Silala Near Field area with the canal and drainage network as it is today. The surface water canal model includes both reaches which are more or less unchanged compared to the original canal construction but also reaches where the canal has been removed or blocked. The baseline scenario is used as a reference to estimate the magnitude of changes.
2) **No canal scenario**. The entire canal and drainage network included in the baseline model is removed. As a result, the surface flows are no longer concentrated in narrow defined channels but can appear and flow across the entire surface area and the direction of flow is largely controlled by the surface topographical slope.
3) **Wetland restoration (undisturbed) scenario**. By removing the canal and drainage network, the basis is created for restoration of the degraded wetlands and riparian corridors. The scenario considers the effects of long-term peat accumulation in wetlands. The scenario was in our former analyses (DHI, 2018) referred to as the "Undisturbed" wetland scenario. We have in this report maintained this title to avoid confusion although "wetland restoration" might be a more appropriate title.

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.

1. The simulated surface water flow at the downstream model boundary (located at the Bolivian-Chilean border) *reduces* by 31-40 % relative to the present situation.
2. The simulated groundwater flow at the downstream model boundary (located at the Bolivian-Chilean border*) increases* by 7-11 % relative to the present canalized situation
3. The total model boundary inflow at the upstream model boundary decreases by 10-15 %.
4. The evapotranspiration increases by 20-30 % by removing the canals and restoring wetlands. This increase amounts to 2-3 l/s in the situation without the canals and is included in the cross-border flow changes mentioned under point 1 and 2
5. For the confluence to border section, a maximum of 25 % of surface water may be lost to subsurface flows. Infiltration loss in this section is included in the cross-border flow changes mentioned under point 1 and 2.
6. All of the scenario results and local model analysis suggest that both surface water flow and groundwater flow cross the border.

The flow impact percentages describe the model results ranges but not the uncertainty on model results. Model predictive uncertainty depends on a number of factors and uncertainty sources, e.g. limitations in input data, model structure, 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.

6 The approach to the sensitivity analyses of the boundary conditions

The differences in model inflow in the above scenarios (Section 7) indicate that model boundaries are affected by the analysed interventions (the removal of the canals). This section describes the approach to the sensitivity analyses aiming at quantifying this effect. Both the upstream and the downstream boundaries influence the results and are analysed separately. The approach taken to the upstream boundaries is to describe the upper and lower limits of the possible flow variations.

6.1 The extent of the Near Field model

Due to the absence of surveyed hydrogeological data further away from the wetlands, the model is confined to an area quite close to the Silala Springs (The Near Field) where the observed groundwater levels have been used as boundary conditions to the model. The rationale of this modelling approach was further described in section 3.2.1 above.

It has been found, however, that the model boundaries are affected by the changes introduced by the removal of the canals and that the choice of boundary conditions will therefore also have a bearing on the produced results for a situation in which the canals have been removed.

When considering the baseline model and the ‘no canal’ scenario results, the sensitivity and uncertainty should be taken into account. This sensitivity analysis is specifically looking at the model boundary sensitivity and does not represent a full model sensitivity or uncertainty analysis. The reason for focusing on the groundwater boundary conditions is that the Silala springs and surface water system are fed entirely by groundwater from a large poorly delineated upstream catchment. The Near Field model include the springs, wetlands and canal features and extends to the Bolivian-Chilean border. It does, however, not represent a closed water balance unit but uses head dependent groundwater inflow boundaries in a restricted area which introduces a potential sensitivity with respect to key model results.

The existing channels provide a network that drain the groundwater and conveys this water rapidly away from the Silala springs. By removing the channels, the groundwater is drained less efficiently, the resistance to flow emerging on the surface is increased and the groundwater levels will increase.

With higher groundwater levels, closer to the surface the evapotranspiration will increase.

The increase in groundwater level within Silala Springs will propagate both upstream and downstream of Silala (although the increase will reduce with distance from the springs). The increased groundwater levels upstream of Silala can reduce groundwater flow into the wetlands, in which case a fraction of the ground water will flow around the model area and the groundwater inflow to the model will then be reduced. Likewise the raised heads inside the model area will lead to higher cross border groundwater discharge and also higher heads on the Chilean side of the border.

6.2 Fixed u/s head boundary (the upper limit to the flow changes)

The flow in surface water and groundwater is linked to the boundary inflow which again depends on the water level differences at the outer groundwater model boundary

Application of a fixed upstream (u/s) head boundary is a good and an appropriate approach for the baseline (present) situation. The groundwater heads can be assessed from borehole observations representing the de-facto conditions in the field.

The Near Field area does not represent a closed catchment unit and the groundwater flow towards Chile extends beyond and also partly bypasses the Near Field area. With extra resistance to overland flow in the Near Field area, the fraction of the total Silala discharge going to superficial flow is expected to decrease and the rest (except the increased loss to evapotranspiration) will discharge as groundwater through the Near Field or the adjacent aquifer sections (assuming the ground water is in balance[2]).

Since the boundary heads are fixed, the gradients near the boundaries will decrease and lead to smaller total flow through the model in the “No canal” and the “Undisturbed wetland” scenarios as compared to the present baseline. Therefore, the *change* in surface discharge as derived from the scenario are considered to represent the upper limit to the flow changes.

6.3 Unchanged u/s flux boundary (the lower limit to the flow changes)

In the scenario, using a fixed upstream flux boundary, we will force the same groundwater flow into the nearfield model area as in the present situation.

If the groundwater drainage capacity is reached, the water levels (heads) will rise above terrain level and create surface flow. This excess flow, that cannot be drained through groundwater, will run off superficially from the wetlands and the ravines as is also observed in other undisturbed bofedales.

The fixed flux boundary condition will exaggerate the total flow through the Near Field since increased heads along the boundary will – in reality – divert part of the groundwater flow around the model area through adjacent aquifer areas.

Hence, results with a fixed flux boundary are likely to give too small changes in the surface flow components and the real situation lies somewhere between the two extremes (a fixed flux boundary representing the smallest changes and a fixed head boundary representing the largest changes).

Since the results originally reported were generated using a head boundary, a sensitivity analysis is made by varying the heads along the boundary.

The groundwater flux into the calibrated baseline model (through the observed fixed head boundaries) have been extracted and introduced in as a fixed flux boundary in the “No canal” and “Undisturbed” scenario, respectively. A simulation of the scenario with this boundary condition produces corresponding groundwater heads along the model

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[2] It has not been proven that the groundwater system is in balance (that recharge to the aquifers matches the outflow), It has been demonstrated , however that the recharge from a plausible groundwater catchment cover a large part of the assessed combined groundwater and surface water discharge trough the Near Field, (DHI, 2018).

boundaries. The differences between these scenario heads and the fixed heads from the simulation have been used to assess the sensitivity of the scenario to the boundary conditions.

6.3.1 The sensitivity runs

Several fractions (0, 0.25, 0.50, 0.75 and 1.0) of the head differences between the baseline and the scenario with unchanged inflow to the model have been added to the original baseline boundary and used to simulate the boundaries influence on the results. Of these simulations, the 0- fraction represent the unchanged original head boundary (head approximation) while the 1.0- fraction represent scenario where the inflow to the model is kept constant (flux approximation).

6.4 The central estimate

The range of surface water flow crossing the international border without the canals (as assessed by this sensitivity analysis) is wide. However, it is not possible from this analysis to determine a ‘best estimate’ within this range.

The best assessment of the canal impact is still considered to the field observations of the pre-canal situation by (Fox, 1922) of 131 l/s or 18% lower than the 160 l/s measured at the de-siltation tank during 2017.

6.5 The influence of the downstream flux boundary.

The removal of the canals may redistribute the groundwater levels in the Near Field with a tendency of having higher groundwater heads and potentially large contribution of overland flow in the downstream part of the model close to the downstream boundary. Therefore, it is also relevant to analyse how the downstream boundary affects the model.

The calibrated baseline scenario uses a fixed groundwater gradient of 0.05 m/m which is close to the overall gradient calculated from borehole observations to the overall slope of the terrain. Local differences in groundwater gradients may, however, easily occur and the sensitivity of the results to smaller changes in this gradient (+/- 20%) has been investigated.

7 The results of the sensitivity analyses

The results described here concern the sensitivity to the model boundary conditions of the “No Canal” and “Undisturbed” scenarios as considered in the original modelling report (DHI, 2018).

7.1 Fixed head boundary - the upper bound of the impact range.

The sensitivity analysis has resulted in a range of possible changes in which the upper bound (the result leading to the largest flow changes from the baseline simulation) is considered to correspond to the changes originally simulated and reported in (DHI, 2018).

The simulated changes in the main flow components as percentages of the baseline flows are listed in Table 7-1 while the specific changes in l/s are included in Table 7-2.

It is noted that in this upper bound impact case, the transborder surface flow is assessed to be around 33% lower than the simulated flows of the baseline with the canals. This corresponds to a drop-in surface water flows in the order of 50 l/s in the “Undisturbed” scenario.

Groundwater flow *through the model* is assessed to increase by 10% and evapotranspiration by 34% (3.4 l/s) – also in the “Undisturbed” scenario.

7.2 Fixed flux into the model – the lower bound of the impact range.

The constant flux boundary is considered to represent a lower bound for the magnitude of the flow changes in the “No canal” and “Undisturbed” scenarios, as compared to the baseline with the canals. We consider this a lower bound case since higher heads along the upper boundaries of the model area will inevitably generate higher flows by-passing the model area, in turn, reducing the head increases along the boundary and boundary flows into the Silala system. A quantification of this by-pass groundwater flow is however difficult due to the lack of hydrogeological characteristics of the ignimbrite aquifer further away from the Silala ravine.

The simulated changes in the main flow components as percentages of the baseline flows are listed in Table 7-1, while the specific changes in l/s are included in Table 7-2.

It is noted that, in this lower bound case, the transborder surface flow is assessed to be around 11% lower than the simulated baseline flows (with the canals). This corresponds to a drop-in surface water flows in the order of 16 l/s.

Groundwater flow *through the model* is assessed to increase by 4% and evapotranspiration by 28% (2.8 l/s, only).

The range in assessed surface transborder flow in the “No canal” and “Undisturbed” scenarios is quite large and it is not possible from this analysis to determine where in this range the most likely superficial flow value will be.

However, the field observations of the pre canal situation by (Fox, 1922) 131 l/s or 18% lower than the 160 l/s measured at the de-siltation tank (the assumed same location) during 2017.

Table 7-1 Results of the outer bounds of the sensitivity analyses of the upper head boundary conditions in % of the flow components in the baseline simulation with the canals[3]

	Canalised situation (l/s)	Change from canalised conditions (% of baseline)	
	Baseline	Lower Bound	Upper Bound
Inflow to model	253.6	0	-11
Surface outflow	149.0	-11	-33
Groundwater outflow	106.3	4	10
Evapotranspiration	10.0	28	34
Storage and num. inacuracy	-11.7		

Table 7-2 Results of the outer bounds of the sensitivity analyses of the upper head boundary conditions as changes in l/s from the flow components in the baseline simulation with the canals

	Canalised situation (l/s)	Changes from canalised conditions (l/s)	
	Baseline	Lower Bound	Upper Bound
Inflow to model	253.6	-1	-27.9
Surface outflow	149.0	-16	-48.6
Groundwater outflow	106.3	4	10.8
Evapotranspiration	10.0	3	3.4
Storage and num. inacuracy	-11.7	8.4	6.6

7.3 The assessed sensitivity range and the pre-canalisation flow observations

The sensitivity simulation results in a rather wide range of possible surface water flow decreases (11% - 33% of the present canal flows) if the canals are removed. It is not possible to identify a central estimate of the surface water changes through the sensitivity analysis.

It is noteworthy though, that the only field observation of the non-canalised flow situation in Silala (Fox, 1922) falls close to the middle of the sensitivity impact range. Fox measured 131l/s (constantly flowing) at a location which from his description must be pretty close to the present de-siltation chamber. This corresponds to 18% of the canalised flow (160 l/s) measured at this site during 2017.

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[3] Note: The "Balance" (4% of the inflow) in the baseline situation cover smaller storage changes and smaller numerical inaccuracies in the hydrodynamic model of the canal flows. The "balance" is not valid for the percent wise changes, which are calculated from different flow components.

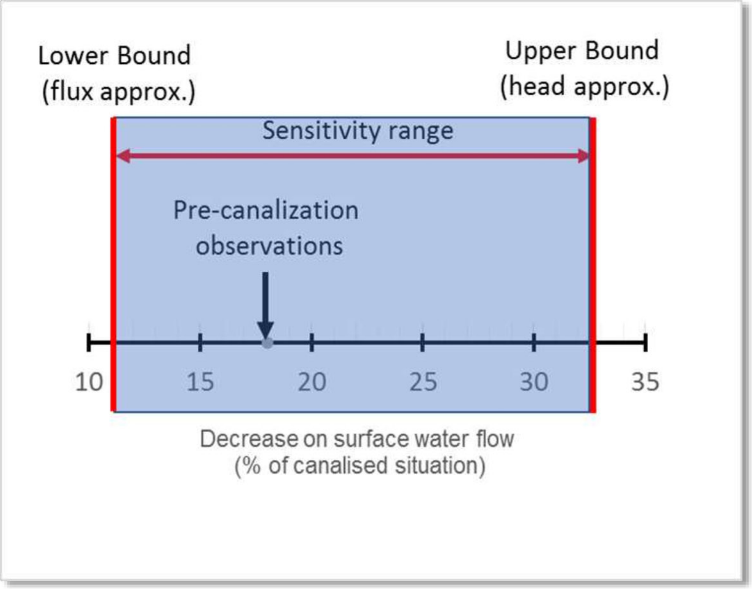

Figure 7-1 Principle sketch of the range of changes in surface water as generated in the sensitivity analysis of the upstream head boundaries.

7.4 Sensitivity to the downstream boundary condition

At the downstream end of the model, a fixed gradient boundary was used. The downstream gradient has an impact on groundwater at the boundary and therefore on the groundwater heads upstream of the boundary. Hence, the gradient influences the fractions of the total transborder flow that will pass as groundwater and as surface water, respectively.

If groundwater heads rise above ground, it will create surface flows.

The sensitivity of model results to this boundary was analysed by varying the gradient with +/- 20% of the calibrated value of 0.05.

The results that are shown in Table 7-3 shows *small impacts* from this gradient on the *total inflow to the model and on the evapotranspiration* while the *fractions of groundwater and surface water outflows are more affected* around +/- 7% and +/- 8% of the values in the baseline simulation with the canals.

It is also noted that the two “No canal” and the “Undisturbed” scenarios respond almost identically to these changes in downstream boundary conditions.

Table 7-3 Results of the sensitivity analyses of the downstream groundwater gradient.

Downstream boundary	Gradient 0.04 (-20%)	Gradient 0.06 (+20%)	Gradient 0.04 (-20%)	Gradient 0.06 (+20%)
Scenario	No canal situation	No canal situation	Undisturbed situation	Undisturbed situation
Unit	% change from org. scenario	% change from org. scenario	% change from org. scenario	% change from org. scenario
Inflow to model	-0.8	0.8	-0.8	0.8
Superficial outflow	7.0	-7.1	7.4	-7.2
Groundwater outflow	-8.2	7.9	-8.0	7.8
Evapotranspiration	-0.1	-0.8	0.3	-0.2

8 Summary and conclusions

8.1 Background

A numerical integrated surface water – groundwater model has been established for the Near Field of the Silala springs and successfully calibrated against observations of surface water flows along the canals and groundwater levels in the area.

The model parameters and configuration are based on a three-dimensional hydrogeological conceptual model, which combine the information collected through an intensive hydrogeological field survey program executed by DIREMAR during 2017 with geo resistivity measurements and detailed surface geological mapping of the Silala area.

Hence, the existing model represents the present conditions of the Near Field of the Silala springs according to the conceptual model. Furthermore, the Near Field model and the parameters are based on the measured parameters from the field and it is considered applicable for simulating the hydrological conditions in a situation without the implemented canalisation works.

Due to the absence of surveyed hydrogeological data further away from the wetlands, the model is confined to an area quite close to the Silala springs where the observed groundwater levels have been used as boundary conditions to the model. It has been found, however, that the model boundaries are affected by the changes introduced by the removal of the canals. The model results are thus sensitive to the boundary conditions.

When considering the baseline model and the 'no canal' scenario results, the sensitivity and uncertainty should be taken into account. This sensitivity analysis is specifically looking at the model boundary sensitivity and does not represent a full model sensitivity or uncertainty analysis. The reason for focusing on the groundwater boundary conditions is that the Silala springs and surface water system are fed entirely by groundwater from a large poorly delineated upstream catchment. The Near Field model include the springs, wetlands and canal features and extends to the Bolivian-Chilean border. It does, however, not represent a closed water balance unit but uses head dependent groundwater inflow boundaries in a restricted area which introduces a potential sensitivity with respect to key model results.

This project has produced a sensitivity analyses of the model boundaries focusing on their bearing on groundwater and surface water in a situation without the canals. Through a number of boundary condition sensitivity simulations, the study has identified ranges of canal impact, which are measured by changes in surface water and groundwater flows relative to the present canalised conditions.

8.2 The approach to the sensitivity analyses

The analyses are carried out as two separate parts.

- A sensitivity analysis of the upstream boundaries and
- An analysis of the sensitivity of the results to changes in the downstream outflow boundary along the border to Chile.

Upstream Boundaries

A groundwater model covering a substantially larger area Than the Near Field could have been useful to estimate of how far away from the Silala wetlands the groundwater heads will be significantly affected by the canal removal. Due to the data and time constraints of this project, it has not been possible to establish and properly calibrate such a model.

Instead, our approach has been to frame the possible range of model results between two sets of assumptions – each considered to represent either the lower or the upper bound of the changes relative to the present baseline situation.

Using fixed upstream groundwater heads between the baseline and the scenarios will lead to the largest flow impacts, hence, it will represent the upper bound. This is the simulation already reported in the original study.

To assess the boundary conditions that would represent smallest impact of removing the canals compared to the present baseline conditions, the following approach is used:

- It is assumed that the discharge through the Near Field without the canals will be the same as without the canals.
- This situation can be obtained by introducing a head increase along the boundary that will maintain the same distribution of ground water fluxes into the model as in the baseline scenario

Downstream Boundary

In the downstream end of the model, fixed gradient boundary was used. The downstream boundary has an impact on the groundwater levels upstream of the boundary and therefore, on the fractions of the total transborder flow that will pass as groundwater and as surface water. The sensitivity of model results to this boundary was analysed by varying the gradient with +/- 20% of the calibrated value of 0.05.

8.3 Results of the sensitivity of the upstream boundary

The sensitivity analysis of the upstream boundary conditions resulted in the following ranges of the transborder flow in the scenario without the canals:

- For the boundary sensitivity cases tested, the simulated range of decrease in transborder surface flow when removing the canals is 11% - 33 %.
- The groundwater flow through the modelled area will increase between 4% and 10 % of the corresponding flow in the present situation
- The evapotranspiration from the wetlands is much better defined and will increase between 28% and 34 % of the baseline values or between 2.8 and 3.4 l/s.

The values do not add up to zero as only one of the analysed boundary conditions assume the same amount of flow through the Near Field with and without the canals, while the other assumes that a part of the original flow bypasses the Near Field in the surrounding groundwater layers.

The range in the assessed surface water flow crossing the border in the scenarios is quite large and it is not possible to quantify the most likely surface water flow value within this interval from this analysis.

The field observations of the pre canal situation made by (Fox, 1922) of 131 l/s or 18% lower than the 160 l/s measured during 2017 (DHI, 2018) is located close to the centre of the range and is regarded to be a valid measure of the impact from dismantling the canals

8.4 Results of the sensitivity analysis of the Downstream Boundary

The groundwater flow across the downstream model boundary located at the Bolivian-Chilean border depends on the hydrogeological model, the hydrogeological unit properties, the water table gradient, the width of groundwater flow section and the downstream hydrogeological conditions in Chile. The boundary is described by a water table gradient and the sensitivity to variations in the gradient is tested.

The downstream gradient does influence the ratio of groundwater versus surface water outflow in the no canal situation. Applying a 20% higher head gradient along the lower boundary increases the groundwater fraction across the border at the expense of the surface water fraction. More specifically, it results in 7 % less overland flow and 8% more groundwater flow across the border. Evapotranspiration is almost unchanged (falling with less than 1 percent).

Application of a 20% lower downstream gradient has the opposite effects.

While the flow through the model increases with the downstream gradient, both in the present baseline situation (with the canals) and in the situation without the canals, the impact from the gradient on the model inflow in these two situations is small (less than 1 percent).

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Annex 26

FUNDECO, “Study of the Water Requirements of the Silala Wetlands”, April 2019

(English Translation)

STUDY OF THE WATER REQUIREMENTS OF THE SILALA WETLANDS

[TRANSLATION]

By:
FUND-ECO - FOUNDATION FOR THE DEVELOPMENT OF ECOLOGY

La Paz – APRIL 2019

EXECUTIVE SUMMARY

The Silala bofedals are unique RAMSAR sites, located in an arid region of the Bolivian south-west, near the border with Chile, and constitute insular ecosystems that are naturally vulnerable to fragmentation. The canalization installed at the beginning of the 20th century severely affected their structure and, therefore, their ecosystem functions. The objective of the present study was to evaluate the water requirements of bofedals for their conservation in original conditions before their intervention. To achieve this, the work comprised three stages: 1) Bofedal characterization (abiotic and biotic aspects); 2) Analysis of the relationship between water variables with the plant community and macroinvertebrates; and 3) Bofedals water demand estimation.

Our results show that bofedals are in a high state of degradation: we have confirmed the loss of peat depth, with current values of 0.1-1.5 m in the North Bofedal and 0.25-0.8 m in the South Bofedal, compared to 4.4 m depth average in the Quebrada Negra wetland. Degradation is particularly greater in the South Bofedal with bare soil cover, salt crust, dead vegetation that exceeds 50% and an area covered by cushions of less than 10%; however, bofedals, in order to be considered in a conserved state, must have a cushion plant cover of more than the 40%. Currently, the [vegetation] cover is dominated by species that are indications of disturbance (*Carex cf. maritima, Puccinella frigida* and different grasses) and that are explained by the depth of the water table. The canalization works also affected macroinvertebrate fauna, having found taxa representative of bofedales (Dorylaimus, Hydrozetes, Homochaeta) in less than five sites of the North bofedal, while in affected places the macrofauna is more typical of environments with high flow rates (Andesiops peruvians, Austrelmis and Hydroptilidae), due to the high water speed resulting from the canalization works.

