Summary of DHI's Scientific Findings Regarding the Dispute over the Status and Use of the Waters of the Silala (Chile v. Bolivia)

Written Statement by DHI

10-01-2022

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This document has been requested by the International Court of Justice (ICJ) in the Dispute over the Status and Use of the Waters of the Silala (Chile v. Bolivia). The document summarises DHI's work in assessing Silala surface water and groundwater flows emphasising the areas where DHI agrees with Chile's experts and the points as to which DHI disagrees with Chile's experts.

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1 EXECUTIVE SUMMARY

The Silala wetlands and springs in Bolivia are located 0.5-3 km from to the border to Chile in the southwestern part of the Potosi Department. During the first part of the last century these wetlands were drained and channelized and their outflow of water utilized by the Antofagasta (Chili) and Bolivian Railway Company Ltd. in Chile. In 2017, upon request by of the Plurinational State of Bolivia, DHI carried out a technical study of the flows of the Silala Wetland and Spring System in Bolivia quantifying the surface and subsurface flows, both in their current condition, with man-made canals and drainage network, and in their assessed natural state.

A key objective has been to make an independent analysis of the Silala surface waters and groundwater aquifers to determine their nature and connectivity. This required gaining and documenting factual physical knowledge and understanding of the Silala system to create a transparent foundation for the analysis and subsequent conclusions.

These objectives were accomplished by employing the following technical methodology:

a) Detailed field data collection programs that were conducted on-site in Bolivia including:
   - detailed surveys and soil sampling programs
   - monitoring of surface water and spring flows in the Silala wetlands in Bolivia and
   - an intensive hydrogeological characterization program of the groundwater aquifer

b) Detailed numerical modelling studies simulating the groundwater/surface water flow patterns and exchanges both under the current and under natural conditions (i.e., without the artificial canals and drainage network and with restored wetlands).

1.1 Main findings in which DHI *agrees* with Chile's experts

1) The main source of surface water of the Silala springs is groundwater discharge[1], and the surface waters interact with the underlying groundwater along their course.

2) The canals have not changed the overall direction of flow in surface water or groundwater.

3) Silala is of a complex nature and comprised of a coupled groundwater-surface water system originating in Bolivian territory (upstream) and extending into Chile (downstream).

4) The evaporation from the wetlands will increase if the canals are removed.

5) Surface water flows will decrease, and groundwater flow increase at the border if the canals are dismantled, and the wetlands restored to their natural conditions.

6) The collected field data and the established models suggest that the water discharged from the Silala catchment[2] (accounting for the evapotranspiration[3] losses from the soils, wetlands and canals) eventually flows to Chile either as groundwater or as surface water, with or without the canals.

1.2 Main findings where DHI *disagrees* with Chiles experts

7) The magnitude of the decrease in cross-border surface water flow in the natural condition (i.e., without the canals and drainage network). DHI's estimated range of decrease, based on on-site field data and modelling, is 11% - 33% while Chile states (without detailed calculations) that it is negligible.

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[1] In hydrology, discharge is the outflow of water from a river, aquifer,lake or other body of water.

[2] A catchment is an area of land where precipitation collects and drains off into a common outlet.

[3] Evapotranspiration is the process by which water is transferred to the atmosphere by 1) evaporation from the soil and other surfaces and by 2) transpiration from plants

8) Historical surface flow measurements from before channelization show an 18% decrease relative to the present flows and is consistent with DHI's range of results. Chile does not recognize the value of these historical measurements.

9) Chile's experts state that due to inaccuracies in the input data, DHI's Near Field model cannot be used to predict impacts on the cross-border flow from the man-made drainage structures. On the contrary DHI finds that the Near Field model, which is based on and calibrated against actual field measurements in the area of impact, provides the best basis for the impact assessments despite inaccuracies or uncertainty that are inherent to all such models.