As a RAMSAR site, the bofedals should be part of the national strategy for a restoration plan that responds to international, bilateral and national commitments; in consequence, the main objective of this work was to estimate the water requirements of this ecosystem. Thus, we use three criteria to estimate bofedal water requirements: 1) the calculation of evapotranspiration; 2) the calculation of the volume of water necessary to saturate them; and the 3) estimation of the minimum “ecological” flow as per Chilean legislation which has several ecological limitations, but is useful to estimate the initial flow values needed to recover the Silala bofedals. 1) The potential evapotranspiration of a bofedal under suitable conditions varies between 1523-1653 mm/year, which equates to a flow of 5.9 l/s on an annual average for a potential area of 11.79 ha. 2) The volume of water currently retained in the peat of the Silala bofedals is 48.4 thousand m^3, considering the potential area (11.79 ha) this value reaches 353.8 thousand m^3 and considering the peat depth of the Quebrada Negra Ravine will reach 443, a thousand m^3. 3) The minimum ecological flow calculated according to Chilean legislation, corresponds to 33.4 l/s annual average.

All these calculations are estimations of the water necessary to restore the bofedals to the potential conditions of their state of conservation and extension, ensuring adequate hydraulic conditions for the development of peat, vegetation and other ecosystem functions. The minimum flow value calculated should only be taken as an initial reference as it will most likely increase, considering that the bofedals are found in an arid region; thus, it is advisable to carry out continuous monitoring of the water table, vegetation and macroinvertebrates, to observe their behavior over time.

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“STUDY ON THE WATER REQUIREMENTS OF THE SILALA WETLANDS”

1. INTRODUCTION

The maintenance of a natural flow in aquatic environments is important for the life cycle of aquatic and terrestrial organisms that benefit from the ecosystem services that these environments provide (Lamouroux and Capra 2002). Attaining knowledge on the water requirement of an aquatic ecosystem helps establishing bases to determine: 1) its state in relation to the characteristics of its environment and, once the characteristics of the aquatic environment have been established, that is, a continuous record of hydraulic parameters and a continuous monitoring of the bio-indicator fauna and flora, 2) tools can be built to objectively determine the use and utilization of water in the ecosystem. This water requirement is called *ecological flow.*

The concept of ecological flow has changed over time. In the 70s, it evolved from a proposal of a simple system of minimum flow with a fixed numerical value based on hydrological data (daily and monthly average flows) to holistic approaches designed to evaluate the process requirements of an entire undisturbed river system (Arthington et al., 2004). The ecological flow is defined as the water regime of a fluvial system necessary to maintain the ecosystems and their benefits, in a condition close to the pristine condition and that could eventually be assigned for activities that require the use of water from a river system, through environmental, social and economic evaluation processes (Dyson et al., 2003).

The methods developed to determine the ecological flow are based on qualitative and quantitative indirect criteria of the functioning of the water body. These indicators are necessary to estimate variations of the status or value by a range of flow and, in some cases, by different hydrological periods. Taking into account these criteria and the associated methods will allow the development of strategies to which the ecosystem is expected to reach adequately (Pouilly et al., 2014).

Within the application of the ecological flow, it is contemplated that the ecosystem to be used has enough natural characteristics to be able to maintain itself in terms of conservation. In other words, when the ecosystem suffers some type of intervention (natural or external), the holistic method of ecological flow cannot be applied. In this case, it is better to carry out restoration and purification programs for the intervention before trying to use the water resource, taking into consideration an alternative to use hydrological method of ecological flow, as a first approach to the concept of Dyson et al. (2003), also given the conditions of intervention of the system

According to the RAMSAR convention, wetlands require an adequate quantity and quality of water to maintain their ecological characteristics and provide ecosystem water-related services and benefits to human beings (Barchiesi, et. al, 2018). In this connection, the Ramsar Wetland Convention recognizes that water, wetlands and people are intrinsically connected and that all wetlands have water requirements that are fundamental to regulate their water cycle. Specifically, High Andean wetlands, within the Ramsar Convention, are recognized as vulnerable, highly fragile ecosystems in which a flora and fauna characteristic of these environments are recognized, reason why they should be considered within the national strategy (RAMSAR 2005).

In the case of Bolivia, the South Lipez Bofedals are recognized as Ramsar sites since 27 June 1990 with an area of 1,427,712 ha (RAMSAR N. 0489). The conservation of our wetlands is of high relevance since Bolivia is recognized for having the largest wetland area, for this reason the Ministry of Environment and Water (2017) has established the: Strategy for the integral management of wetlands and RAMSAR sites, promoting management principles, strategic guidelines and strategic alliances for their conservation.

Depending on their nature and hydrogeological, physical, chemical and biological characteristics, wetlands have different water requirements. For example, it is known that bofedals require a high phreatic level to maintain their functions of moisture retention, peat storage and flow regulation (Cooper et al., 2015). In high Andean bofedals dominated by Distichia muscoides (Cordillera Real and Occidental of Bolivia) a positive relationship was found between leaf elevation and the mean phreatic level of bofedals. In fact, a site with a phreatic level depth of nearly constant 100-cm for a year seems to have disconnected the plants from their groundwater source, causing the surrounding plant-life to wither.

In altered systems, the water regime varies in the time scale of hours, days, seasons and years, controlling the ecology (its diversity and functioning). Therefore, the following aspects must be taken into account for the water/flow regime: the minimum and maximum flow, the occurrence-frequency of each flow, the duration, the period with the specific flow, the regularity – predictability and the rate/velocity of change. All these aspects produce alterations and therefore the degradation of the ecosystem (Poff et al. 1997).

1.1. Optimal bofedal conditions

The natural characteristics of a stable bofedal are generally: peat depth, which is formed in anoxic situations in cold environments, where the decomposition of plants does not exceed production (Aerts et al., 2001). Bofedals are ecosystems with vegetation that has a high organic matter content and, particular, peat that relies on water. Peat has the capacity to retain water for longer times, functioning as a sponge and ensuring the availability of water for plants—especially during the dry season.

In the central zone of the Andes (between Bolivia and Peru), preserved bofedals are formed mainly by plants that form cushions of the juncaceae family (*Distichia muscoides* and *Oxychloe andina*) on which other species are develop (Ruthsatz 2012, Salvador et al. 2014). These cushion plants retain their withered leaves, are the basis for peat formation and best retain water compared to other species (Lorini 2013, Benavides et al. 2015). Bofedal vegetation is directly related to land and aquatic fauna, forming the fauna community structure. Fauna inhabits, consumes and establishes its biological cycle as a function of the resources that surround the bofedal.

The aquatic fauna that lives in the bofedal waterbodies is directly related to vegetation, since the water dilutes what is stored in the riverbanks. For example, the diversity of macroinvertebrates depends on the physical-chemical characteristics of the water and microhabitat structures. These conditions will be modeled on basis of the water characteristics, the soil and the type of vegetation where the bofedal develops. According to the study by Oyague and Maldonado-Fonkén (2015), some of the most important parameters for the development of macroinvertebrate communities in the bofedal waterbodies are vegetation cover, aquatic vegetation and water level. The availability of water and, in particular, its depth level, is a key element in determining the composition and abundance of macroinvertebrates in the community, because these characteristics give way to different types of microhabitats for the colonization of these organisms. Conversely, although bofedal vegetation requires permanent water, the maintenance of the phreatic level is not necessarily related to water depth (Oyague and Maldonado-Fonkén 2015). It is for this reason that both the vegetation and the macroinvertebrate community should be considered as bio-indicators to study the status of a bofedal.

1.2. Water requirement of the vegetation

Plant productivity is determined by the amount of water available in the soil. Thus, to estimate how much water a plant needs to grow (produce new biomass), it is necessary to have information on its water requirement (Medrano et al., 2007). For instance, in a crop field, this relationship is estimated through accumulated biomass (g/ha) and water used (m^3/h). If this comparison is made for a single species, it is possible to determine the water availability regimes as a function of the water to be used.

A plant's biomass production is the result of photosynthetic activity and water expenditure (transpiration). This process involves the absorption of water from the soil through the roots, the conduction of the water to leaves, the entry of water into stomata wall, and water evaporation from stomata into the surrounding air (Dingman 2002). The more open the stomata, the higher the entry of CO_2 necessary to produce photosynthesis (which is essential to produce biomass), but, at the same time, the greater the loss by transpiration. This water spent in the form of transpiration depends on the plant type and environmental conditions.

Biomass production depends on the efficiency of transpiration. Therefore, to understand the efficiency of the use of water, it is necessary to comprehend the physiological processes that exist in the water flow of plants. Consideration must be given to the availability of water in the soil (precipitation, groundwater, etc.), root type, plant surface, and climate conditions. Currently, there is various literature on the indexes that indicate the efficiency of water used by a certain species; nevertheless, this type of studies was focused on cultivated species of global importance.

Under the agronomic-hydrological perspective, water requirement can be understood as the potential evapotranspiration (PET), that is, the amount of water that evaporates from the soil and vegetation under optimal conditions, without limitations to the availability of water (phreatic level, flow speed, etc.). The PET in wetlands can be calculated using different methodologies such as: Renewal of the surface (Paw and Brunet 1991), LIDAR (Eichinger et al., 2000) both of which require the use of specialized equipment. Empirical formulas such as Blaney and Criddle, Priestley and Taylor (1972) and others have been determined in environments other than bofedales and their applicability is questionable unless a calibration is performed (Drexler et al., 2004). Another formula that has been successfully tested in wetlands is the Penman-Montheith equation (Drexler et al., 2004). Despite having some limitations such as not knowing all the parameters accurately (vegetation stomatal conductivity, leaf area index), this is the most rigorous approach to evapotranspiration from the physics of the process (Dingman 2002). The calculation of the PET requires the data of the leaf index (Leaf Area Index), the stomatal conductivity (Federer et al., 1996), and the climatic conditions of the area.

2. OBJECTIVES OF THE STUDY

General objective

To evaluate the water requirements of the Silala bofedals on basis of a characterization and conceptualization of their hydrological and ecological functioning, and the estimation of the water quantity and hydraulic convictions necessary for their preservation in an ideal state.

Specific objectives

- To determine characteristics of the Silala Bofedals, taking into account the studies carried out by DIREMAR;

- To deduce the alterations and impacts that the Silala wetlands have endured, taking into account the studies carried out by DIREMAR to date;

- The establish the relationships between the hydrological and ecological variables (vegetation and macroinvertebrates) of the Silala wetlands, identifying the most important variables for their conservation;

- To estimate the water demand required by the Silala bofedals in Bolivian territory.

3. METHODOLOGY

3.1. Area studied

The Silala is located in Canton Quetena, in South Lipez municipality, within the Potosi Department, between the 4,200 and 5,400 meters above sea level. Geographically, the area studied is found at a mean south latitude of 22° 0' and a mean west longitude of 68°0'. The North Bofedal, with a surface area of 20,373 m^2 and the South Bofedal, with a surface area of 90,503 m^2 are both found within this area (Figure 1). These bofedals constitute an important RAMSAR site and are part of the "Eduardo Abaroa Andean Fauna National Reserve."

The climate of the region is predominantly arid, characteristic of high mountain desert areas. Throughout the year, it presents a high thermal amplitude, with minimal temperatures of -19°C and maximum temperatures of 21°C, from day to nighttime, respectively, and an annual average of 1.6ºC.

The lowest temperatures are recorded between May to August and the highest ones from December to March (Figure 2). Precipitation is unimodal, with a marked rainy season from December to March and an annual average of 125 mm/year. According to the Koppen climate classification, the area's climate falls within the category of cold high mountain climates (Montes de Oca, 1997).

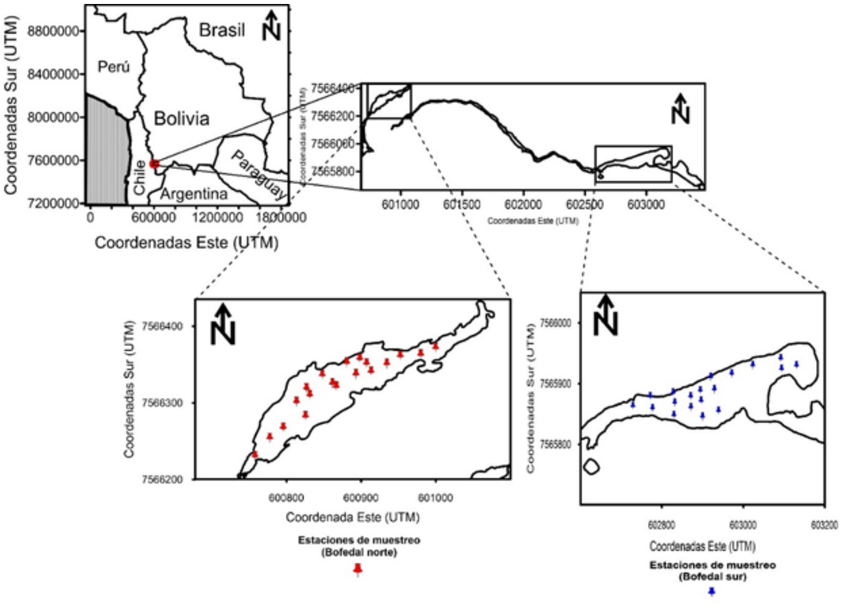
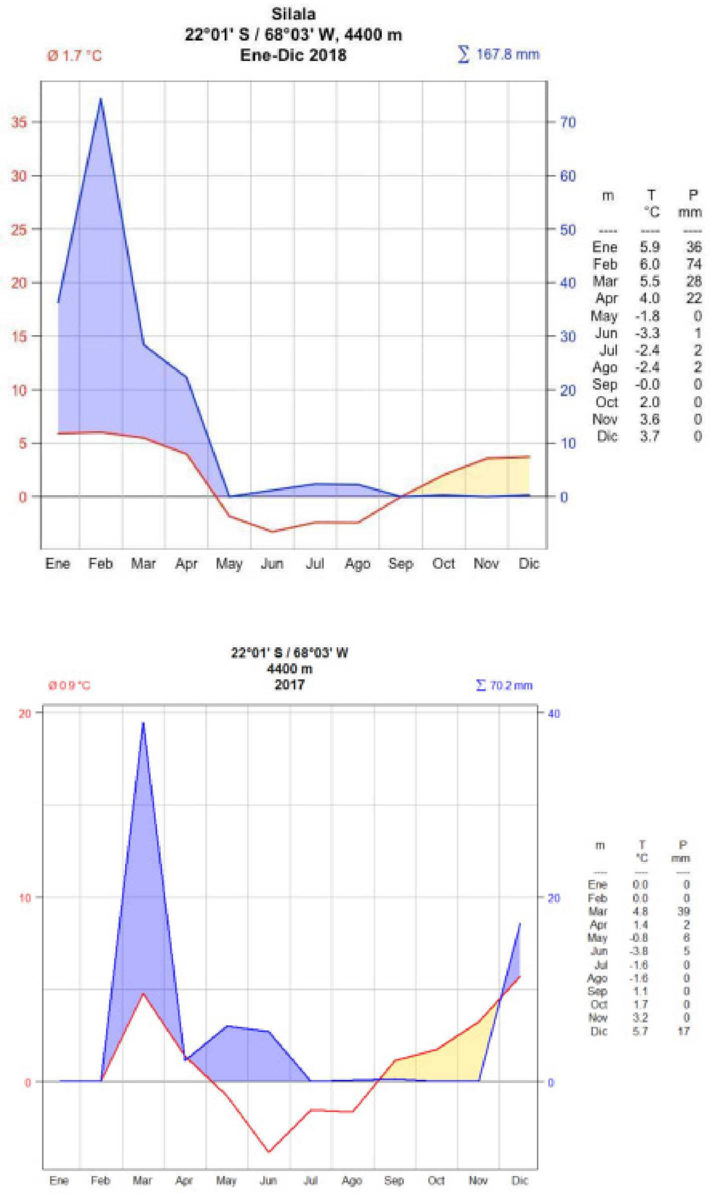


Figure 1. Location of the Silala Bofedals, Potosi, Bolivia. The red dots represent the sampling sites of the North bofedal, and the blue ones those of the South Bofedal.

The region is characterized by a predominance of xerophytic puna systems (Ministry of Foreign Affairs 2014, Rivas-Martinez et al., 2011), with a record of 86 species, subdivided into 65 genera of 35 families, where the Poaceae family is the most diverse (FUNDECO, 2018a). An amount of sixty-one and seventy-seven springs have been found in the South and North bofedal, respectively (TECHNICAL CONSULTANTS, 2018).



m	T °C	P mm
----	----	----
Ene	5.9	36
Feb	6.0	74
Mar	5.5	28
Apr	4.0	22
May	-1.8	0
Jun	-3.3	1
Jul	-2.4	2
Ago	-2.4	2
Sep	-0.0	0
Oct	2.0	0
Nov	3.6	0
Dic	3.7	0

m	T °C	P mm
----	----	----
Ene	0.0	0
Feb	0.0	0
Mar	4.8	39
Apr	1.4	2
May	-0.8	6
Jun	-3.8	5
Jul	-1.6	0
Ago	-1.6	0
Sep	1.1	0
Oct	1.7	0
Nov	3.2	0
Dic	5.7	17

Figure 2. Climate diagram for 2018 (above) and 2017 (below) of the Silala Weather Station. Prepared on basis of data from the National Meteorology and Hydrology Service (SENAHMI, for its Spanish acronyms) Bolivia.

3.2. Relation between the bofedal’s plant and macroinvertebrate communities with environmental (hydrological and physical-chemical) variables

A 1 x 1 m^2 area was systematically selected in 20 sites for the North bofedal and 22 sites for the South bofedal, trying to take the representative microhabitats of the bofedal in a representative manner (Figure 3). The coordinates of the sites selected are presented in Annex 1. The work was carried out from 1 April to 5 April 2019. Biotic and abiotic data (hydric variables) were both taken from each quadrant. At the same site, when there was an associated pool or the closest waterbody, the macroinvertebrates were recorded and the physicochemical variables were measured.

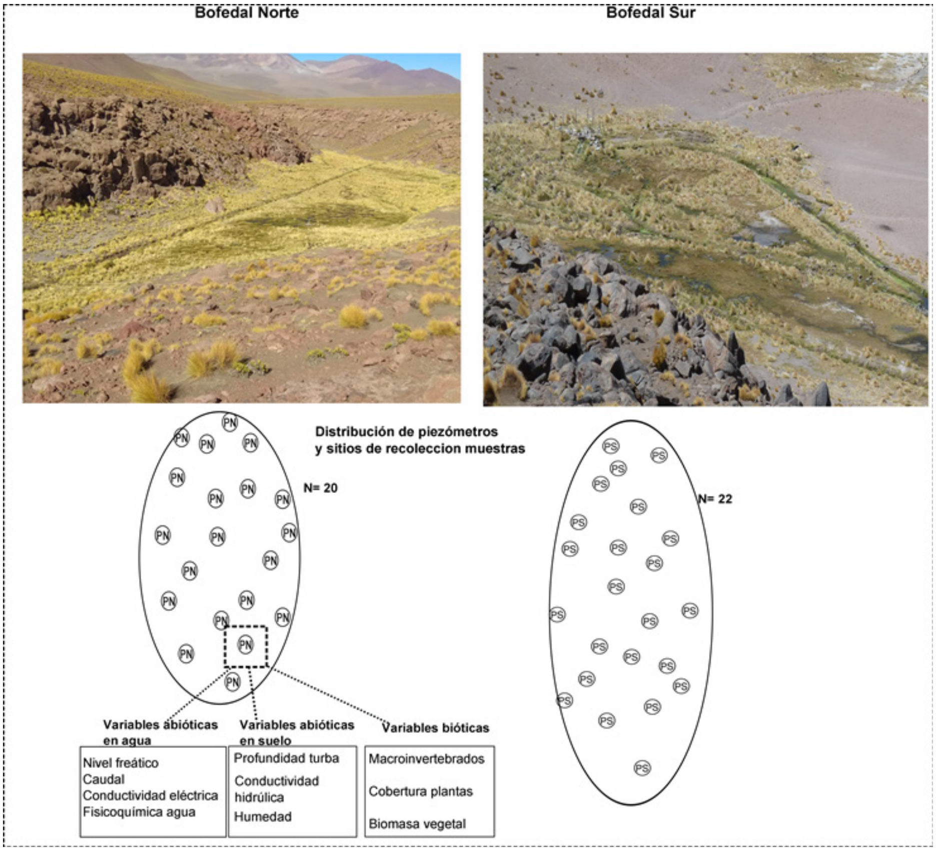


Figure 3. Sampling design to relate macroinvertebrate and plant communities with relation to the environmental variables (hydric and physical-chemical). PN indicates the piezometers installed in the North Bofedal and PS those installed in the South Bofedal. Photographs by A.C. Simon Pfanzelt and Loly Vargas Callisaya.

3.2.1. Vegetal and biomass cover

At each sampling site (see coordinates in Annex 1), the vegetation composition was evaluated using a $1m^2$ quadrant—one of the most common sampling methods for herbaceous vegetation (Stohlgren 2007). This method allows recording almost all species and their cover in bofedals (Garcia 2004). $10cm^2$ of vegetal biomass was then extracted from the central part of each of the initial quadrants. Each sample was labeled and stored in Ziploc® bags and deposited in a container to then register their wet and dry weight at the National Herbarium of Bolivia, Ecology Institute of the Higher University of San Andres.

3.2.2. Macroinvertebrate abundance and wealth

Samples of macroinvertebrates were collected in each of the determined sampling sites or otherwise in the nearest water bodies. A Surber trawl net (15 x 15 cm, $0.02\ cm^2$, with a 250 µm mesh opening) was used for the collection. In total, 38 samples were collected, 18 and 20 in the South and North bofedal. The samples were preserved in alcohol at 96% and evaluated in the Limnology Unit of the Institute of Ecology of the Higher University of San Andres.

3.2.3. Physical-chemical variables

a) Soil moisture: At each sampling site, a soil sample was taken from the central part of each quadrant. The soil samples were of 4 cm in diameter by 10 cm in length (Figure 4) and were collected at 3 different depths: 1) 10 cm, 30 cm and 50 cm to determine moisture flow (Darcy 1856, Campbell 1974, Dingman 2002). The moisture flow calculation procedure is described in section 3.3.3.) The soil samples from depths B and C were taken when it was possible to extract the material. The soil samples were labelled and stored in Ziploc® bags to preserve their moisture. At the end of the day, the wet samples were weighed with a balance of 0.01 g. of precision (Denver Instrument, Canada).

Figure 4. From left to right: drilling, extraction and measurement of samples to determine soil moisture.

b) Peat depth: Three peat depth measures (m) were randomly taken from each quadrant, using a depth gauge (Aquatic Research Instruments brand).

c) Physical-chemical parameters: In the waterbodies associated with the sampling sites the pH, electrical conductivity, and dissolved oxygen (mg/l and %) were measured using Hach equipment (HQ 40D, USA, multi-parameter). The distance to the sampling site and habitat characteristics (water body depth (m), point width (m), velocity (m/s, (Global Water BA1100 model FP111 Flow Probe, 3.7-6 Handle) were also measured as part of this study (Figure 5).