10) Chile's experts dispute DHI's measurements, interpretations, analyses and models but have not presented any detailed alternative analyses reflecting Silala site conditions and the varying properties of the Silala wetlands. Nor have they presented any detailed hydrological analysis or in-depth impact assessment.

2 ABOUT THE EXPERT

11) DHI (formerly named: Danish Hydraulic Institute) is an independent and not-for-profit organisation based in Denmark with 30 offices and about 1,100 full-time employees worldwide. DHI is a research and advisory company specialised in solving challenges in the water environment. For more than 50 years, DHI has spearheaded the development of applied technology for water resources assessments and has executed multiple studies of resource availability and sharing, flood forecasting and planning, and assessment of impacts on the water environment from manmade infrastructure. Since advanced software packages for simulating the water flows are often crucial parts of such projects, DHI encapsulates its experience and knowledge from such projects into advanced water modelling software packages (commercialized under the "MIKE" trademark). For decades, thousands of water professionals around the world (authorities, water utilities, energy and irrigation companies and engineering consultants) use DHI know-how and technologies to solve their water challenges. The MIKE SHE software is developed by DHI specifically for detailed investigations of hydrological systems in which surface water and groundwater interact closely, which makes this software particularly well suited to investigate the Silala case.

12) DHI has been involved in projects all over the world and is very experienced in sustainable management of water resources, including interacting groundwater and surface water resources. DHI has worked intensively with mountain hydrology, not least in the Andes, and has built water management systems for large wetlands such as the Everglades, the Okavango and some of the largest deltas in the world, among others Ganges/Brahmaputra, Mekong, Ayeyarwady and Yangtze. DHI has also been instrumental in the development of modern principles for integrated water resources management and has a standing collaboration centre with the United Nations Environment Programme (UNEP) to further promote this topic.

13) Furthermore, DHI has been responsible for the hydraulic designs of large internationally sensitive infrastructure projects ensuring low environmental impacts, such as the large bridge crossings of the Great Belt and the Oresund potentially influencing the salinity of the Baltic Sea. The Institute has also participated as technical expert in transboundary water cases such as the *"Land reclamation by Singapore in and around the straits of Johor (Malaysia vs. Singapore)"* case before the ITLOS, the *"Gabčíkovo-Nagymaros Project (Hungary v. Slovakia)"* case before the ICJ and the *"Indus Waters Kishenganga Arbitration"* (Pakistan v. India).

2.1 DHI's experts

14) **Mr. Roar A. Jensen** (MSc) has led DHI's team in this project. Mr. Jensen is a senior hydrologist and water resources expert. He has more than 35 years of experience in water resources planning and water resources assessment originating from numerous projects carried out in many European, Latin American, Asian and African countries where, over the years, he has collaborated with numerous water

resources institutions, acting both as Project Manager and as a principal hydrologist. He has been responsible for flood management and forecasting projects, assessment of water availability and water resources planning, with conjunctive use of groundwater and surface water. Mr. Jensen is a very experienced mathematical modeller with extensive experience from the high Andes.

15) **Dr Torsten V. Jacobsen** has been the principal surface water and groundwater modelling specialist. He has an MSc in Civil engineering with specialization in hydraulic and hydrological models, a PHD in fluid dynamics and more than 25 years of experience in complex hydraulics and hydrology obtained from water resources projects in Denmark, elsewhere in Europe, USA, Africa, Asia, South America and Australia. In these projects he has been a principal expert in the fields of integrated hydrology, water resources modelling and water management. He has managed a wide range of consultancy and research projects, which have included assessment of surface and groundwater resources and their interaction, water resources management, wetland management and restoration, groundwater protection and climate change. Dr Jacobsen has also worked extensively on wetlands in both arid, semi-arid and humid basins.