Figure 5. Field sampling at the waterbodies: a) physical-chemical variable measurement, b) macroinvertebrate sample collection with the Surber net; and c) hydric variables.

a) Piezometer installation: Piezometers were installed in the central part of each quadrant, where the plants were evaluated to relate the soil moisture data and phreatic levels with the vegetal cover characteristics. The present study is not intended to monitor the regional flow of the groundwater in the bofedals, but rather the local vertical flows.

The installation of the piezometers was carried out with the help of a drilling machine - linear sampler and an auger (Figure 6) following the following procedure: 1) the drilling-sampler was introduced, in some cases with the help of manual percussion up to the depth of the sampler (30 cm); 2) sample is collected; 3) the drilling-sampler is introduced again, and so on. Normally, it was possible to recover 30 to 45 cm of soil, after which the introduction of the drill was no longer possible due to the presence of clasts in the ground or, in some cases, due to the resistance of the ground; 4) the drilling depth was extended with the use of an augur to a depth sufficient to measure the water table, and up to a maximum of 1.50 m.

The piezometers are constructed with a PVC pipe of 1.5 inches in diameter. They were lined with micrometric silk (100 µm approx.) near the filter. In the North bofedal, an additional piezometer was installed in the PN17 and PN29 sites, at different heights to observe pressure differences and to calculate the vertical flow of water in porous material (Darcy 1856).

Figure 6. Piezometer installation in the Silala bofedals. Right side: expansion of the hole made with augers. Center: piezometer installation. Left side: site with the two piezometers installed (PN17).

The phreatic level was measured in each of the piezometers installed using a manual probe. The measurements were made 24 hours or more following the piezometer installation to ensure the representative of the measured values.

b) Piezometer calibration: Topographic measurements were made to determine the location, terrain altitudes and the altitude of the upper part of each piezometer in order to calculate the altitude and depth of the phreatic level at each point (Figure 7). The measurements are linked to the polygonal base installed by DIREMAR in 2017.

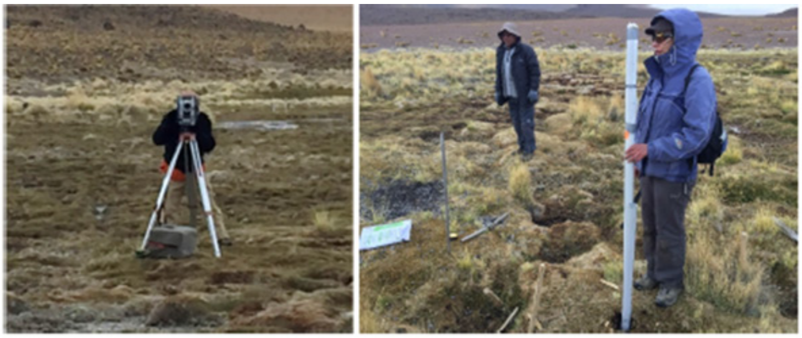


Figure 7. Topographical piezometer location and altitude measurement.

3.2.4. Laboratory data processing

The vegetable biomass samples were cleaned of excess organic matter and manually separated at the level of genus or species. These were then weighed by species using a precision balance Sartorius model Acculab in the facilities of the Limnology Laboratory of the IE-UMSA. The samples were dried to reach a constant weight in the facilities of the National Herbarium of Bolivia, IE-UMSA.

The macroinvertebrate samples were cleaned, separated and identified at the highest taxonomic resolution possible in the Limnology laboratory (Figure 8). The dissection plate assessment was used to determine the structures of taxonomic importance, based on each taxon and with the help of specialized bibliography (Dominguez and Fernandez 2009, Epler 2001).

3.2.5. Data analysis

a) Diversity indexes calculation: With the vegetation (subheading 3.1.2.) and macroinvertebrate (subheading 3.1.3.) data, the Shannon diversity index (H), Shannon Equality (EH), and inverse diversity of Simpson (Cinv) were all calculated. The Inverse diversity of Simpson was calculated for macroinvertebrates (Annex 7).

For macroinvertebrates, an index of bofedal health (IBH) was calculated from the flow values (with the measures of velocity, depth and width) as a function of the similarity to the communities with a composition reference of the sites that were better preserved in the North and South Bofedals using the UPGMA arithmetic grouping and Sorensen linkage methods.

Figure 8. Evaluation of macroinvertebrate samples in the Limnology-IE laboratories.

b) Statistical analysis: A descriptive statistic was applied to explore biotic vegetation and macroinvertebrate data, together with the hydrological abiotic (phreatic level, electrical conductivity) and soil (soil moisture and peat depth) data. These analyses were performed to characterize both bofedals.

A DCA (Discriminant Correspondence Analysis) and CA (correspondence analysis) were used respectively to determine if there is any grouping in the vegetation composition and in the composition of macroinvertebrates, respectively. An ANOSIM Similarity Analysis was used to observe the differences between macroinvertebrate communities of the North and South bofedals.

To determine the relationship between the hydrological and biological variables, the Canonical Correspondence Analysis (CCA) was used. This analysis allows establishing the relationship between 1) the composition and biomass of the plants and/or 2) macroinvertebrate composition of the North and South Bofedals with respect to the environmental variables (phreatic level, soil moisture, peat depth, distance from the canals, pH, electrical conductivity, dissolved oxygen, and total dissolved solids). In the analysis of macroinvertebrates, the environmental variables included the width and depth of the waterbody. With the variables that showed some type of relationship, tests of significance were performed through permutations to determine the significance of these relationships.

Analyzes were then run separately evaluating the influence of each environmental variable with respect to the plant composition or macroinvertebrate composition. The forward selection method was used to discard the variables that were not relevant for vegetation and macro-invertebrates.

The multivariate analyzes were completed with the statistical analysis software R 3.5.3. and the Correspondence Analysis and boxplot graphs to evaluate the [effects of the] canalization on macroinvertebrates were completed in PAST (V. 316)

3.3. Estimation of water demand

3.3.1. Effect of the phreatic level on the vegetation

A preserved bofedal is mainly formed by species that compose its structure and over which other species develop (Ruthsatz, 2012). We have chosen a cover of O. Andina as a reference for a preserved bofedal patch. The effect of the phreatic level on the coverage of O. andina was evaluated using a generalized linear model (GLM) and assuming a binomial distribution. The independent variables were groundwater level, peat depth, pH and electrical conductivity. GLM analyzes and graphs were performed in R 3.5.3.

3.3.2. Potential evapotranspiration calculation (PET)

Evapotranspiration is a collective term for all the processes through which water on the surface of the soil, or close to it, becomes part of the water contained in the atmosphere in the form of vapor. The term includes direct evaporation from the soil surface, transpiration through the leaves of plants, evaporation from water bodies and sublimation from ice or snow surfaces (Dingman, 2002); In bofedals, it is assumed that the amount of evaporated water depends on the amount of water available in the soil and environmental factors such as temperature, radiation and relative humidity. Potential evapotranspiration (PET) is the amount of water that enters the atmosphere assuming that water availability is not a limiting factor (Medrano et al., 2007). From another perspective, it is the amount of water that must be added to the bofedal to maintain a constant water content.

In the present study we have used the Penman-Montheith equation to estimate the evapotranspiration rate from a vegetated cover surface incorporating the hydraulic conductivity of the foliage (Monteith 1965). This equation has been successfully tested in wetlands (Drexler et al., 2004) and in different environments (Calder 1977, Berkowicz and Prahm 1982, Lindroth 1985, Allen et al., 1998).

The Penman-Monteith formula is described below.

$$ETP = \frac{\Delta(K + L) + \rho_a c_a C_{at} e_a^*(1 - W_a)}{\rho_w \lambda_v [\Delta + \gamma(1 + C_{at}/C_{can}]}$$

Where: Δ is the slope of the saturation vapor curve as a function of temperature; K + L = incident net radiation; ρ_a = air density; c_a = specific heat of the air; e_a* = air vapor saturation pressure; W_a = degree of air saturation; ρ_w = water density; λ_v = latent heat of water evaporation; γ = psychrometric constant air; C_{at} = atmospheric conductance; C_{can} = leaf conductance.

The atmospheric conductance (Cat) can be calculated as:

$$C_{at} = \frac{v_a}{6.25\left[ln\left(\frac{z_m - z_d}{z_0}\right)\right]^2}$$

Where: V_a is the average wind speed at a height of 2 meters above ground level; Zd is the height of the plane of zero displacement, approximately equal to 0.7 of the height of the vegetation; Z^0 is the roughness of the terrain; it is calculated as 0.1 of the height of the vegetation; Z^m is the height above the vegetation to which the wind speed is measured; 2 meters by default.

Foliage conductivity (C_{can}) can be abstracted as the equivalent conductivity of the set of leaves, with their respective conductivity, working in parallel. It can be calculated as:

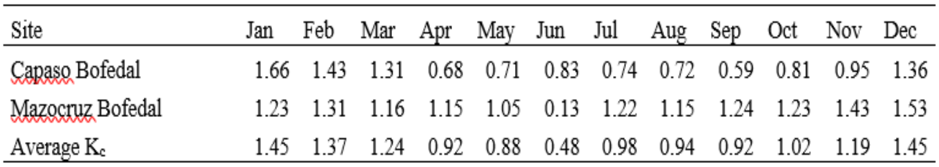
$$C_{can} = f_s \times LAI \times C_{leaf}$$

Where: f_s = factor of shelter that takes into account that the leaves cover one another from the wind and the sun. The values of f_s vary between 0.5 and 1. The Leaf Area Index is the relation between the total surface of the leaves of the plants and the horizontal surface covered by vegetation. C_{leaf} = stomatal conductance of the leaves, is calculated from the maximum stomatal conductance C^*_{leaf} applying a series of reduction factors that allow taking into account the effect of different environmental variables on the opening of the stomata: incident radiation (illumination), the deficit of vapor pressure in the air, the temperature and the water deficit in the soil (Tobin et al.,1988).

The PET calculations were made with the climatic data available at the time level from March 2017 to May 2018 obtained at the Silala weather station. Two approaches or methodologies were used: 1) that of the crop coefficient and 2) that of the simulation of the evapotranspiration process. To calculate the foliage conductivity, the approximations were the following: To calculate the shelter factor we used the value 0.9 since the vegetation does not produce much shade. The LAI is calculated based on the amount of vegetation coverage over the total coverage. To calculate the stomatal conductance, we calculate the model using two approaches:

1) The crop coefficient (kc) for a surface covered with grass. Zea Mamani (2015) based on experimental data with lysimeters established culture coefficients for each month adapted to High Andean bofedals in Puno, Peru (Table 1). These coefficients can be considered representative for the bofedals of Silala.

Table 1. Crop coefficient K_c for dry puna bofedals, based on Zea-Mamani (2015)

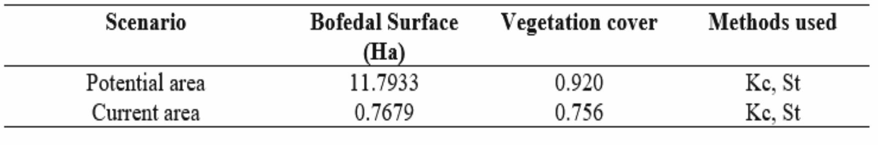


Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Capaso Bofedal	1.66	1.43	1.31	0.68	0.71	0.83	0.74	0.72	0.59	0.81	0.95	1.36
Mazocruz Bofedal	1.23	1.31	1.16	1.15	1.05	0.13	1.22	1.15	1.24	1.23	1.43	1.53
Average K_c	1.45	1.37	1.24	0.92	0.88	0.48	0.98	0.94	0.92	1.02	1.19	1.45

2) Simulation of the evapotranspiration process (st); we have adopted a value of LAI = 4 and a maximum stomatal conductance C^*_{leaf} = 6.6 mm / s according to recommendations for fully covered wetland surfaces (Federer et al., 1996).

We propose the calculation of two PET scenarios (Table 2), according to their potential (ideal conservation conditions) and current surface areas. In turn, each of these scenarios was calculated using the crop coefficient adapted by Zea Mamani (2015) and the simulation of the process of evapotranspiration (St).

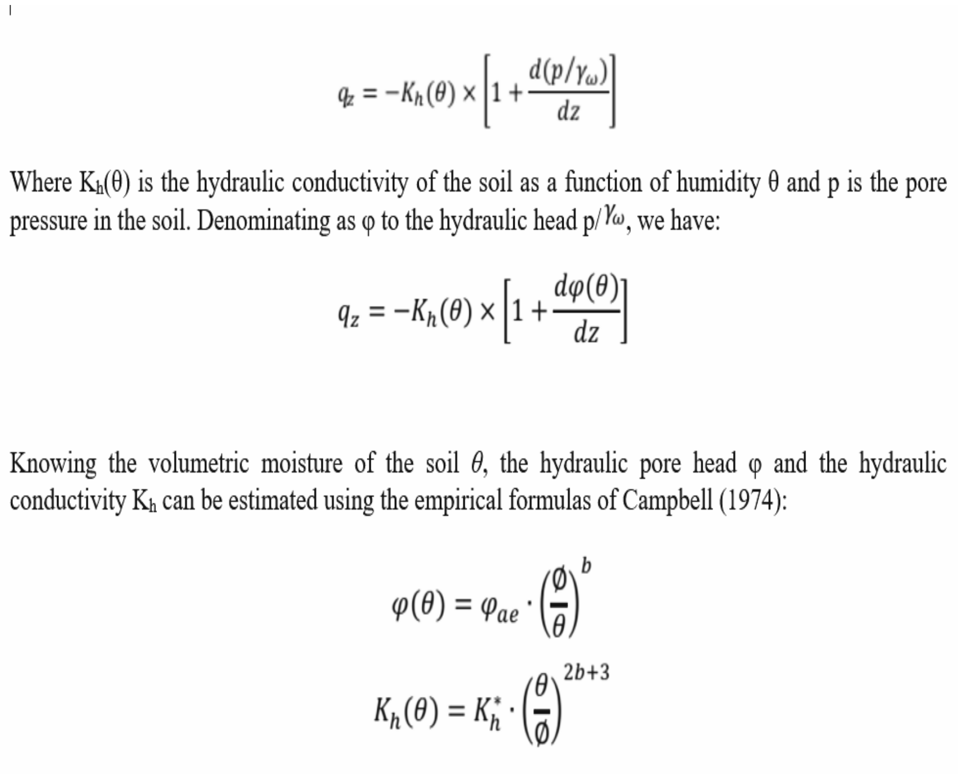
Table 2. Proposed scenarios to determine the ETP of the Silala bofedales. The symbol St stands for transpiration simulation



Scenario	Bofedal Surface (Ha)	Vegetation cover	Methods used
Potential area	11.7933	0.920	Kc, St
Current area	0.7679	0.756	Kc, St

3.3.3. Calculation of the vertical flow of water in the soil

This calculation was completed on basis of the soil moisture content and phreatic level. Just as the recharge of water in the soil by infiltration produces a downward movement in unsaturated flow, the water consumption of the plants also produces an upward movement of water in the soil. This flow is reflected in a depression of the capillary fringe, together with the establishment of a characteristic humidity profile that can be established theoretically through the solution of Darcy's differential equation for unsaturated vertical flow:



$$q_z = -K_h(\theta) \times \left[1 + \frac{d(p/\gamma_\omega)}{dz}\right]$$

Where $K_h(\theta)$ is the hydraulic conductivity of the soil as a function of humidity θ and p is the pore pressure in the soil. Denominating as φ to the hydraulic head p/γ_ω, we have:

$$q_z = -K_h(\theta) \times \left[1 + \frac{d\varphi(\theta)}{dz}\right]$$

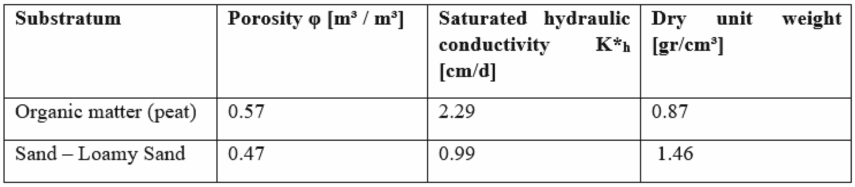
Knowing the volumetric moisture of the soil θ, the hydraulic pore head φ and the hydraulic conductivity K_h can be estimated using the empirical formulas of Campbell (1974):

$$\varphi(\theta) = \varphi_{ae} \cdot \left(\frac{\emptyset}{\theta}\right)^{b}$$

$$K_h(\theta) = K_h^* \cdot \left(\frac{\theta}{\emptyset}\right)^{2b+3}$$

Where φ is the soil porosity, φ_{ae} is the input voltage of air in the soil, K^*_h is the saturated hydraulic conductivity of the soil and b is a constant that depends on the type of soil. The limitation in the application of these formulas is in: (i) the uncertainties that exist in relation to the porosity, hydraulic conductivity and the (ii) coefficient b of the soils, which present in general, large variations from one point to another and in depth (e.g. Dingman, 2002). The impossibility of determining the pore tension when the material above the water table is saturated (capillary fringe), since in this zone the pore tension varies as long as the humidity is constant. We have used the porosity and hydraulic conductivity vales (Table 3) obtained from the work carried out by Orsag et al., (2017).

Table 3. Soil variables used for the calculation of vertical flows. Source (Orsag et al., 2017).



Substratum	Porosity φ [m³ / m³]	Saturated hydraulic conductivity K*h [cm/d]	Dry unit weight [gr/cm³]
Organic matter (peat)	0.57	2.29	0.87
Sand – Loamy Sand	0.47	0.99	1.46

Once the pore stress φ and the hydraulic conductivity K_h have been estimated, the flow is estimated using the finite difference method applied to the Darcy equation:

$$q_z = -K_h(\theta) \times \left[1 + \frac{\Delta\varphi(\theta)}{\Delta z}\right]$$

In some cases, the depth of the water table can be used as data, where it is known that the pore stress φ=0 and that the hydraulic conductivity K_h is equal to the hydraulic conductivity in saturated soil k^*_h.
At points where two piezometers are installed at different depths (PN17 and PN29), the Darcy equation is also applied considering saturated conditions.

$$q_z = -K_h^* \times \left[1 + \frac{\Delta\varphi}{\Delta z}\right]$$

3.3.4. Calculation of the bofedal water level

To calculate the volume of water, we use the following formula:

$$V = a * h * P$$

Where, a = area of the bofedal, h = average height (depth of the peat); p = porosity of the peat has a value of 0.57 based on the work of Orsag et al., (2017). We propose three scenarios of water volume for both bofedals based on the potential and current area of both bofedals calculated by FUNDECO (2018a) and the depth of the peat.
Scenarios:

a) Potential volume 1: It includes the potential area of both bofedals (11.79 ha) and the maximum depth of peat reported (6.6 m) in the Negra Ravine (Muñoz and Suarez 2019).

b) Potential volume 2: It includes the potential area (11.79 ha) and the potential depth of the topographic relief measured from the difference between the maximum and minimum levels in 40 transects. This was done based on the potential area and the average depth of the bofedals measured in this work (Figure 9).

a) Current volume: Includes the current area (0.76 ha) and the average depth of the bofedals measured in the present study (Figure 9).

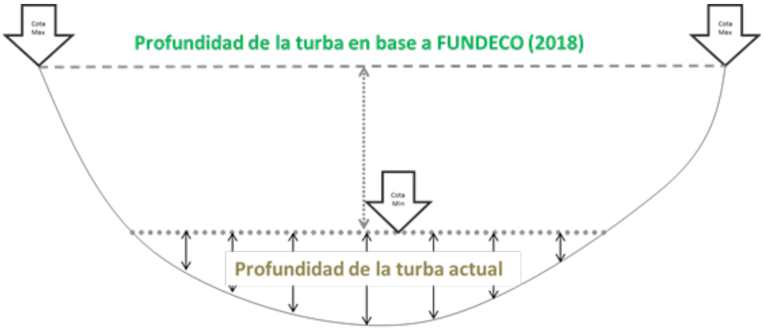


Figure 9. Profile of the bofedal showing the potential and current area. On basis of the potential area, the dimensions were calculated to determine the potential depth of the bofedal. The arrows indicate the maximum and minimum levels.

3.3.5. Ecological flow

The minimum ecological flow is that which is imposed on the new rights of use of waters that are constituted in natural water channels. Its objective is to avoid the abiotic effects, such as the decrease of the wet perimeter, the depth, the velocity of the current and the increases in the concentration of nutrients produced by the reduction of flow, significantly alter the natural conditions of the channel (Boettiger, 2013).

In Bolivia we do not have a regulation that specifies the ecological flow that ecosystems need. That is why in this study we carried out this calculation according to our neighboring country (Chile). Its regulation for the determination of the minimum ecological flow (MMA 2012), approved by Decree N° 14 of 22 May 2012, Article 3 establishes: For each month of the year, the minimum ecological flow at the requested collection point will be determined considering the flow rate equivalent to twenty percent of the average monthly flow (QMM) of the respective surface water source. This value will have a maximum limit of twenty percent of the annual average flow (QMA) and using hydrological statistics of the last 25 years. Additionally, in Articles 6 and 7, indicates that, in qualified cases, such as those in which risks are identified for the habitat of such magnitude that compromise the survival of the species, a higher value of minimum ecological flow may be set, which may not exceed forty percent of the annual average flow (QMA).

For the Silala bofedals we use the output flow from 2013 to 2016. Based on the data from the Silala station, to this average monthly flow we calculate its monthly average flow of 20% (QMM). Then we calculate the difference between the QMM and the QMA to calculate the minimum ecological flow. Finally, given that seasonality does not influence the flow, we obtained the average for the year. The details of the calculation are presented in results in subtitle 4.4.5.

4. RESULTS

4.1. Characterization of the North and South Silala wetlands

4.1.1. Climate

The Silala area has an automatic meteorological station located at the PMA-Silala Advanced Military Post (UTM WGS84, East 601944 m, North 7566064 m). The variables monitored by this station are precipitation, maximum, minimum and average temperature, maximum relative humidity, minimum and average, maximum and average wind speed, wind direction, atmospheric pressure, insolation and average solar radiation. However, given the few data (since March 2017) they do not allow a direct characterization of the climate in the bofedals, so the Laguna Colorada and Sol de Mañana stations were taken as support.

In Silala, rainfall has an annual average of 125 mm/year (Laguna Colorada Station, 1980-1998). Most of the precipitation takes place between December and March. The average monthly maximum temperatures are greater than zero and show a low year-on-year variation between 12 and 20 °C depending on the time of year and the minimum is less than zero all year round, with an inter-annual variation between -5 and -20 °C. The average monthly relative humidity has values lower than 50% most of the year. The low contribution of humidity along with the high convective capacity of the wind is responsible for the low levels of precipitation.