16) **Mr. Michael M. Gabora (MSc)** led the hydrogeological characterization study and hydrogeological conceptual model development components of the project. He has over 22 years of professional experience in scoping, implementing and managing hydrologic and hydrogeologic studies. His experience includes a wide range of projects but have primarily been focused on hydrogeologic characterization and numerical groundwater modelling of fractured rock aquifers for dewatering, groundwater exploration, groundwater–surface water interactions and contaminant transport studies. Mr. Gabora has worked extensively throughout the arid Andes in Bolivia, Chile, Argentina, and Peru on projects concerning evaluation of environmental impacts for planned or existing infrastructure, engineering designs and support of water related decision-making. This experience includes hydrogeological studies in well-developed high-altitude wetlands (bofedales) in Argentina, as well as many other studies for which groundwater–surface water interactions were a critical component of the environmental impact analysis. Mr. Gabora has a Bachelor of Science in Earth and Planetary Sciences and a Master of Water Resources degree, both from the University of New Mexico. Mr. Gabora is also a Professional Geoscientist (Ontario, Canada), a Registered Geologist (Arizona, USA) and a Certified Professional Hydrologist by the American Institute of Hydrology.

2.2 DHI's role in the proceedings

17) In 2017, at the request of the Plurinational State of Bolivia, DHI carried out a technical study of the flows of the Silala Wetland and Spring System, quantifying the surface and subsurface flows, both in their current condition and in their natural state, i.e. flows without the man-made canal and drainage network. A key objective has been to make an independent analysis of the Silala surface waters and groundwater to determine their nature and connectivity. It was also important to gain and document factual physical knowledge and understanding of the Silala system to create a scientifically based foundation for the analysis and subsequent conclusions.

18) In this connection DHI prepared the following reports which have been submitted to the Court:

- **(DHI 1)**: Study of the Flows in the Silala Wetlands and Springs System (part of Bolivia's Counter Memorial (BCM, Annex 17). This report and its annexes describe in detail the extensive field data collection and analyses of the hydrological and hydrogeological conditions in Silala along with flow impact assessments.
- **(DHI 2)**: Technical Analysis and Independent Validation Opinion of Supplementary Technical Studies Concerning the Silala Springs, December 2018 (Bolivia's Rejoinder, Annex 23). This report contains DHI's overall technical review of Bolivian technical Studies on the Silala initialized after (DHI 1). The report includes copies of the original Bolivian Studies.
- **(DHI 3)**: Analysis and Assessment of Chile's reply to Bolivia's counter claims on the Silala Case, Mar 2019, (Bolivia's Rejoinder, Annex 24) containing DHI's comments on the observations of Chile's experts regarding (DHI 1) and (DHI 2).

- **(DHI 4)**: Updating of the mathematical hydrological model scenarios of the Silala spring waters with: Sensitivity analysis of the model boundaries, April 2019 (Bolivia's Rejoinder, Annex 25). This report describes the results of a sensitivity analysis of more restrictive boundary conditions leading to the impacts of the artificial drainage system being defined as a range between an upper and a lower bound. The report also comments on Chile's experts' responses (W&P 3 and W&P 4).

After the submission of DHI's last report to the Court, Chile's experts have, in Chile's Additional Pleading (W&P 5), raised further considerations on DHI's assessments. DHI has not had the opportunity to comment on these latest considerations to the Court.

3 THE CHARACTERISTICS OF THE SILALA

19) The Silala bofedales are Ramsar-designated wetlands[4] located in the Bolivian high Andes at an altitude of around 4300 m above sea level, close to the Bolivia-Chile border. The surrounding catchment and the wetlands are sloping from Bolivia towards Chile and surrounded by volcanoes rising to 5600 m above sea level. It is an area with a harsh windy and cold climate, very sparse vegetation, and the closest populated area in Bolivia is more than 20 km away. Coarse soils dominate the catchment upstream of the Silala springs and allow for the sparse precipitation to infiltrate into the topsoils, leaving few traces of flowing surface water. Much of the infiltration from the smaller precipitation events evaporates from the topsoil in the dry climate. Hence only larger precipitation events provide significant recharge to the groundwater.