4.1.2. Hydrology

Flow Rates: The Silala bofedals are crossed by a series of drainage canals that were built at the beginning of the 20th century. These have changed the flow patterns, favoring the collection of a greater amount of water, to the detriment of the bofedals. The North Bofedal is crossed by a network of 688 meters of main canals and 1,112 meters of secondary canals, with a drainage density of 887 m/ha (IHH, 2018). The South Bofedal is crossed by a network of 2,021 meters of main canals and 814 meters of secondary canals with a drainage density of 789 m/ha.

Based on data from SENAMHI (2017) and the DGA (2019) we have plotted the outflow of Bolivia and the inflow for Chile (Figure 10) for the period from 2013 to 2016.

Both flows show little variation throughout the year, suggesting that there is no marked effect of seasonality. On the other hand, the registered flows could not be simulated through the hydrological modeling of the topographic basin leading to the conclusion that the hydrogeological basin covers a larger territory (TECHNICAL CONSULTANTS 2018). Both indicators indicate that the bofedals are fed by deep groundwater sources.

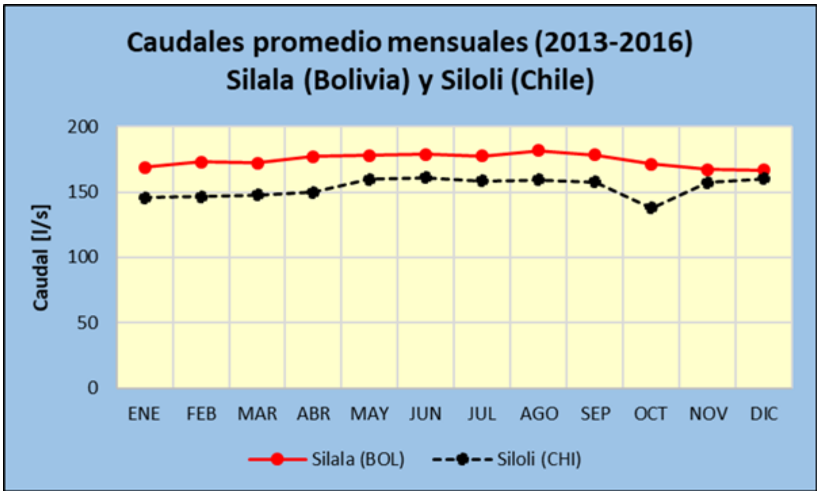


Figure 10: Average monthly outflow of Bolivia and inflow to Chile. Both calculations were made for the period 2013 to 2016 based on data from SENAMHI (2017) and data from the DGA (Directorate General of Water, Chile).

Water table: The depth of the water table varied between 0.1 to 0.5 meters during the first week of April. The lowest values indicate that the water is close to the surface. The North Bofedal presented the level of water closest to the surface in comparison with the South Bofedal. However, in both bofedals the values have a wide variation indicating that there is a lot of heterogeneity in the amount of groundwater present in the bofedals (Figure 11).

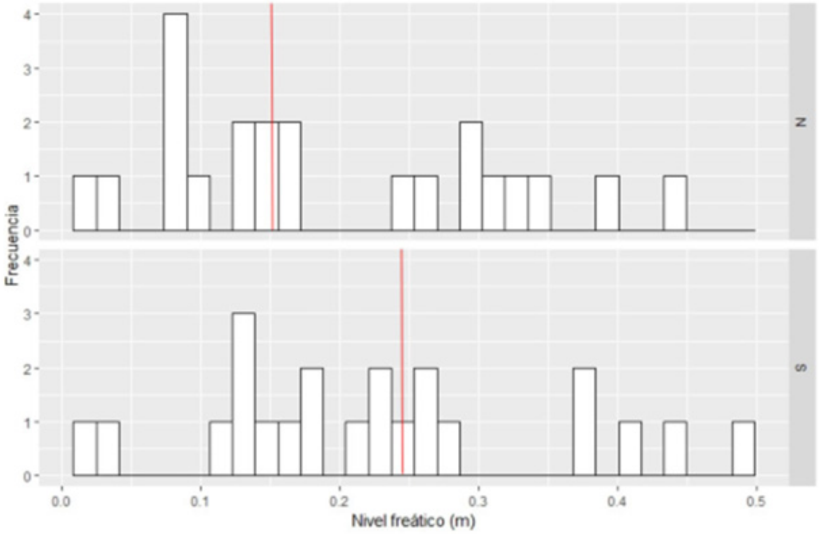


Figure 11. Histogram of the water table of the first week of April 2019 for the North and South bofedals. The red line indicates the average in each site. It is appreciated that the median of the water table is 0.19 meters for the North Bofedal and 0.22 meters for the South Bofedal.

4.1.3. Soils

The soils of the Silala bofedals are of alluvial origin with a superficial horizon formed by organic matter (Alzerreca et al., 2001). Because this material is in proportions greater than 20%, allows the retention of high amounts of water during the rainy season (Orsag et al., 2017).

Depth of the peat: The North Bofedal presented a greater depth of peat compared to the South Bofedal (average: 0.88 and 0.56 meters) respectively. The variation in the North Bofedal was from 0.1-1.95 meters and in the South Bofedal from 0.25-0.8 meters (Figure 12). Annex 4 details the depths and coordinates of each of the evaluated sites (Annex 6).

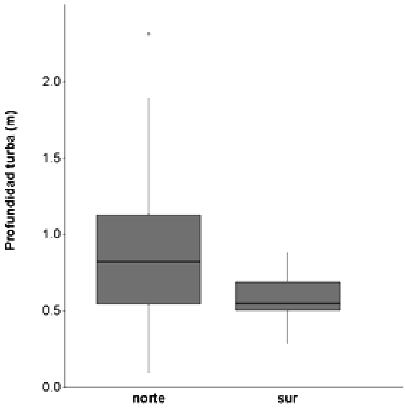


Figure 12: Depth of peat in the North and South bofedals. Number of samples n = 22 north and 20 south

4.1.4. Physicochemical variables

In general, there are differences between the physicochemical variables evaluated in the North and South bofedals (Table 5). The water in the South Bofedal is more basic, with greater electrical conductivity and a greater concentration of dissolved oxygen. In contrast, the North Bofedal has slightly acidic to neutral conditions. The values of the physicochemical variables of each of the sites are presented in Annex 6.

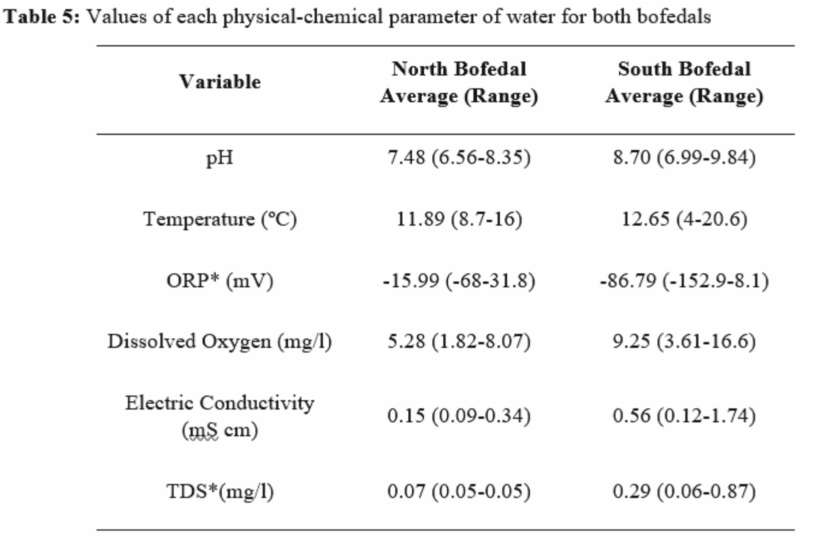


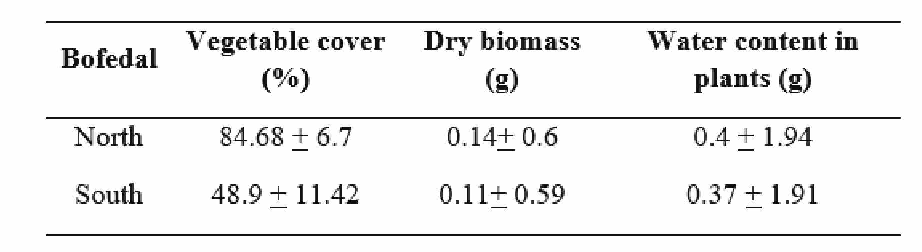
Table 5: Values of each physical-chemical parameter of water for both bofedals

Variable	North Bofedal Average (Range)	South Bofedal Average (Range)
pH	7.48 (6.56-8.35)	8.70 (6.99-9.84)
Temperature (°C)	11.89 (8.7-16)	12.65 (4-20.6)
ORP* (mV)	-15.99 (-68-31.8)	-86.79 (-152.9-8.1)
Dissolved Oxygen (mg/l)	5.28 (1.82-8.07)	9.25 (3.61-16.6)
Electric Conductivity (mS cm)	0.15 (0.09-0.34)	0.56 (0.12-1.74)
TDS*(mg/l)	0.07 (0.05-0.05)	0.29 (0.06-0.87)

4.1.5. Characterization of the vegetation

The vegetation cover had an average of 84.68 and 48.9% in the North and South bofedals respectively. Both the productivity (g) and the water content in the plants (g) were higher in the North Bofedal compared to the South Bofedal (Table 4).

Table 4: Averages and standard deviation of the coverage (%), productivity (g) and water content (g) of the North and South bofedals.



Bofedal	Vegetable cover (%)	Dry biomass (g)	Water content in plants (g)
North	84.68 ± 6.7	0.14± 0.6	0.4 ± 1.94
South	48.9 ± 11.42	0.11± 0.59	0.37 ± 1.91

Regarding the composition, the vegetation in the South Bofedal is quite fragmented and even the deterioration seems to be greater compared to the composition evaluated by FUNDECO (2018). Specifically, the southernmost and middle section of the bofedal is dominated by Carex cf. maritima, data that agrees with the evaluation of this year. In the evaluation of March 2018 it was observed that the central part of the bofedal was composed of small patches of vegetation with less degradation of Festuca potosiana and Oxychloe andina (this last cushion species is typical of bofedals). However, this year the coverage of O. andina was smaller and in general the patches were dry although this year was particularly rainier. The southernmost section (reaching the water tank) was dominated by F. rigescens, followed by O. andina (FUNDECO 2018), data that agrees with what was found this year.

In the North Bofedal, we recorded that the cover is mainly formed by Oxychloe andina, Zameioscirpus muticus, Eleocharis atacamensis, Phylloscirpus deserticola. According to the Principal Component Analysis (PCA) carried out on the year 2018, the Festuca potosiana grass was shown as the dominant species followed by O. andina, which reached a total coverage of 15%. Conversely, this year there seems to be a change in the dominance of species. Our evaluation sites were dominated by Zameioscirpus sp. and O. andina and thirdly by F. potosiana (Figure 13).

Figure 13. Presence of some individuals of Festuca sp. of medium height on the cushions of O. andina. North Bofedal

4.1.6. Macro-invertebrates associated with the bofedals

A total of 9,164 individuals of macro-invertebrates were obtained. Which are grouped into 35 taxa, of these 31% corresponds to the group of non-insects (Acari, Tricladida, Tardigrada, Crustacea, Nematoda and Oligochaeta) and 69% to the group of insects (Plecoptera, Trichoptera, Ephemeroptera, Diptera, Coleoptera, Hemiptera). Compared to the previous report of macro-invertebrates (FUNDECO 2018a), the information was supplemented and new taxa specific to bofedals were added.

Diversity: The diversity and equitability indexes of each evaluated site are presented in Annex 7. There are significant differences between the communities of the North Bofedal and the South Bofedal (Figure 14), these differences are mainly due to the presence of a higher density of Nematodes (Dorylalmus sp.), Oligochaetes (Homochaeta sp.) and mites (Hydrozetes sp.). However, no significant differences were found in relation to the indexes of diversity and evenness (Cinv, H and EH).

The health index of the bofedal (ISB) was calculated, which refers to the similarity using the Sorensen beta diversity index on an average of the composition of the stations in the best state of conservation in this case the PN7, PN21, PN23, PN24 and PN27 points (Figure 15). In this sense, the North Bofedal presents a macro-invertebrate fauna more similar to the bofedal water wells.

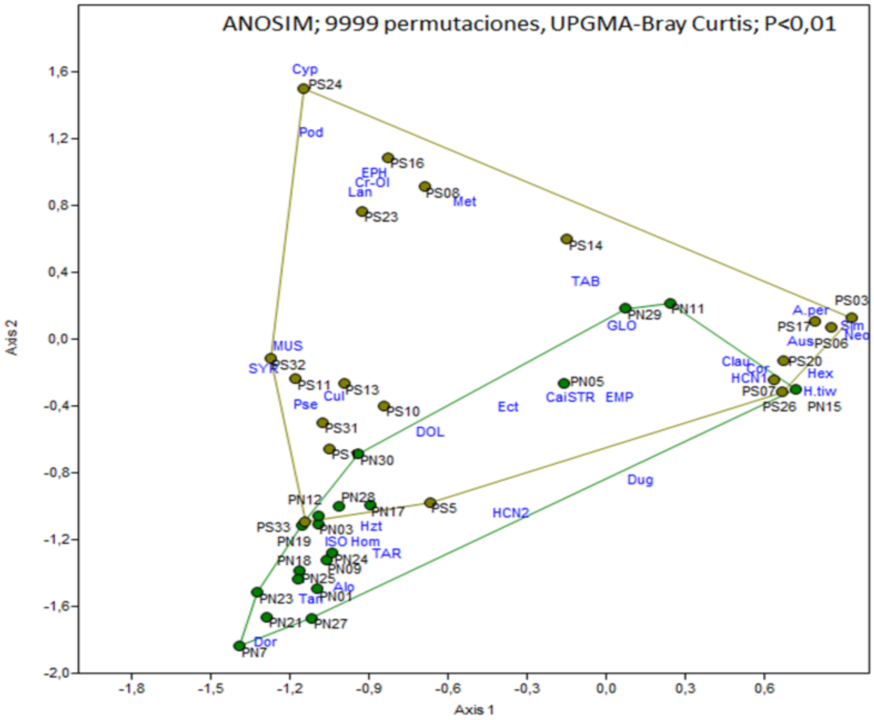


Figure 14: Correspondence Analysis (CA) and ANOSIM test of macro-invertebrate communities.

4.2. Determination of the most determinant hydrological variables for the vegetation and macroinvertebrates in the North and South Silala bofedals

4.2.1 Vegetation relationship with environmental variables

Vegetation composition: For the North Bofedal the global composition of plants was not explained by any of the environmental variables (water table and depth of the peat) according to the Canonical Correspondence Analysis (Trace = 0.18, P = 0.26).

Despite the absence of a relationship, we observed a trend: O. andina, Zameioscirpus sp. and Philloscirpus desertícola (species of bofedals) prefer sites of greater depth of peat and low water table (close to the surface). However, these conditions are not decisive for characterizing the vegetation at least during the month of sampling (April).

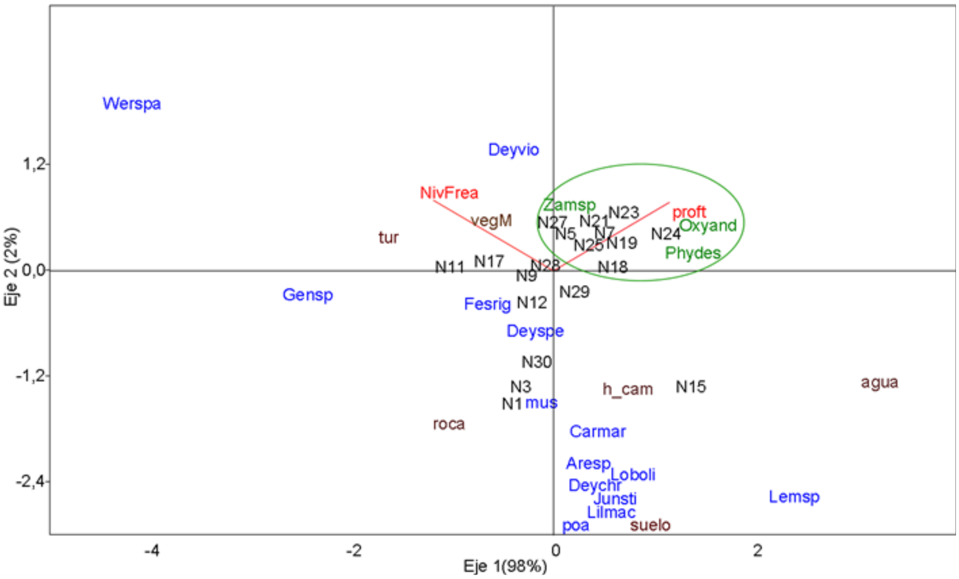


Figure 15. Relationship between environmental variables and the plant community of the North Bofedal. NivFrea = water table, Proft = peat depth. In brown are the abiotic components, in blue the plants and in green the typical species of bofedal. The acronyms of species are in Annex 2. The Canonical Correspondence Analysis was applied.

The sites with the deepest water table, that is, with the lowest water availability, are located at points N17 and N11. These sites correspond to places with greater disturbance (with a higher proportion of Festuca rigescens and peat without vegetation) and visually drier sites. Conversely, places with a lower depth of water table are related to greater coverage of O. andina. Some points that are grouped are sites N19, N23, N24, N27, which in turn have presence of species associated with high water levels.

In the South Bofedal the composition of the vegetation was significantly explained by the groundwater level and depth of the peat (Trace = 0.46, $P < 0.05$) (Figure 16).

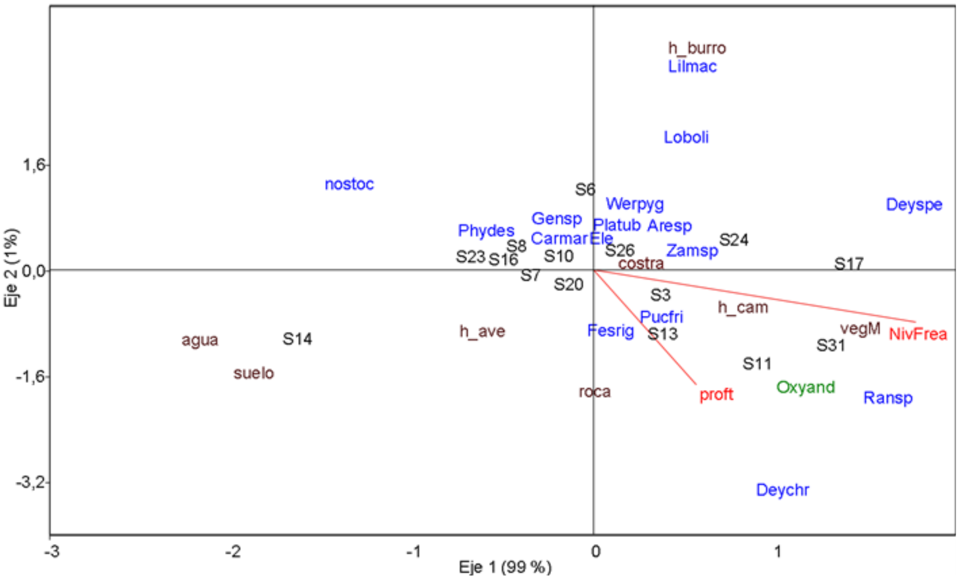


Figure 16: Relationship between environmental variables and the plant community of the South Bofedal. NivFrea = water table, Proft = peat depth. In brown are the abiotic components, in blue the plants and in green the typical bofedal species. The acronyms of species are in Annex 2. The Canonical Correspondence Analysis was applied.

Oxychloe andina has high coverage at sites S11, S31 where the peat depth is high. Given the degradation process in place in the same sites, high coverage of dead vegetation was also found.

Water content in plants and productivity Both the water content in the plant (Annex 8) (g) and productivity (dry biomass g) (Annex 9) presented a similar response to what was found with the composition of the species. In the North Bofedal, the CCA with the water content did not generate a significant model (Trace = 0.05, P = 0.98). The water content of O. andina does not respond to the water table and the peat depth (Figure 17).

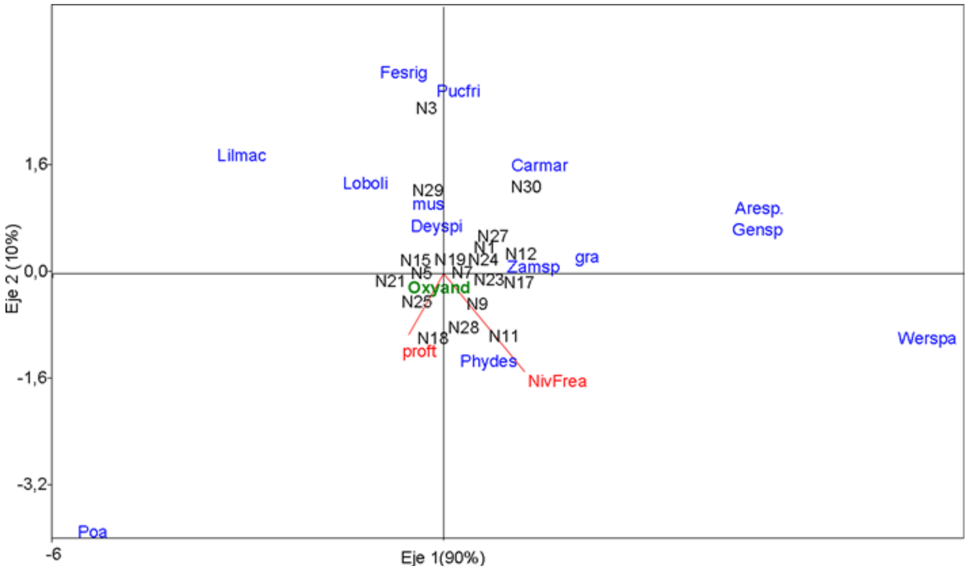


Figure 17: Relationship between environmental variables and the water content of the North Bofedal plants. NivFrea = water table, Proft = depth of the peat. In green the typical bofedal species. The acronyms of species are in Annex 2. The Canonical Correspondence Analysis was applied.

The water content in the plants (Annex 8) is positively associated with the depth of the peat and intermediate conditions of the water table (Trace = 0.46, P <0.05). While species such as Werneria spathulata and Eleocharis do not require high depth of peat and are indifferent to the conditions of the water table (Figure 18).

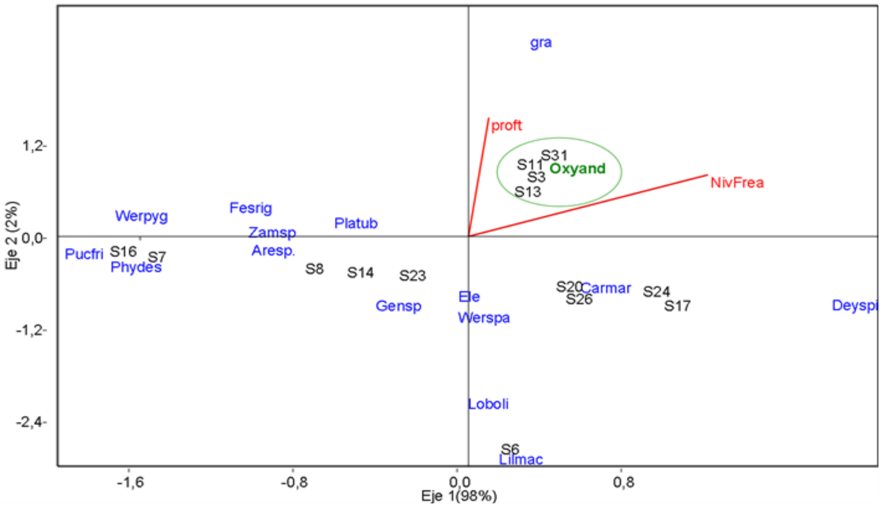


Figure 18: Relationship between environmental variables and the water content of the plants of the South Bofedal. NivFrea = water table, Proft = depth of the peat. In green the typical bofedal species. The acronyms of species are in Annex 2. The Canonical Correspondence Analysis was applied.

4.4.2 Macro-invertebrate relationship with environmental variables

The variation between the environmental variables (physical-chemical water and morphometric) can be explained by the first two main components by 68% (Figure 19). The first axis separates the sites according to physical-chemical variables pH, Dissolved Oxygen (DO) and electrical conductivity (EC) and physical variables such as bed width. The second axis orders the sites according to the variables such as average speed, average depth and flow (Q). At first glance it is observed that groups are formed according to the North and South bofedals, which differ according to the environmental variables. The sampling points of the South Bofedal are more dispersed in relation to the sampling points of the North Bofedal, indicating that these are more homogeneous with respect to the mentioned variables. The scatter-grams of correlations between all the variables measured in water are in Annex 4.1.

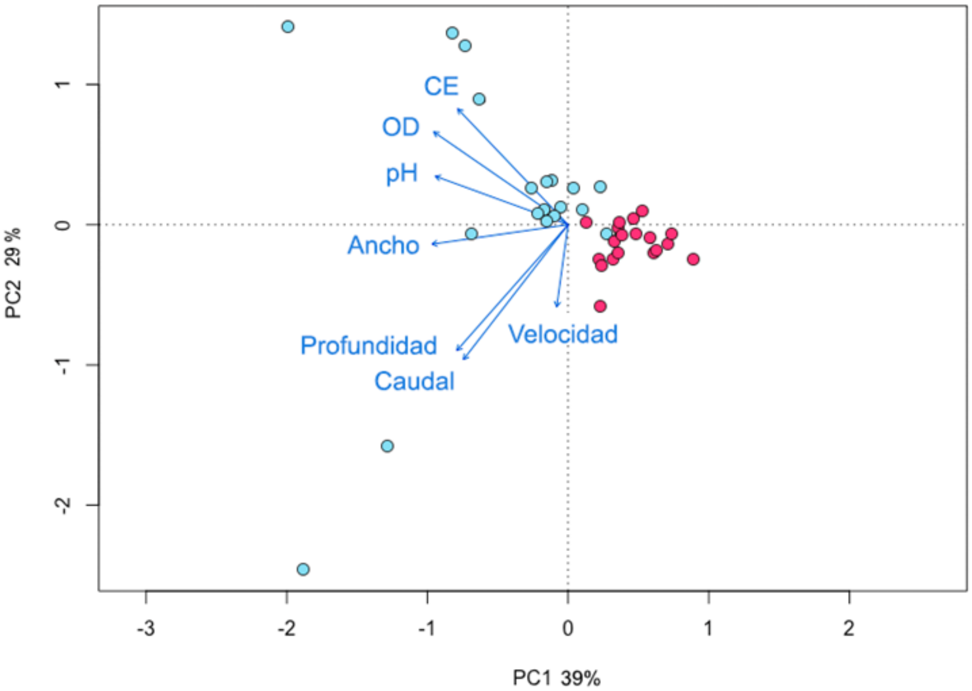


Figure 19: Sorting of the sites according to the Principal Component Analysis (PCA) according to environmental variables (physical-chemical water and morphometric). The light blue points correspond to the sites of the South Bofedal (PS) and the red points to the sites of the North Bofedal (PN).

In order to evaluate that the bofedals have different characteristics in terms of environmental parameters, a boxplot was carried out (Figure 20). In the figure it can be seen that there are significant differences (Kruskal-Wallis, Table 6) between both bofedals, in terms of pH, Dissolved Oxygen (DO) and Electrical Conductivity (EC).

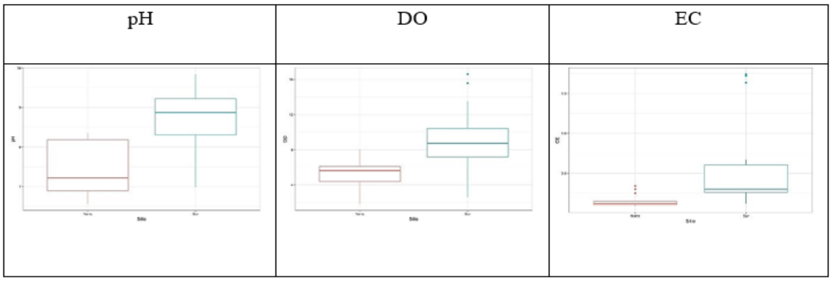

pH DO EC

Figure 21. Boxplot of each physical-chemical variable of both the North (Red) and South (Sky blue) Bofedal.

Table 6. Kruskal-Wallis analysis of each physical-chemical variable as a function of the South and North Bofedals. Value of $p \leq 0.001$ ***

Variable	***Chi²***	***Df***	***p – value***
pH	16.60	1	4.6 e-5 ***
DO	16.71	1	4.4 e-5 ***
EC (mS cm)	19.23	1	1.2 e-5 ***

The cumulative variability of the relationship between environmental and biological (macro-invertebrates) variables can be explained by the first two axes by 53% significantly according to the Canonical Correspondence Analysis (CCA) (Figure 21). In axis 1 the variables: width, depth of the water column and flow (Q) (Table 7), in these sites predominate organisms such as Simulidae and two taxa belonging to the order Trichoptera; that is, these organisms are present in environments where water conditions provide speed and also maintain a considerable depth to house coarse substrate. These taxa inhabit and develop their metabolic activities on this type of material.

Axis 2 explains the variables pH, dissolved oxygen and inversely the depth of the peat (Table 7), in these environments taxa such as Glossiphoniidae predominate. These taxa are related to environmental conditions; in the case of taxa associated with peat depth, they will be present in greater abundance when the amount of peat is shallower, which is interpreted as a requirement associated with the dynamics of the water body's bank. This variable is what explains the tendency of separation of the North Bofedal, in conjunction with other variables with less impact such as conductivity.

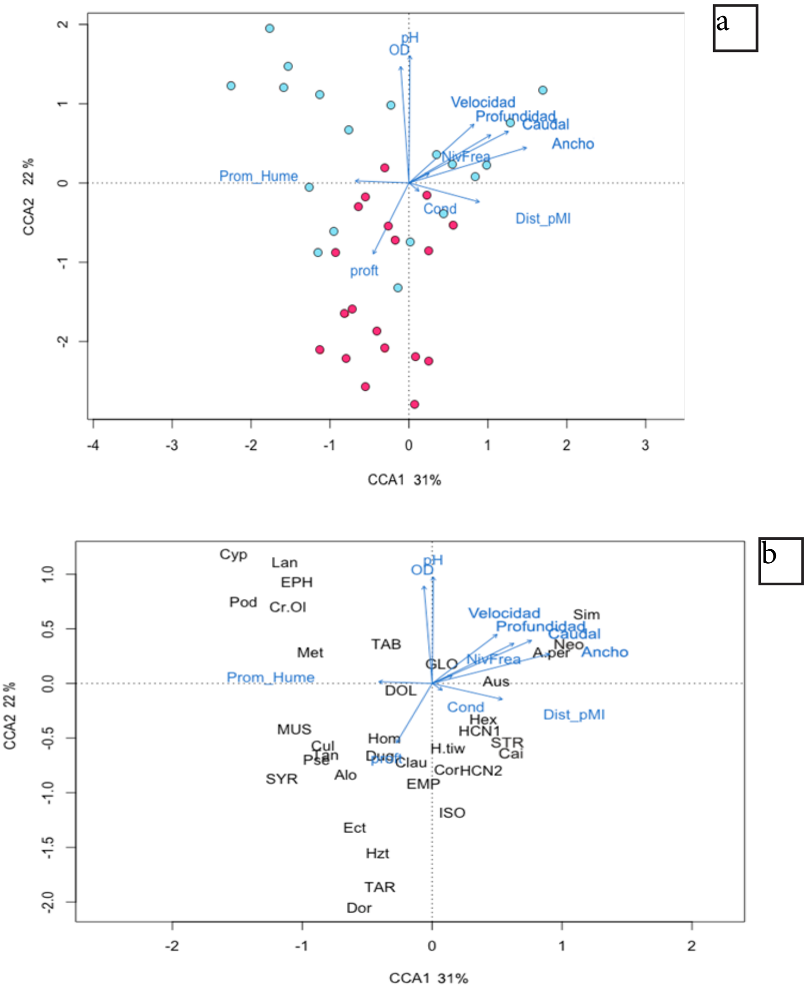
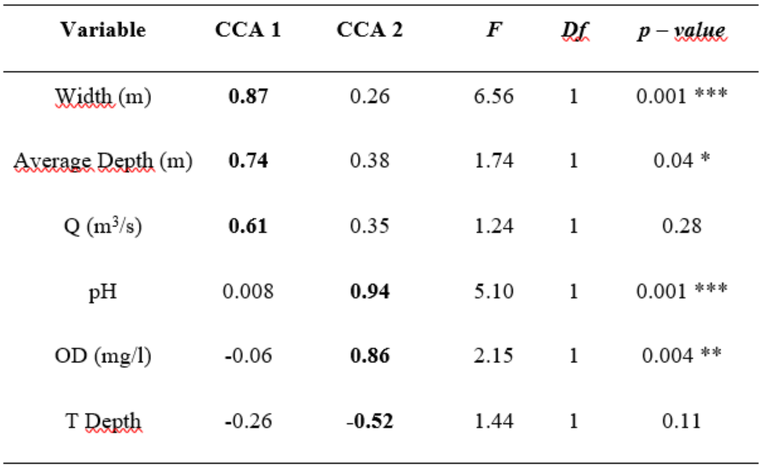


Figure. 22. Canonical Correspondence Analysis (CCA) show the sorting of sites sampled in the area of the bofedals studied, according to the abundance of the macro-invertebrate community and the most relevant environmental variables. a) Ordering by visualizing the macro-invertebrate taxa and b) ordering by visualizing the sampling sites in red in the North Bofedal sites and in light blue ones in the South Bofedal, the vectors indicate the environmental variables.

Table 7. Contribution scores of each contrast variable, of greater weight in each component of the CCA and statistics of significance with 999 permutations.



Variable	CCA 1	CCA 2	*F*	*Df*	*p – value*
Width (m)	**0.87**	0.26	6.56	1	0.001 ***
Average Depth (m)	**0.74**	0.38	1.74	1	0.04 *
Q (m^3/s)	**0.61**	0.35	1.24	1	0.28
pH	0.008	**0.94**	5.10	1	0.001 ***
OD (mg/l)	-0.06	**0.86**	2.15	1	0.004 **
T Depth	-0.26	-**0.52**	1.44	1	0.11

4.3. Relationship between vegetation and macro-invertebrate fauna

In the North Bofedal the sites PN7, PN21, PN23, PN24, PN25 and PN27 are related to the species: O. andina, Zameioscirpus, mosses and macro-invertebrates such as: Dorylaimus (Nematoda), Homochaeta (Oligochaeta) and Hydrozetes (Acari). Thus, this group of taxa is part of the biodiversity of conserved bofedals. The sites PS03, PS06, PS17, PS20, PS26 and PN15 are associated with bodies of water with higher flow rates, which is related to plant species such as: Lilaeopsis macloviana, Lemna sp., Eleocharis sp. and macro-invertebrates such as: Simulium sp. Neotrichia sp., Andesiops peruvianus, Hexatoma sp., Hyallela tiwanacu and Austrelmis sp. Finally, sites PS08, PS23 and PS24 are shallow bodies of water that do not exceed 5 cm and are related to Nostoc sp. (Cyanophyta), Cricotopus-Oliveiriella, Metrichia sp. and Cyprinotus sp. (Fig. 24).

Based on the characteristics found in the sites PN7, PN27, PN25, PN27, based on the macro-invertebrate fauna, the bofedal health index (ISB) was generated. The index values vary from 0 to 0.2, from 02 to 0.4 and from 0.4 to 0.9. This index compares the ideal composition of the fauna of macro-invertebrates in conserved bofedals and the Silala bofedals. When comparing this index with the abundance of O. andina, a good relationship between these variables could be seen in the North Bofedal ($R^2 = 0.6$, $p < 0.05$) because it has some patches with a better state of conservation (Figure 24).

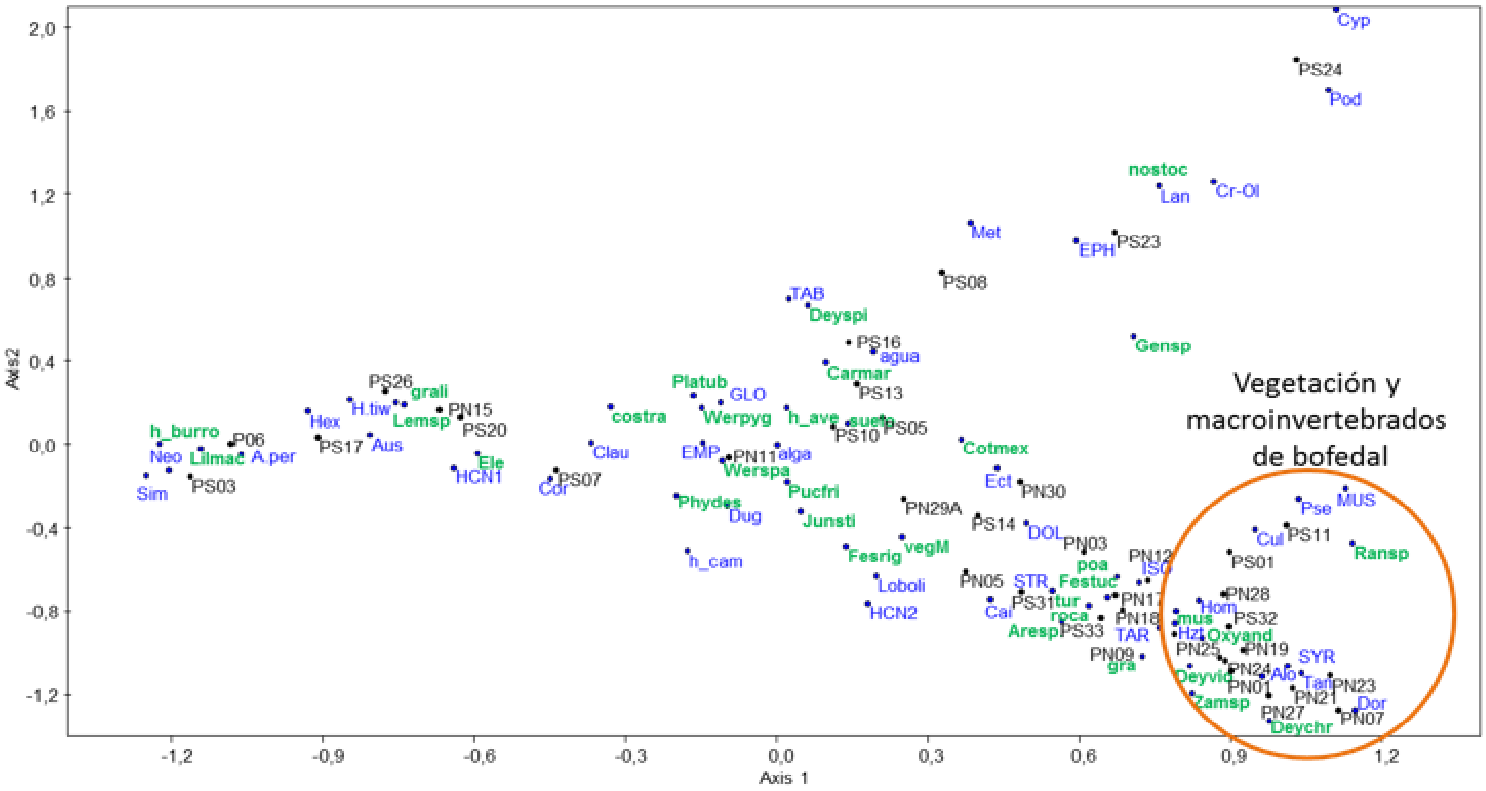


Figure 24: Correspondence Analysis (CA) between the taxonomic proportion of vegetation composition and abiotic coverage and macro-invertebrate fauna.

Figure 25 shows the spatial relationship between the ISB bofedal health index and the cushion coverage of *O. andina*

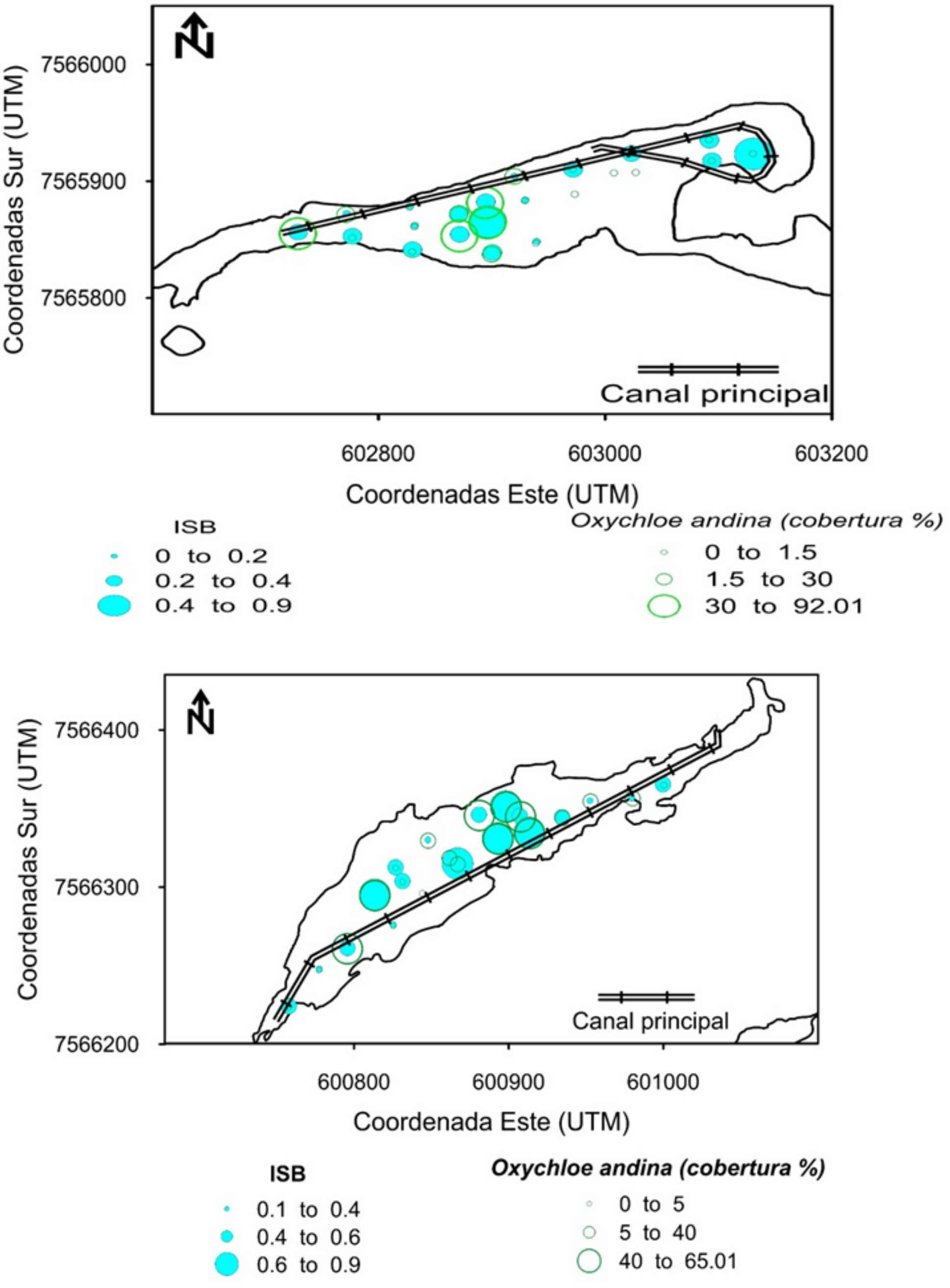


Figure 25. Vegetal cover of Oxychloe andina (%) in relation to the Bofedal Health Index (ISB) in the South (above) and North (below) bofedals.

4.1. Estimation of the water demand of the Silala bofedals

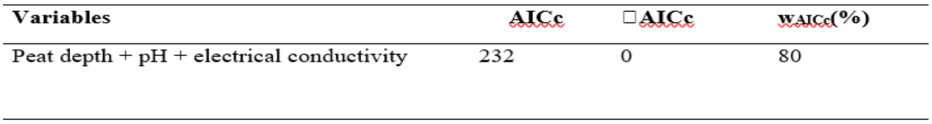
The water demand for the maintenance of bofedals has been determined by evaluating different aspects:

1) O. andina relationship with respect to environmental variables. Since O. andina is a typical species and forms the bofedal structure, knowing how environmental variables and especially water influence their coverage and biomass gives us guidelines to understand the minimum requirements needed by plants that form the bofedal structure.
2) Calculation of the amount of water needed to maintain both bofedals (ETP) from the potential and current condition. We propose two values from the potential and current area, see scenarios subtitle 3.3.2).
3) Estimation of the water volume of the bofedals. The volume that the bofedals can store will be the result of their area and depth. We calculate this volume based on its current and potential area, see scenarios subtitle 3.3.3)
4) Calculation of vertical flow. It is related to the amount of rising water that is the reflection of the evapotranspiration process.
5) Calculation of the minimum ecological flow. We present a minimum flow value based on Chilean regulations. However, this is still approximate data that should be studied in greater detail in future work.

4.4.1. Coverage ratio of O. andina (typical species of bofedals) vs. environmental variables

For the North Bofedal the models that better explain the coverage of O. andina are the depth of the peat, pH, electrical conductivity and flow (Table 8).

Table 8: Models that affect the coverage of O. andina.



Variables	AICc	□AICc	wAICc(%)
Peat depth + pH + electrical conductivity	232	0	80

The peat depth (above 0.5 m) has a positive effect on the coverage of O. andina (Figure 23 a). O. andina coverage reduces when the pH level increases. A greater coverage of O. andina is related to low levels of electrical conductivity that does not exceed 0.15 mS/cm. Contrary to our expectations, the coverage of O. andina was not related to the water table. However, it seems that the water table fluctuates between

between 0.1 and 0.3 meters for O. andina. The South Bofedal data had high dispersion (chat value = 1291.6) and did not comply with the assumption of variance homogeneity, so the GLM analysis with binomial and/or quasi-binomial distribution was not performed.

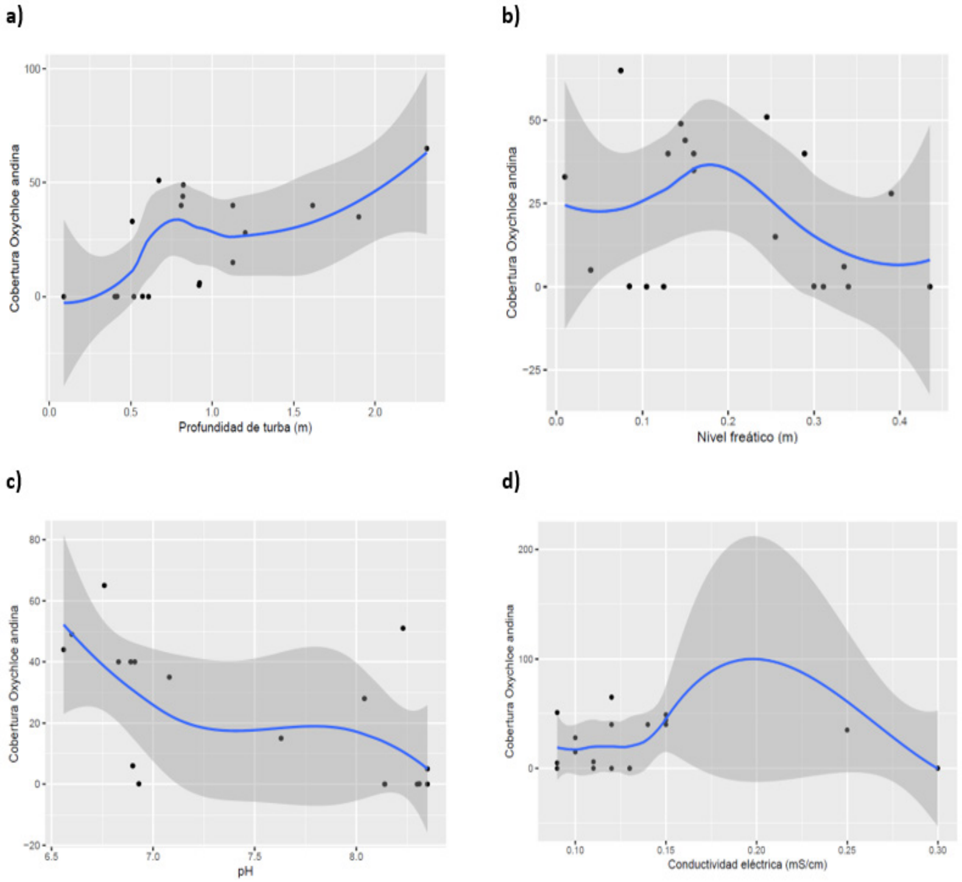


Figure 23: Coverage of Oxychloe andina with respect to environmental variables in the North Bofedal. Dispersograms elaborated based on the variables that best explain the coverage according to the binomial GLM and logistic link function.

Spatial representation

The representation of some environmental variables in the South Bofedal suggests the low correspondence with the increase in O. andina coverage and the depth of the peat, water table, pH and electrical conductivity (Figure 24).

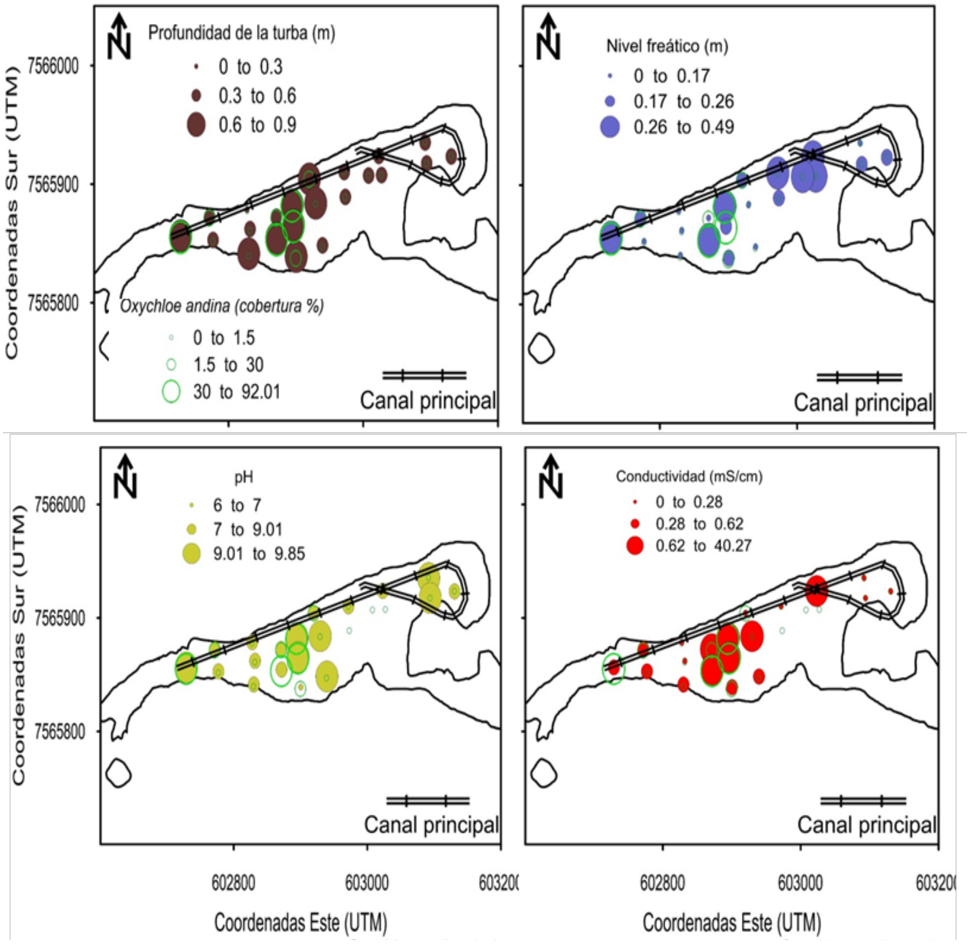


Figure 24: Vegetal cover of Oxychloe andina (%) in relation to the depth of the peat (m), water table (m), pH and electrical conductivity (mS/cm) in the South Bofedal.

In the North Bofedal (Figure 25), the peat depth where the coverage of O. andina varies from 30-90% corresponds to sites from 0.15 m of peat. The water table closest to ground level (between 0.15-0.31 m) is associated with sites with greater coverage of O. andina. In sites with low pH (slightly acid to neutral), the sites with the highest coverage of O. andina are found. While the correspondence is not so clear with the electrical conductivity.

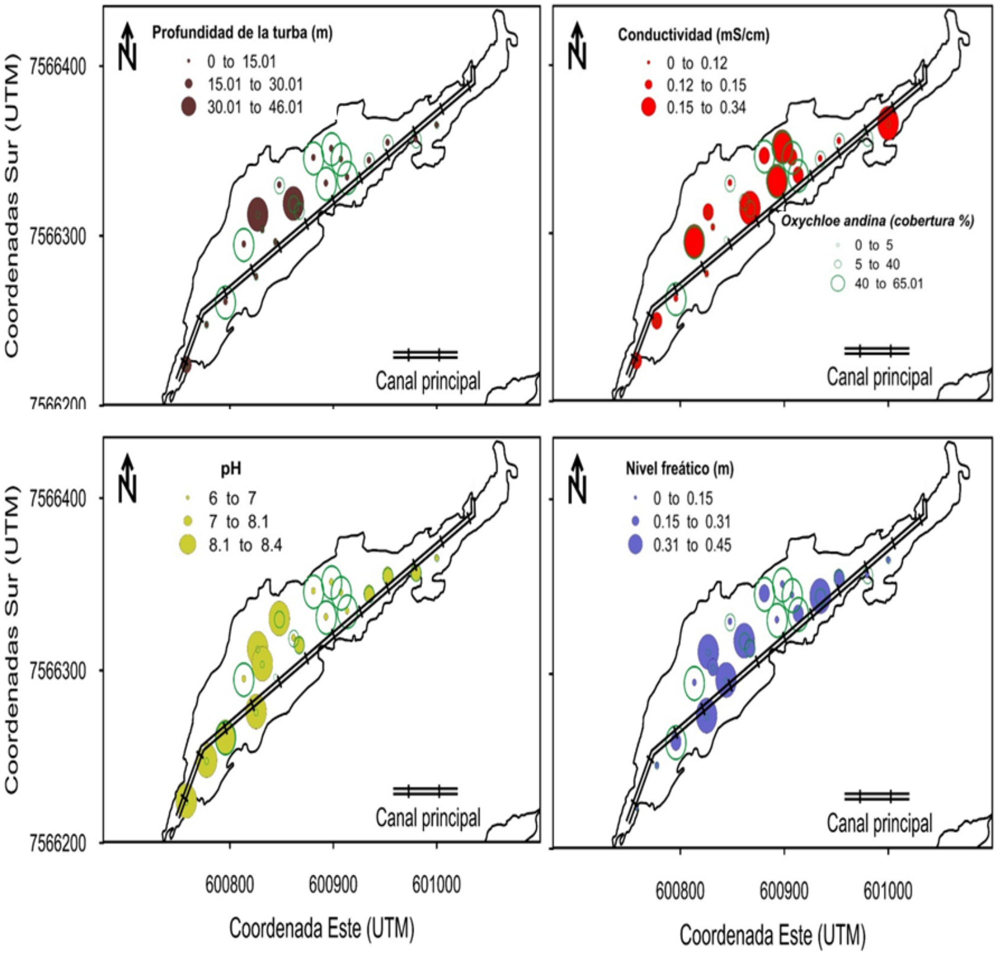


Figure 25: Vegetal cover of Oxychloe andina (%) in relation to the depth of the peat (m), water table (m), pH and electrical conductivity (mS/cm) in the North Bofedal.

4.4.2 Potential evapotranspiration (PET) calculation. Value of the water requirements for the preservation of the Silala bofedal.

ETP for the current area: For the scenario of extension and current state of bofedals (0.76 ha, vegetation cover of 76%), the average annual flow required for maintenance is **0.34 l/s** (Figure 26). Using the crop coefficient or the simulation of evapotranspiration and crop coefficient, they show similar results. This ETP value differs over the months.

ETP for the potential area: In the scenario of potential extension of the bofedals (11.79 ha, vegetation cover of 92%), the flow rate for the conservation of the Silala bofedals is of **5.9 l/s on average annually,** with a fluctuation between **3 and 9 liters per second** between the dry and wet seasons respectively (Figure 27). Using the Crop or evapotranspiration simulation coefficients, both indicate comparable values, which reinforce the reliability of our results. Highlighting that the months that need a greater flow are between November and February. More details can be found in Annex 10.

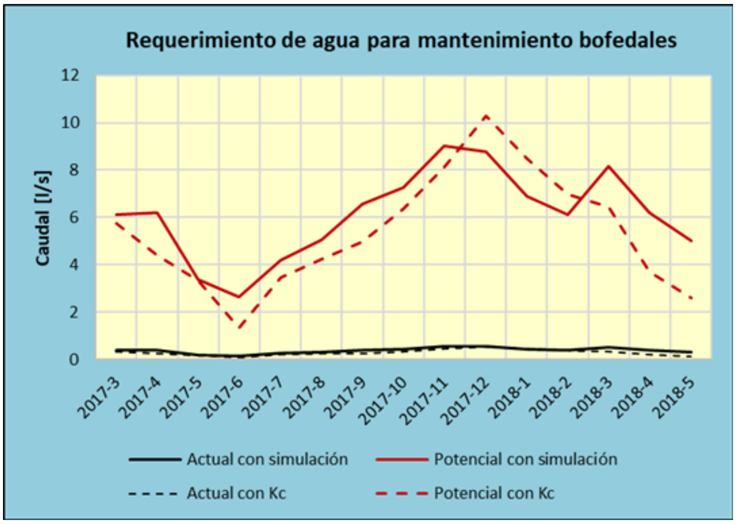


Figure 26: Water requirement for maintenance of the Silala bofedals in liters per second. In black the results are shown for the current area and in red for the potential area.

Annual evapotranspiration (ETP) is **1256 to 1563 mm/year** in the current scenario and **1523 to 1623 mm/year** in the potential area scenario. In both cases the lowest value corresponds to the cultivation coefficient method and the highest to the evapotranspiration simulation. The monthly variation of the monthly evapotranspiration in the bofedals, throughout the study period, is shown in Figure 27. The summary of the ETP calculation for the four developed scenarios is presented in Annex 7.

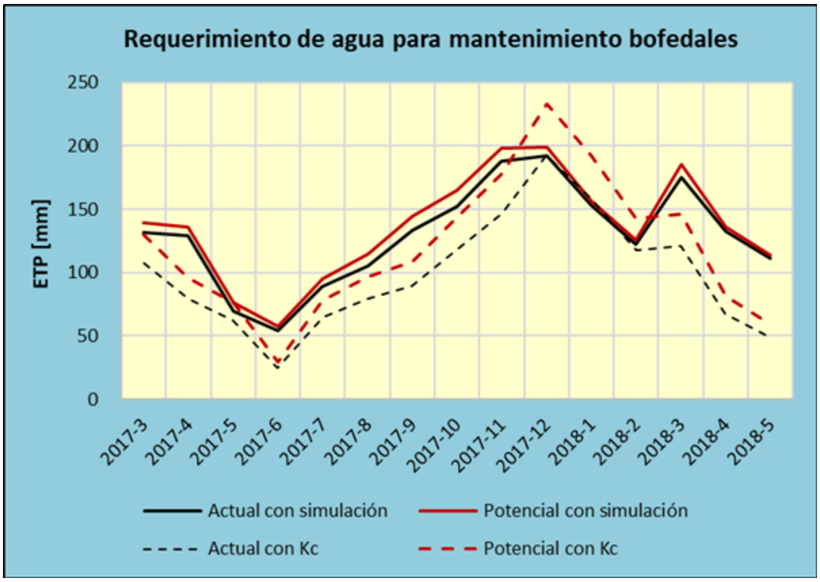
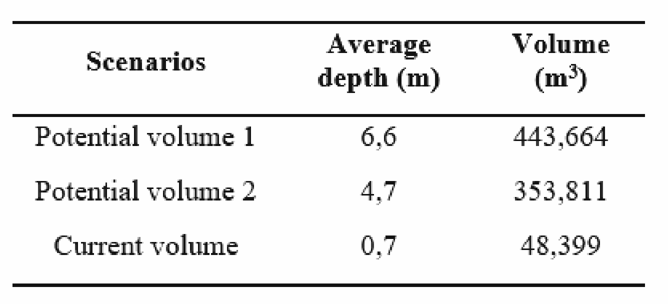


Figure 27. Evapotranspiration in the Silala bofedals in millimeters/month. The results are shown in black for the current area and in red for the potential area.

4.4.3 Calculation of the water volume of the bofedal

Based on our formula and proposed scenarios we obtained three water values (Table 9) that the bofedals need. Under the first scenario with a potential area and an average peat depth of 6.6 m, we would expect the water level to have a minimum of 444 m^3. A second potential volume but adjusting to an average depth of 4.7 m, the volume required for the bofedals is 354 $m^{3.}$ Finally, the current value at which the bofedals are likely to be found is 48.4 m^3.

Table 9. Potential water volume values in the three scenarios.

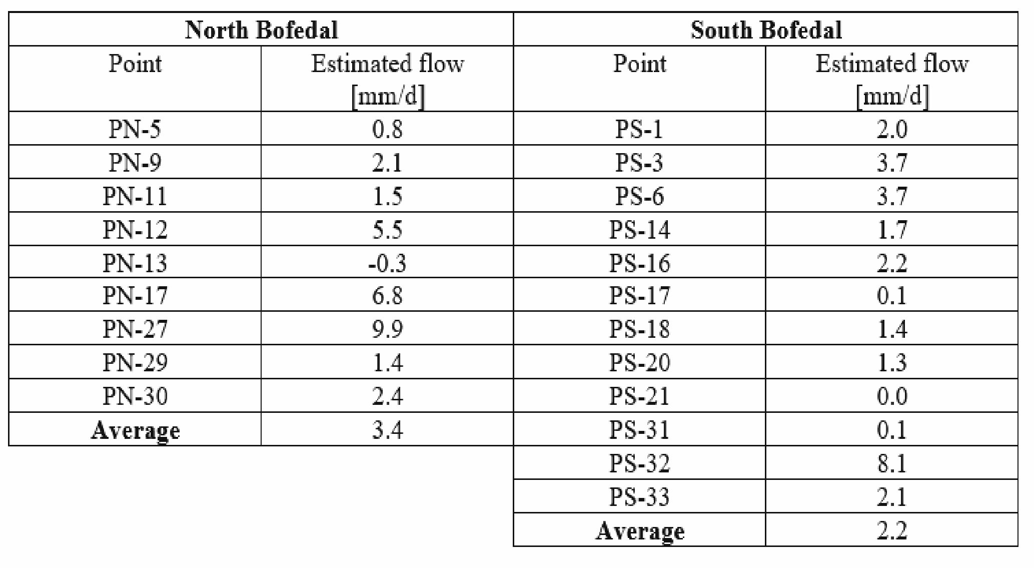


Scenarios	Average depth (m)	Volume (m^3)
Potential volume 1	6,6	443,664
Potential volume 2	4,7	353,811
Current volume	0,7	48,399

4.4.2 Vertical flow calculation

The calculation of vertical flow in the soil from soil moisture and groundwater data shows a predominance of upward flows, which are a reflection of the evapotranspiration process. In the North Bofedal, calculated flows range from 0.8 mm/day to 9.9 mm/day, averaging 3.4 mm/day. In the South Bofedal the calculated flows vary between 0.1mm/d and 8.1 mm/d, averaging 2.2 mm/d. Table 10 shows the results obtained. The evapotranspiration (ETP) for the month of April in the current situation is 131 mm/month, which would be equivalent to a vertical flow of 4.37 mm/day for both Silala bofedals. The calculation of the vertical flow is presented in Annex 8.

Table 10. Vertical flows estimated from humidity and water table measurements

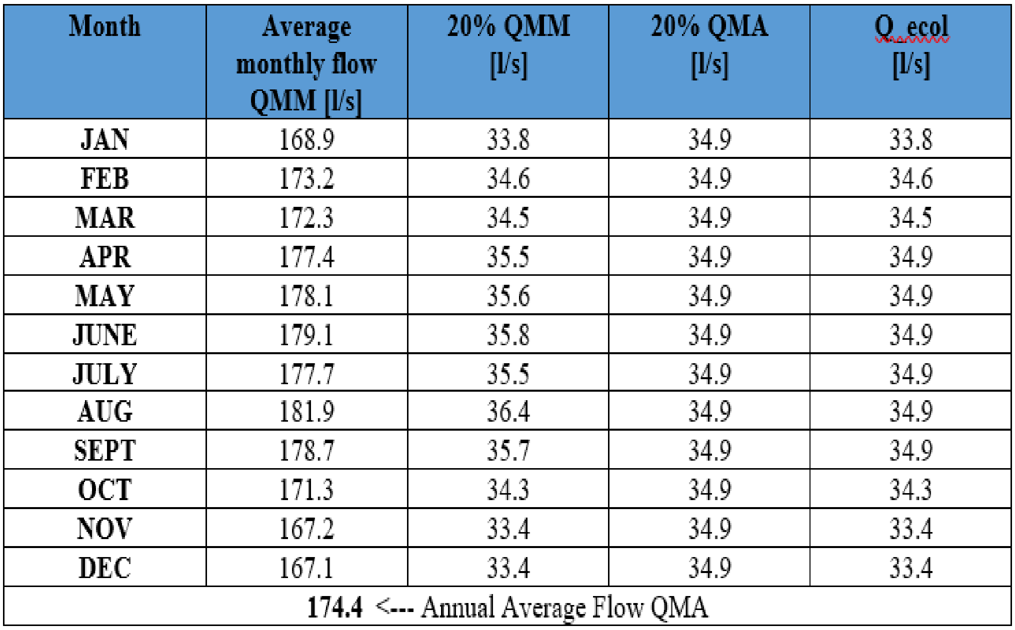


North Bofedal		South Bofedal	
Point	Estimated flow [mm/d]	Point	Estimated flow [mm/d]
PN-5	0.8	PS-1	2.0
PN-9	2.1	PS-3	3.7
PN-11	1.5	PS-6	3.7
PN-12	5.5	PS-14	1.7
PN-13	-0.3	PS-16	2.2
PN-17	6.8	PS-17	0.1
PN-27	9.9	PS-18	1.4
PN-29	1.4	PS-20	1.3
PN-30	2.4	PS-21	0.0
Average	3.4	PS-31	0.1
		PS-32	8.1
		PS-33	2.1
		Average	2.2

4.4.5 Calculation of the minimum ecological flow

In the study area, there are flows with little or no seasonal and inter-annual variation (TECHNICAL CONSULTANTS 2018). That is why the available 2013-2016 flow series are representative and can be used in the calculation of the minimum ecological flow. Table 11 shows the calculation and results obtained.

Table 11. Calculation of the minimum ecological flow according to regulations to determine the minimum ecological flow. Decree 14 (MMA, 2012).



Month	Average monthly flow QMM [l/s]	20% QMM [l/s]	20% QMA [l/s]	Q ecol [l/s]
JAN	168.9	33.8	34.9	33.8
FEB	173.2	34.6	34.9	34.6
MAR	172.3	34.5	34.9	34.5
APR	177.4	35.5	34.9	34.9
MAY	178.1	35.6	34.9	34.9
JUNE	179.1	35.8	34.9	34.9
JULY	177.7	35.5	34.9	34.9
AUG	181.9	36.4	34.9	34.9
SEPT	178.7	35.7	34.9	34.9
OCT	171.3	34.3	34.9	34.3
NOV	167.2	33.4	34.9	33.4
DEC	167.1	33.4	34.9	33.4
174.4 <--- Annual Average Flow QMA				

The calculated minimum ecological flow has little seasonal variation, so it can be reduced to an average value of **Q_{ecol} = 33.4 l/s.**

5. DISCUSSION

5.1. Bofedal characterization

The depth of the water table was greater in the South Bofedal compared to the North Bofedal, suggesting lower water availability in the South Bofedal. In spite of having a punctual data for April, our data are similar to those obtained by the study by Orsag et al. (2017). Our evaluation gives us a general idea about water availability and how it varies in different points of the bofedal. However, the water table must be monitored at least during one hydrological cycle (Table 12). This is because the water level can be affected by the annual and eventual hail of the zone.

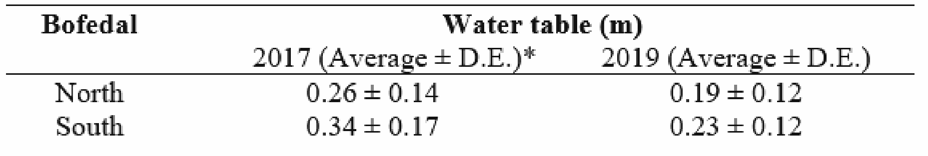
The variability of the water table depth was high in the Silala bofedals. This suggests that water availability is not the same for the entire plant community. Wetlands and bofedals in good conservation status are closely related to near-surface water levels and these values are almost constant throughout the bofedal (Lorini 2013, Cooper et al. 2019). Therefore, our data point to unfavorable water conditions, which affects peat formation, plant species composition and macroinvertebrates.

Average peat depth data were less than 1 m, values similar to those found by Orsag et al. (2017) also for the Silala (Table 12). However, our values are somewhat lower compared to the UERH-COFADENA study (2017) which suggests an average thickness of 1.3 m for the South Bofedal and up to 4 m in the deepest parts of the North Bofedal. We take several sampling points trying to cover the whole bofedal so we consider that we have high reliability of these data.

An average peat of less than 1 m indicates degradation of this ecosystem and its functionality. This is because the conserved bofedals have a much higher level of peat. For example, the peat depth reaches between 3 and 4 m in Aychuta, Sajama (Meneses et al. 2014) or between 4.4 and 6.6 m in Quebrada Negra, Chile (Muñoz and Suárez 2019). Peat production is the result of the balance between plant production and its decomposition (Hribljan et al. 2015, Cooper et al. 2015). Thus, alterations in vegetation and reduced water availability can alter the carbon sink in peat and function more as a resource (Limpens et al. 2008).

That is to say, to cause an increase of CO_2 gases in the atmosphere. In addition, it causes a decrease in water retention capacity.

Table 12. Average value and standard deviation of the water table in the Silala bofedals *Data extracted from Orzag et al. (2017)



Bofedal	Water table (m)	
	2017 (Average ± D.E.)*	2019 (Average ± D.E.)
North	0.26 ± 0.14	0.19 ± 0.12
South	0.34 ± 0.17	0.23 ± 0.12

5.2. Relation between the hydric conditions and the macroinvertebrate and plant community

In the spatial analysis taking into account the important variables it was corroborated that pH and dissolved oxygen are the most important variables to determine not only the key characteristics of each bofedal but also the association with the communities of macroinvertebrates. As in many other aquatic systems, oxygen availability is an important factor in defining the trophic status of habitats that influences the aquatic composition of macroinvertebrates (Wetzel 2001, Domínguez and Fernández 2009).

The depth of the water column is also a determining factor for the macroinvertebrate community. In bofedals it is a critical factor because it affects microhabitat availability, water quality, connectivity and water exchange rate. It therefore influences the composition and richness of macroinvertebrates. It is therefore essential to maintain a depth appropriate to the natural characteristics of the bofedal.

Each of the bofedals that we evaluated had a particular environmental heterogeneity, given by the physicochemical conditions of the water as well as its diversity. Like the Peruvian bofedales (Oyague and Maldonado-Fonkén 2015), the Silala bofedales are important for the physical characteristics of the habitat before the chemical ones. This shows that the conditions of the riverbank and its relationship with the vegetation of the bofedal have a great weight on the community structure.

The peat depth showed high association with a large group of macroinvertebrates including Dugesia, Oligochaeta and several Diptera. This result suggests the existence of preserved patches in the North Bofedal. The relationship with the aquatic fauna is direct and has to do with the degree of vegetation cover as mentioned by Oyague and Maldonado-Fonkén (2015). The bofedal dynamics is very complex, but the relationship between the vegetation and the macroinvertebrate community goes hand in hand, so that the degree of conservation in which the bofedal is found will also be reflected in the structure of the aquatic communities. Where those taxa that are more adapted to this type of environment will be present in greater abundance. Coincidentally, the results with the vegetation suggest that peat depth is an important factor in the structuring of the communities in the North Bofedal, although we did not find that this variable is important to explain the variation in species cover in the South Bofedal.

The water table did not show a significant effect on the composition of plants, both in the North and South bofedal, probably because the point measurements we made are not yet sufficient to explain the coverage of plants, in addition the degraded state of many sites evaluated may be masking the role of this variable in the structuring of plant communities.

Contrary to multivariate results (which take into account all species and various environmental variables), analyses focused on understanding the coverage of Oxychloe andina according to the environmental variables measured, we determined that the peat depth and the physical-chemical conditions of the water (pH and electrical conductivity) are important factors that explain the coverage of this species in the North Bofedal.

5.3. Water requirement of the Silala bofedals

The species O. andina forms the bofedal structure, so its cover and biomass can be used as indicators of representative bofedal sites. Our results show a positive relationship between the cover of this species and the peat depth. This suggests the importance of the productivity of this species for the formation and accumulation of peat. Our analyses also indicate that basic pH conditions and high electrical conductivity are limiting factors for O. andina. This suggests that O.

andina in the Silala bofedal prefers slightly acidic to neutral conditions although it has a wide tolerance range (Meneses 1997).

In our study we did not find a direct relationship between the water table and soil moisture with the cover and biomass of O. andina. It is possible that a specific data as in our case is not enough to understand the relationship of this plant in cushion with the water level. However, Lorini (2013) showed that places with greater coverage of Andean O. are closely related to water table levels between 0 and 0.8 m in a preserved bofedal (Aychuta, PN Sajama). While in a slightly disturbed bofedal (Lagunas, PN Sajama) O. andina is generally found between 0-0.5 m. In addition, according to Lorini (2013) throughout the year, sites with O. andina cover remain more constant and homogeneous compared to sites that are composed of other species. This shows the water retention capacity of this species, which is similar throughout the year. In Silala, the interventions of the canals reduce the water flow even in places where the cushions are, which is why there is no clear pattern. It is hoped that future data from the Silala on the water table will help us to better understand this relationship.

The amount of water required by the Silala bofedals to maintain their condition (ETP) is: 1523 to 1653 mm/year, equivalent to an average annual flow of **5.9 l/s.** This ETP value only shows the volume needed to maintain the system once an adequate volume has been reached. The values we obtained were almost double the one calculated by Muñoz and Suarez (2019) for the Quebrada Negra (1653 versus 698 mm/year), but their data were based on indirect methods (NDVI). However, our calculation is comparable to the work of Zea Mamani (2015), who used the direct method (lysimeter) to calculate ETP in dry puna bofedals in Peru. Thus, our results are very close to the reality of the system. But to have a greater approximation, future studies must evaluate physiological variables of the bofedal vegetation as estomatic conductance of the species and its Index of foliar area.

The evapotranspiration values calculated by DHI (2018) for the current and restored bofedals conditions reach 125 mm/year and 164 mm/year respectively. These values are not comparable with our results because they cover the entire area known as the Near Field, with a total surface area of 2.5 km^2 or 250 ha, including a large expanse of desert, while our results refer to bofedals only up to a potential surface area of 11.79 ha. On the other hand, according to DHI (2018), the evapotranspiration flow between the situation of restored bofedals and the current (reference) situation increases by 3 l/s (from 10 l/s to 13 l/s). In our study, the increase in evapotranspiration flow from the bofedal between the same scenarios is 5.56 l/s (5.9 l/s - 0.34 l/s). If we introduce our result in the water balance calculated by DHI, the flow to Chile will be reduced by 2.5 l/s more than predicted by DHI (2018).

Under current conditions, the Silala bofedals have barely 10% water volume with respect to their potential capacity. In other words, they need to reach an adequate volume (via recovery and conservation) in order to allow the recovery of the peat and the plant community. In time scale, reaching an adequate water level does not mean the same time scale for the vegetation and peat recovery. The plants that form the bofedal structure grow at a rate of less than 10 cm per year as observed for Distichia muscoides (Cooper et al. 2015). And in the peat case, the production of plant matter and favorable (anoxic) and water conditions are needed to achieve proper functioning. This process could take more than ten years until both bofedals are restored.

The vertical flow of water in the soil, estimated from the moisture content in April 2019, varies from 2.2 to 3.4 mm/day; these values reflect the actual evapotranspiration in the Silala bofedals and can be compared with the value of the potential evapotranspiration calculated for the same month, of 4.37 mm/day, for an ideal condition without hydric stress. The lower values obtained in the field show that the bofedals are currently in a state of hydric stress due to the water table depression as a consequence of the drainage of the bofedals through the canals.

We calculate the ecological flow according to Chilean regulations. This estimated value for the Silala bofedals corresponds to 33.4 l/s. According to this regulation, it is the minimum needed to restore potential conditions, guaranteeing adequate hydraulic conditions for the development of peat and vegetation. However, this flow value could increase considering that we are in an arid region and the bofedals need to be restored first.

6. CONCLUSIONS

Based on our results (abiotic and biotic variables) we conclude that both Silala bofedals are in a state of degradation, particularly the South Bofedal. The peat depth of both bofedals varies between 0.1-1.5 m in the North Bofedal and between 0.25-0.8 in the South Bofedal. This value is much lower compared to neighboring and better preserved bofedals that have an approximate of 4 m. The water table depth is high and variable in most of the sites evaluated, indicating heterogeneity in the habitat and non-ideal conditions regarding the water level for the plants. In accordance with these degradation conditions, abiotic cover (bare soil, saline crust, dead vegetation) in the South Bofedal exceeds 50% and 15% in the North Bofedal. The South Bofedal is dominated by species indicating disturbance (Carex cf. maritime) and the North is dominated by Zameiocirpus sp. with some patches of Oxychloe andina. This last species, in spite of being typical of bofedal, is in the middle of the high presence of graminoids.

Preserved bofedal sites are related to a composition of macroinvertebrates associated with bofedales (Dorylaimus, Hydrozetes, Homochaeta), in addition to the Silala bofedals, are positively related to the well depth and peat, providing data on their indicator value of bofedals in good condition.

The vegetal composition of the North Bofedal was not related to the environmental variables (hydric). While the South Bofedal were related to the water table. Since there is no relationship with the environmental variables in the North Bofedal, this does not mean that water availability is not relevant. It should be noted that the water table is a dynamic variable and the water value can be influenced by local events such as hail and it is necessary to know its fortnightly fluctuation ideally. The lowering of the water table at the site also caused the greater gradation of organic matter that reduced the peat depth at the site. Peat depth is an important factor according to our results, we found positive relationship between O. andina cover and peat depth, supporting the role of peat in water retention to maintain healthy O. andina cushions.

It was determined that the vertical upward flow of water in the soil predominates in the Silala bofedals, showing that the evapotranspiration process predominates and not the water infiltration process, supporting the rest of the results on the degradation of the site.

The water requirement to maintain bofedals in potential conditions is 1523 to 1653 mm/year and in current conditions 1256 to 1563 mm/year. These values are comparable between methodologies used (culture coefficient and evapotranspiration simulation) and also according to direct measurement works in similar bofedals.

The volume of water currently retained in the peat of the Silala bofedals is 48.4 thousand m^3, only 10% of its capacity. However, this level should reach a value between 353,811 - 443,664 m^3 to reach its potential volume. The time in which both bofedals can reach their ideal condition is unknown.

The minimum ecological flow rate for the Silala bofedals is 33.4 l/s. This value is based on Chilean regulations. However, the best adaptation must be sought for an arid system, which first needs specific hydric conditions for its recovery. Considering the area estimated by FUNDECO (2018a), the volume that the bofedal should reach is approximately 353.8 thousand m^3 and up to 443.7 thousand m^3 considering the peat depth of Quebrada Negra, values that should be reached before establishing the real ecological flow for the Silala bofedals.

The water requirement to maintain the Silala bofedals in the potential conditions (11.79 ha) is 1523 to 1653 mm/year, which is equivalent to a flow of 5.9 l/s in annual average, with a fluctuation between 3 and 9 liters per second between the dry and wet seasons respectively.

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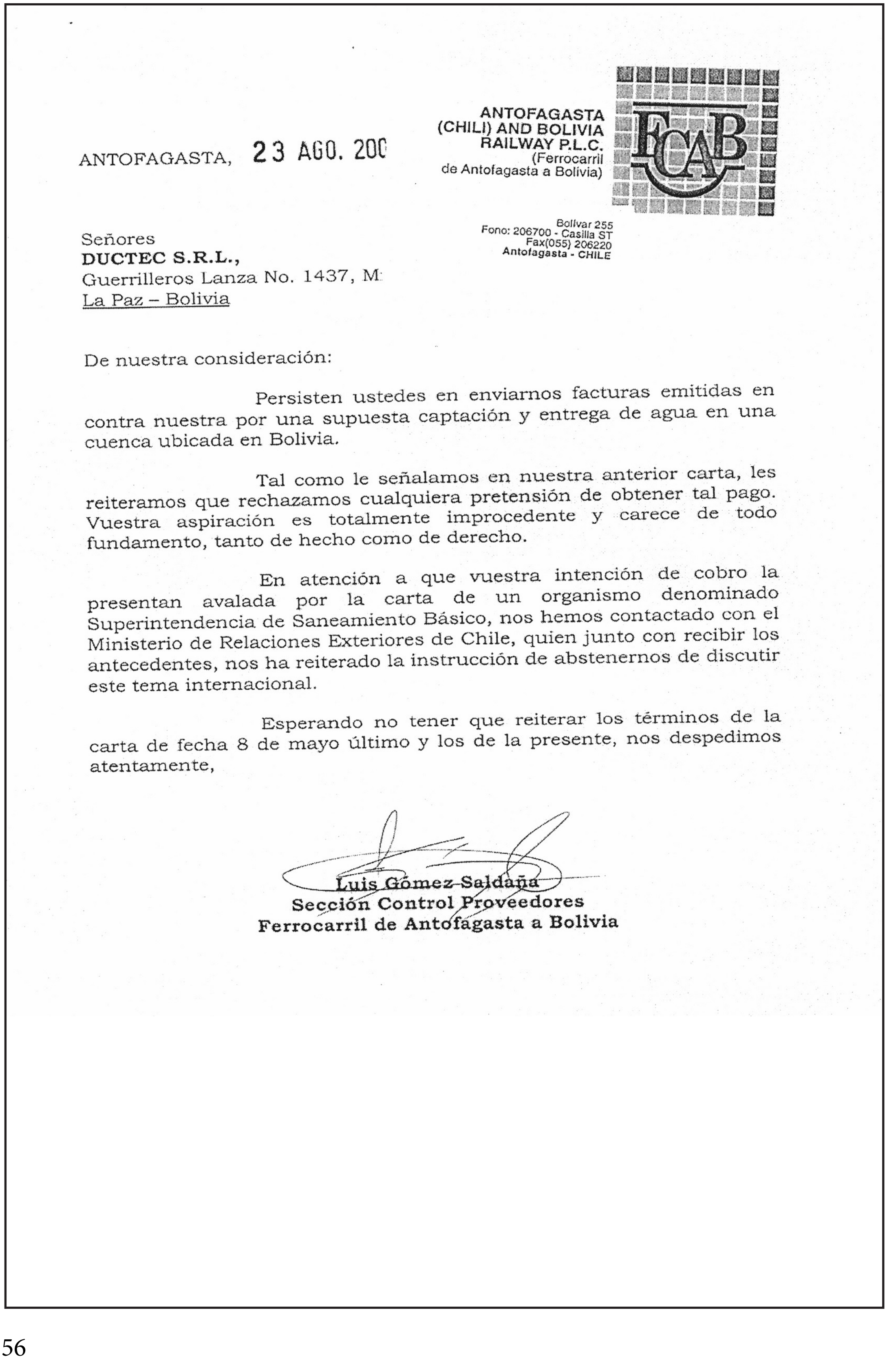
Annex 27

Note S/N of The Antofagasta (Chili) and Bolivia Railway P.L.C addressed to the Company DUCTEC S.R.L., Antofagasta, 23 August 2000

(Original in Spanish, English Translation)



ANTOFAGASTA
(CHILI) AND BOLIVIA
RAILWAY P.L.C.
(Ferrocarril
de Antofagasta a Bolivia)

FCAB

Bolivar 255
Fono: 206700 - Casilla ST
Fax(055) 206220
Antofagasta - CHILE

ANTOFAGASTA, 23 AGO. 200

Señores
DUCTEC S.R.L.,
Guerrilleros Lanza No. 1437, M
La Paz – Bolivia

De nuestra consideración:

Persisten ustedes en enviarnos facturas emitidas en contra nuestra por una supuesta captación y entrega de agua en una cuenca ubicada en Bolivia.

Tal como le señalamos en nuestra anterior carta, les reiteramos que rechazamos cualquiera pretensión de obtener tal pago. Vuestra aspiración es totalmente improcedente y carece de todo fundamento, tanto de hecho como de derecho.

En atención a que vuestra intención de cobro la presentan avalada por la carta de un organismo denominado Superintendencia de Saneamiento Básico, nos hemos contactado con el Ministerio de Relaciones Exteriores de Chile, quien junto con recibir los antecedentes, nos ha reiterado la instrucción de abstenernos de discutir este tema internacional.

Esperando no tener que reiterar los términos de la carta de fecha 8 de mayo último y los de la presente, nos despedimos atentamente,

Luis Gómez Saldaña
Sección Control Proveedores
Ferrocarril de Antofagasta a Bolivia

Letterhead on this page: FCAB's Logo, address and contact information]
ANTOFAGASTA, [Affixed with a date-stamp reading 23 August 2000]

To
DUCTEC S.R.L.,
1437, M Guerrilleros Lanza Street
La Paz-Bolivia

Of our consideration,

You persist in sending invoices issued against us for an alleged abstraction and delivery of water from a basin found in a Bolivia.

As we had explained in our preceding letter, we hereby reiterate that we reject any intention to receive such payment. Your aspiration is completely inadmissible and unfounded, in the facts and law.

Given that your intention to collect charges is underpinned by the letter addressed by an organ named the Superintendence of Basic Sanitation, we have gotten in touch with the Ministry of Foreign Affairs of Chile which, along with receiving the background [data], has reiterated the instruction that we are to abstain from discussing this international matter.

Hoping we will not have to repeat the terms of the letter addressed to you last 8 May, or those of the present letter, we respectfully bid you farewell,

[Signed by]
Luis Gomez Saldana Supplier
Control Area
Antofagasta-Bolivia Railway

Annex 28

1906 Chilean Concession to
THE ANTOFAGASTA-CHILI AND BOLIVIA RAILWAY P.L.C.
Obtained from the data base of Chile's Direction-General of Water, 2019

http://www.dga.cl/Paginas/default.aspx
(Original in Spanish, English Translation)

Derechos de aprovechamiento de aguas registrados en DGA

En esta sección se encuentra la información correspondiente a los derechos originales y solicitudes asociadas registradas en la Dirección General de Aguas, tales como traslados del ejercicio del derecho, cambios de punto de captación y de abastecimiento aprobados, así como a transferencias informadas por usuarios, de acuerdo a lo contemplado en el artículo 122 del Código de Aguas.

La información se proporciona a través de un buscador de derechos, en archivos históricos por región y un consolidado nacional con una actualización mensual.

Listado de derechos concedidos por región:

- XV Región de Arica y Parinacota
- I Región de Tarapacá
- II Región de Antofagasta
- III Región de Atacama
- IV Región de Coquimbo
- V Región de Valparaíso
- Región Metropolitana
- VI Región del Libertador General Bernardo O'Higgins
- VII Región del Maule
- VIII Región del Bío Bío
- IX Región de la Araucanía
- X Región de los Lagos
- XIV Región de los Ríos
- XI Región de Aysén del General Carlos Ibáñez del Campo
- XII Región de Magallanes
- Consolidado nacional

Nota: Los datos proporcionados, están sujetos a constante modificación y actualización, como parte de las labores de fortalecimiento del Catastro Público de Aguas que realiza la DGA y que permitirán disponer de información confiable y oportuna a nuestros usuarios. De la misma forma, esta información, no acredita vigencia del dominio de los derechos de aprovechamiento de aguas registrados en la DGA.

Fecha de actualización: 16/11/2018

Utilitarios

Para poder visualizar los documentos asociados a este contenido le sugerimos visitar estos vínculos:

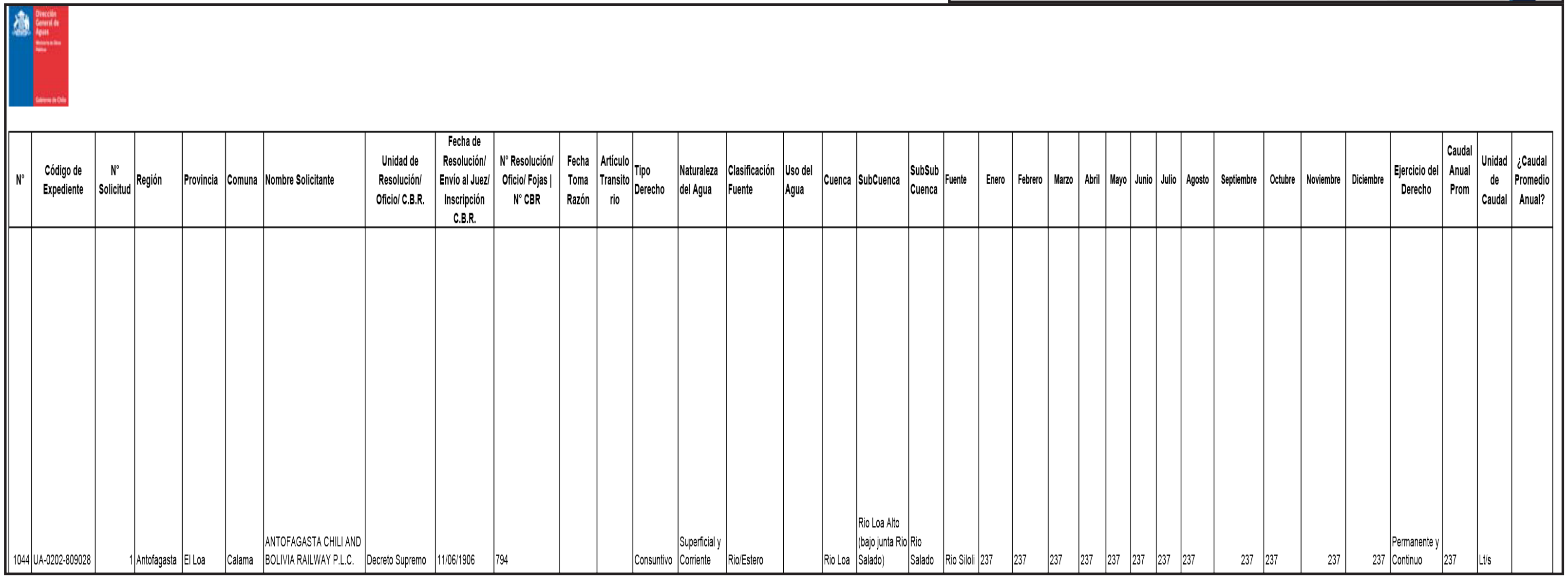
Acrobat Reader

El software Adobe Reader es el estándar mundial para compartir documentos electrónicos. Es el único programa de visualización de archivos PDF que puede abrir todos los documentos PDF e interactuar con ellos.

Word Viewer

Con Word Viewer y el Paquete de compatibilidad, podrá ver, imprimir y copiar el contenido de los documentos en otro programa. No obstante, no podrá editar un documento abierto, guardarlo, ni crear un documento nuevo.

Excel Viewer



N°	Código de Expediente	N° Solicitud	Región	Provincia	Comuna	Nombre Solicitante	Unidad de Resolución/ Oficio/ C.B.R.	Fecha de Resolución/ Envío al Juez/ Inscripción C.B.R.	N° Resolución/ Oficio/ Fojas | N° CBR	Fecha Toma Razón	Artículo Transitorio	Tipo Derecho	Naturaleza del Agua	Clasificación Fuente	Uso del Agua	Cuenca	SubCuenca	SubSub Cuenca	Fuente	Enero	Febrero	Marzo	Abril	Mayo	Junio	Julio	Agosto	Septiembre	Octubre	Noviembre	Diciembre	Ejercicio del Derecho	Caudal Anual Prom	Unidad de Caudal	¿Caudal Promedio Anual?
1044	UA-0202-809028	1	Antofagasta	El Loa	Calama	ANTOFAGASTA CHILI AND BOLIVIA RAILWAY P.L.C.	Decreto Supremo	11/06/1906	794			Consuntivo	Superficial y Corriente	Rio/Estero		Rio Loa	Rio Loa Alto (bajo junta Rio Salado)	Rio Salado	Rio Siloli	237	237	237	237	237	237	237	237	237	237	237	237	Permanente y Continuo	237	Lt/s	

N°	File Code	Application N°	Region	Province	Community	Applicant Name	Date of Resolution/ Sent to Judge/ Registration in C.B.R.*	Water Nature	Source Classification	Water Use	Basin	Sub-Basin	Sub-Sub-Basin	Source	Exercise of Right	Annual Average Flow	Flow Unit
122584	UA-0202-809028	1	Antofagasta	The Loa	Calama	ANTOFAGASTA CHILI AND BOLIVIA RAILWAY P.L.C.	11/6/1906	Superficial and Flowing	River/Estuary		Loa River	Loa Alto River (under the Salado River)	Salado River	Siloli River	Permanent and continuous	237	L/s

Caudal Ecológico (l/s)	¿Caudal Ecológico Promedio?	Acciones en el Cauce	Acciones en la Fuente	UTM Norte Captación (m)	UTM Este Captación (m)	Huso	Datum	Latitud Captación	Longitud Captación	Datum	UTM Norte Restitución (m)	UTM Este Restitución (m)	Latitud Restitución	Longitud Restitución	Referencia a puntos conocidos de captación	Referencia a puntos conocidos de restitución	Distancia	Unidad Distancia	Desnivel (m)	C.B.R.	Fojas	Nº CBR	Año	Código Expediente Antiguo	¿Posee más de un punto de captación?	Nº Certificado/ Año
		0	0	7566250,000	600925,000	19	1956				0	0			F.C.A.B. ES DUEÑA DE UN DERECHO DE 20.500 M3/DIA EQUIVALENTE A 237 L/S. QUE SE CAPTAN DE DOS REPRESAS. REPRESA 1: UBICADA EN EL CAUCE NATURAL DEL RIO SILOLI, EN TERRITORIO DE R. BOLIVIA, A 575 MTS. AL ORIENTE DEL LIMITE INTERNACIONAL CON LA R. DE C HILE. COOR. UTM: 7566250 N Y 600925 E. REPRESA 2: EN EL CAUCE SILOLI, EN TERRITORIO DE CHILE, A 36 MTS. AL OESTE DEL LÑIMITE INTERNACIONAL CHILE-BOLIVIA, COO. UTM. 7565750 N Y 600925 E. LA FUENTE DEL RIO SILOLI ESTA SITUADA EN UNA ZONA DENOMINADA V ERTIENTE DEL CAJON Y PARTE DE LAS VERTIENTES ORIENTALES DEL DEPTO. DE POTOSI, PROV. DE SAN ANTONIO LOPEZ , VICECANTON QUETENE, BOLIVIA, A 3,5 KMS. AL ORIENTE DE LA FRONTERA ENTRE CHILE Y BOLIVIA.		0		0	C.B.R. Calama	2 VTA.	2	1990	PAG. 26 LIBRO II		2778/2011

UTM North Collection Works	UTM East Collection Works	Reference to known points of collection	C.B.R.	Pages	C.B.R. N°	Year	Old File Code	Certificate N° / Year
7566250	600925	F.C.A.B. owns a right of 20,500 m^3/day equivalent to 237 l/s that are collected from two dams. Dam 1: Located in the natural course of the Siloli River, in the territory of the Republic of Bolivia, 575 meters east of the international boundary with the Republic of Chile, UTM Dam 2: In the Siloli channel, in the territory of Chile, 36 meters west of the Chile-Bolivia international boundary, UTM Coordinates: 7565750 N and 600925 E. The source of the Siloli River is located in an area called the Cajon spring and part of the eastern springs of the Department of Potosi, Province of San Antonio Lopez, Quetene Vice-Canton, Bolivia, 35.5 kilometers east of the border between Chile and Bolivia.	Calama C.B.R.	2 VTA.	2	1990	Page 26, Book II	2778/2011

Datos usuario

Código de expediente / Número solicitud		
UA-0202-809028/1		
RUN / RUT	**Nombre solicitante**	**Tipo solicitante**
81148200-5	ANTOFAGASTA CHILI AND BOLIVIA RAILWAY P.L.C.	Juridico
Región	**Provincia**	**Comuna**
Antofagasta	El Loa	Calama

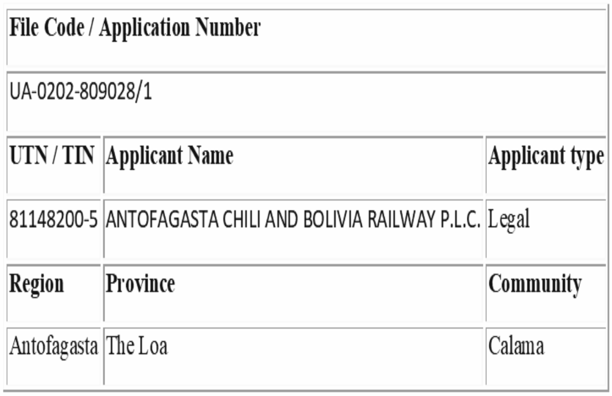
Datos derecho concedido

Naturaleza del agua	Clasificación fuente	Tipo derecho
Superficial y Corriente	Rio/Estero	Consuntivo
Unidad de resolución/ Oficio/ C.B.R.	**Fecha de resolución/ Envío al juez/ Inscripción C.B.R.**	**Nº resolución/ Oficio/ Nº CBR**
Decreto Supremo	11/06/1906	794
Fecha toma razón Contraloria	**Artículo transitorio**	**Uso del agua**
	NULL	NULL
Cuenca	**Subcuenca**	**Subsubcuenca**
Rio Loa	Rio Loa Alto (bajo junta Rio Salado)	Rio Salado
Fuente	Rio Siloli	

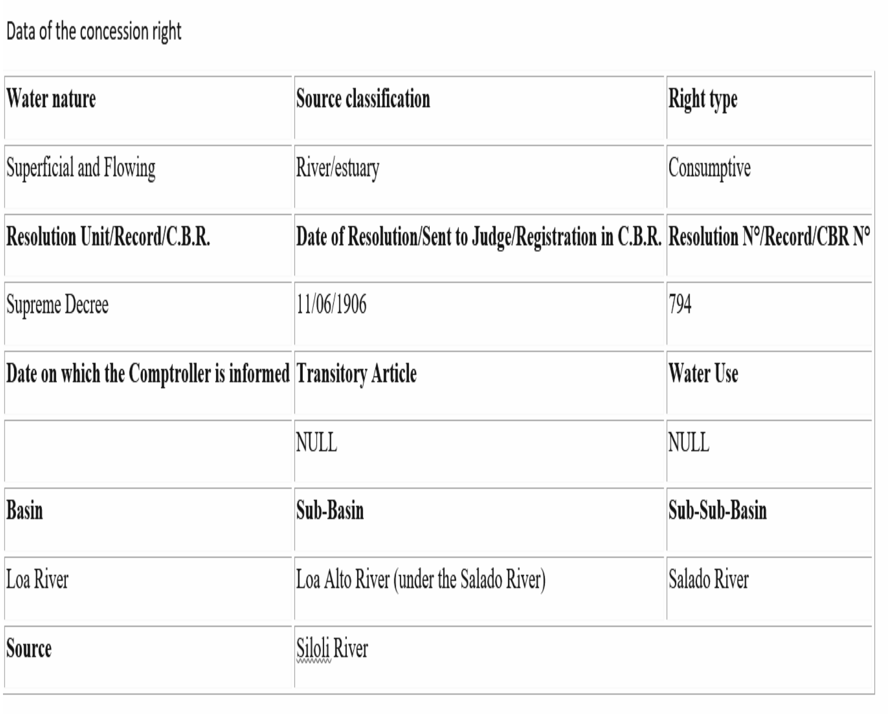
Datos de caudal

Enero	Febrero	Marzo	Abril	Mayo	Junio	Julio	Agosto	Septiembre	Octubre	Noviembre	Diciembre
237	237	237	237	237	237	237	237	237	237	237	237

Ejercicio del derecho	Caudal anual promedio	Unidad de caudal	¿Caudal promedio anual?

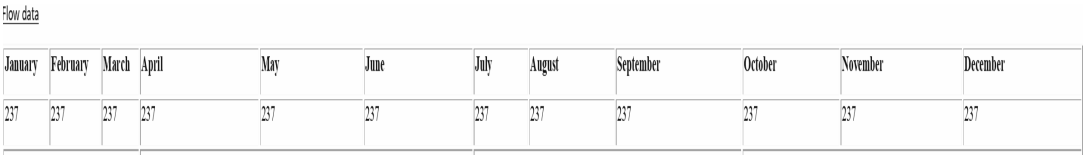


File Code / Application Number		
UA-0202-809028/1		
UTN / TIN	**Applicant Name**	**Applicant type**
81148200-5	ANTOFAGASTA CHILI AND BOLIVIA RAILWAY P.L.C.	Legal
Region	**Province**	**Community**
Antofagasta	The Loa	Calama



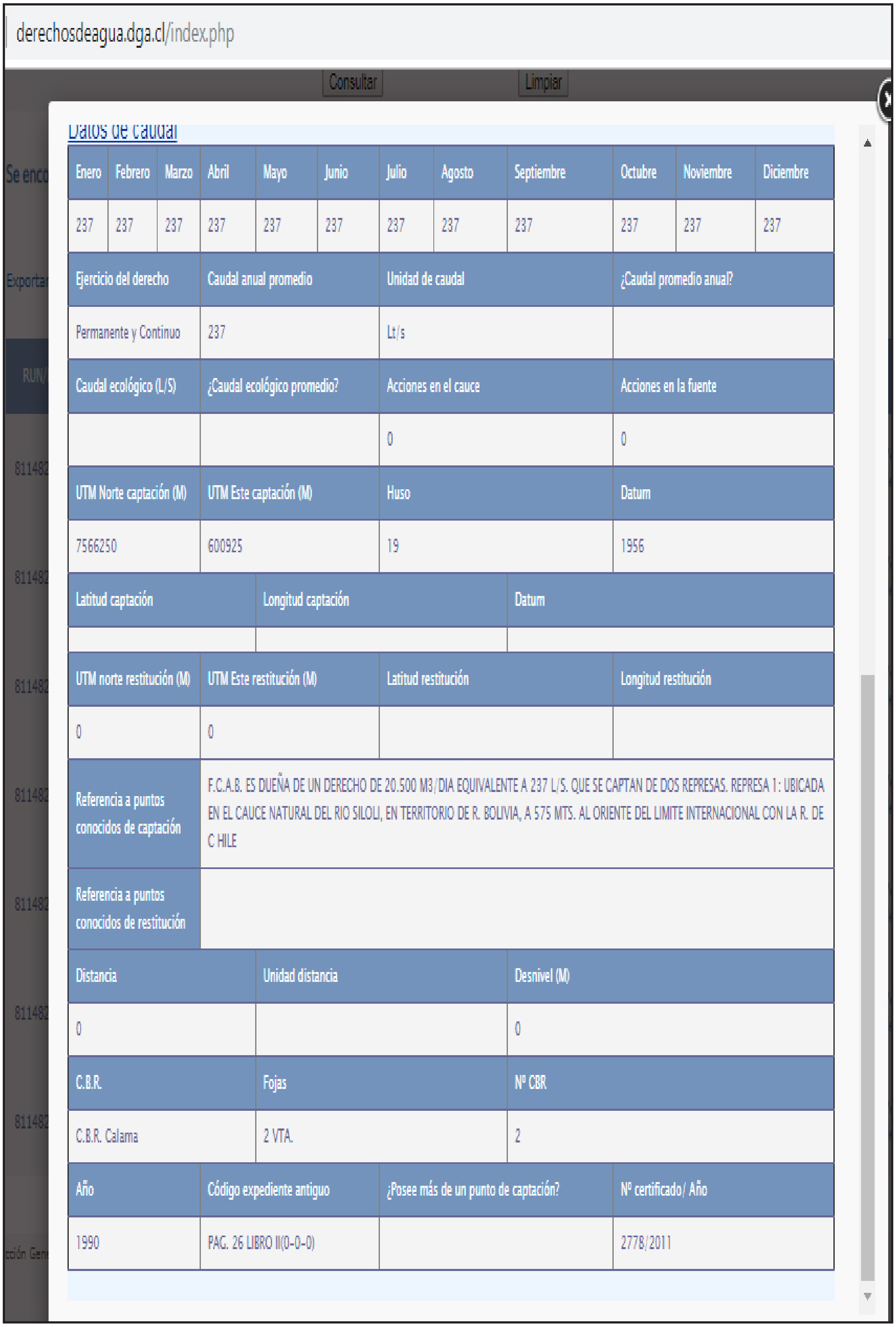
Data of the concession right

Water nature	Source classification	Right type
Superficial and Flowing	River/estuary	Consumptive
Resolution Unit/Record/C.B.R.	**Date of Resolution/Sent to Judge/Registration in C.B.R.**	**Resolution N°/Record/CBR N°**
Supreme Decree	11/06/1906	794
Date on which the Comptroller is informed	**Transitory Article**	**Water Use**
	NULL	NULL
Basin	**Sub-Basin**	**Sub-Sub-Basin**
Loa River	Loa Alto River (under the Salado River)	Salado River
Source	Siloli River	



Flow data

January	February	March	April	May	June	July	August	September	October	November	December
237	237	237	237	237	237	237	237	237	237	237	237



Datos de caudal

Enero	Febrero	Marzo	Abril	Mayo	Junio	Julio	Agosto	Septiembre	Octubre	Noviembre	Diciembre
237	237	237	237	237	237	237	237	237	237	237	237

Ejercicio del derecho	Caudal anual promedio	Unidad de caudal	¿Caudal promedio anual?
Permanente y Continuo	237	Lt/s	

Caudal ecológico (L/S)	¿Caudal ecológico promedio?	Acciones en el cauce	Acciones en la fuente
		0	0

UTM Norte captación (M)	UTM Este captación (M)	Huso	Datum
7566250	600925	19	1956

Latitud captación	Longitud captación	Datum

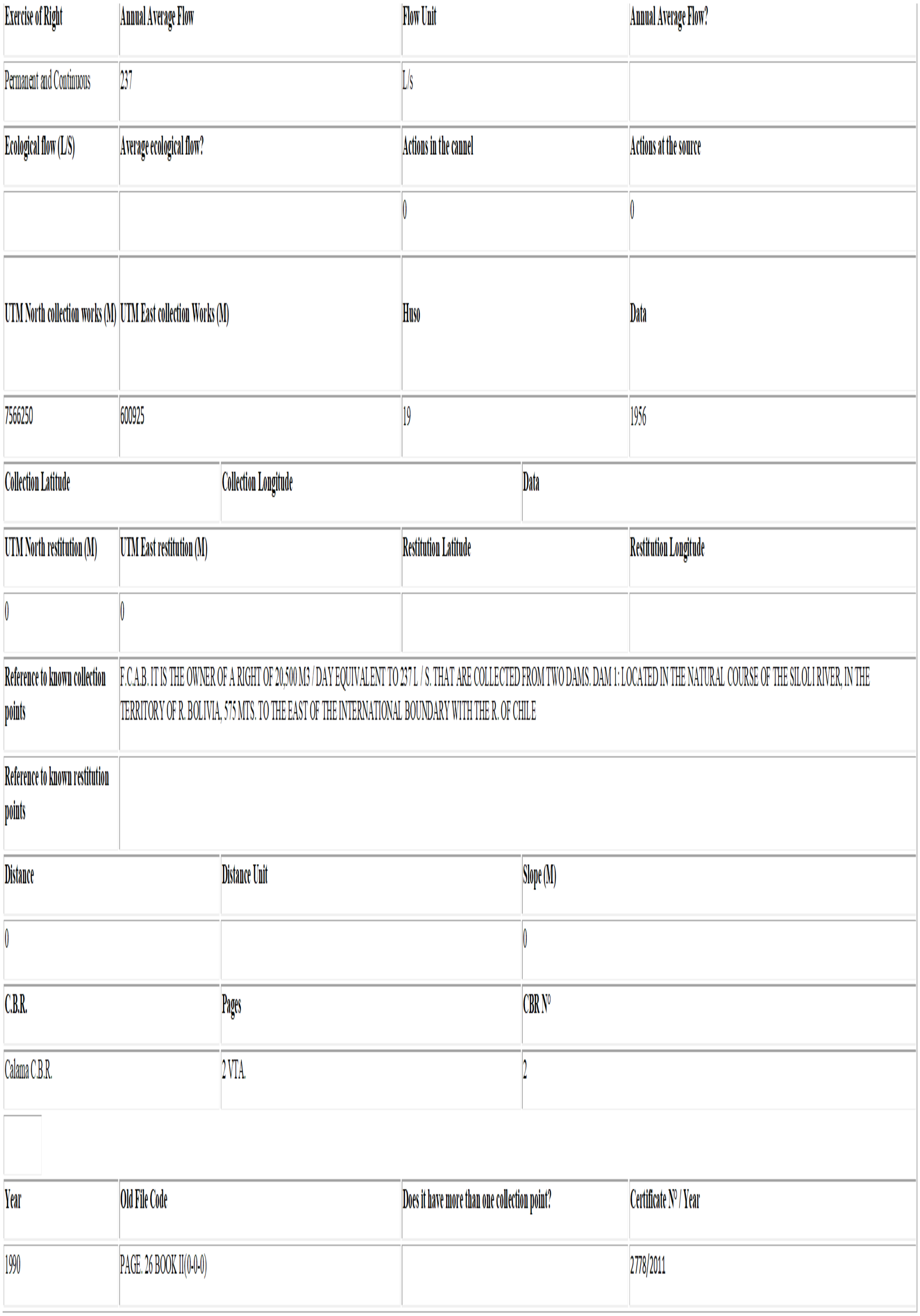
UTM norte restitución (M)	UTM Este restitución (M)	Latitud restitución	Longitud restitución
0	0		

Referencia a puntos conocidos de captación	F.C.A.B. ES DUEÑA DE UN DERECHO DE 20.500 M3/DIA EQUIVALENTE A 237 L/S. QUE SE CAPTAN DE DOS REPRESAS. REPRESA 1: UBICADA EN EL CAUCE NATURAL DEL RIO SILOLI, EN TERRITORIO DE R. BOLIVIA, A 575 MTS. AL ORIENTE DEL LIMITE INTERNACIONAL CON LA R. DE C HILE
Referencia a puntos conocidos de restitución	

Distancia	Unidad distancia	Desnivel (M)
0		0

C.B.R.	Fojas	Nº CBR
C.B.R. Calama	2 VTA.	2

Año	Código expediente antiguo	¿Posee más de un punto de captación?	Nº certificado/ Año
1990	PAG. 26 LIBRO II(0-0-0)		2778/2011



Exercise of Right	Annual Average Flow	Flow Unit	Annual Average Flow?
Permanent and Continuous	237	L/s	

Ecological flow (L/S)	Average ecological flow?	Actions in the cannel	Actions at the source
		0	0

UTM North collection works (M)	UTM East collection Works (M)	Huso	Data
7566250	600925	19	1956

Collection Latitude	Collection Longitude	Data

UTM North restitution (M)	UTM East restitution (M)	Restitution Latitude	Restitution Longitude
0	0		

Reference to known collection points	F.C.A.B. IT IS THE OWNER OF A RIGHT OF 20,500 M3 / DAY EQUIVALENT TO 237 L / S. THAT ARE COLLECTED FROM TWO DAMS. DAM 1: LOCATED IN THE NATURAL COURSE OF THE SILOLI RIVER, IN THE TERRITORY OF R. BOLIVIA, 575 MTS. TO THE EAST OF THE INTERNATIONAL BOUNDARY WITH THE R. OF CHILE
Reference to known restitution points	

Distance	Distance Unit	Slope (M)
0		0

C.B.R.	Pages	CBR Nº
Calama C.B.R.	2 VTA.	2

Year	Old File Code	Does it have more than one collection point?	Certificate Nº / Year
1990	PAGE. 26 BOOK II(0-0-0)		2778/2011