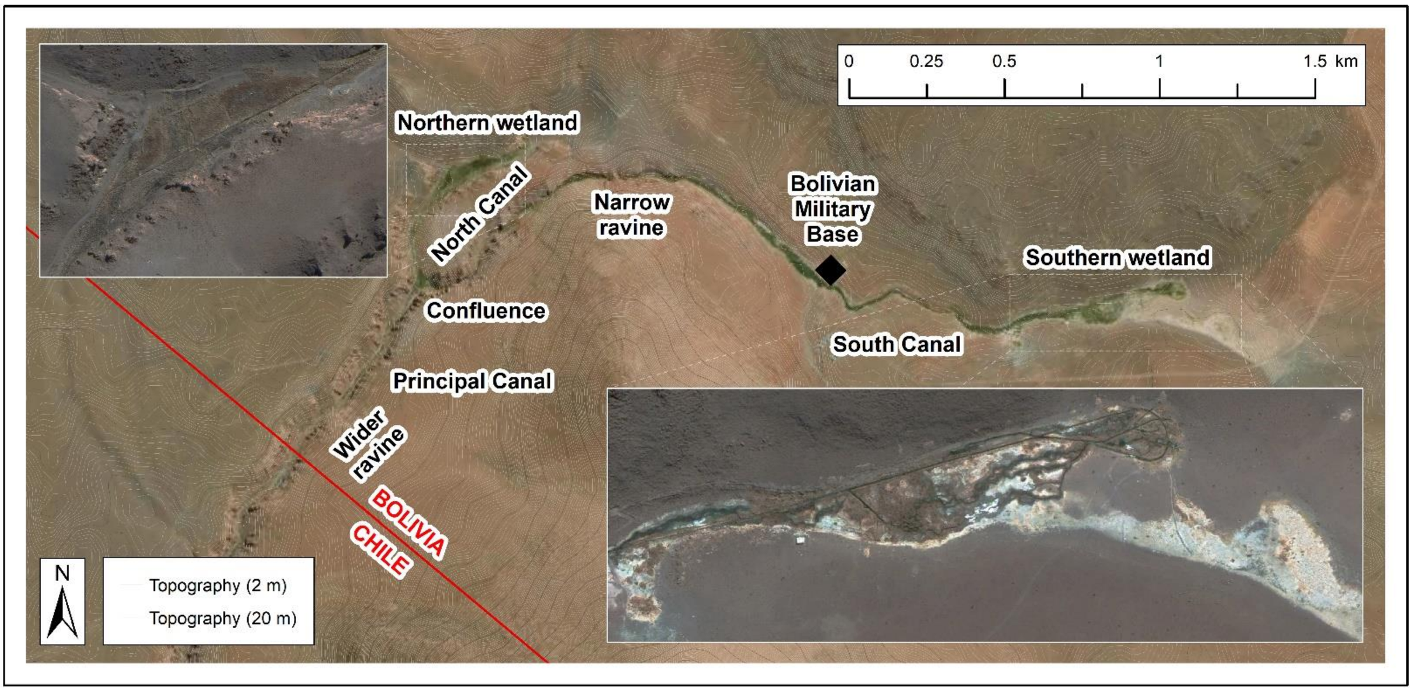

Figure 3-1 Sketch of the Silala wetlands in Bolivia.

20) The bofedales of Bolivia (the type of high-altitude wetlands to which the Silala wetlands belong) constitute fragile ecosystems with unique flora and fauna – a sort of oasis in the dry arid landscape. The spring discharge and partly inundated topsoils of natural bofedales support a unique ecosystem. These conditions that were natural to the Silala have been seriously degraded. With exception of the

[4] A Ramsar designated wetland is a site regarded to be of international importance under the 1971 Ramsar Convention on Wetlands of International Importance Especially as Waterfowl Habitat ("Ramsar Convention").

rather inaccessible crater lakes on the top of Volcan Inacaliri, the Silala wetlands and related surface waters constitute the only permanent fresh surface water source in Bolivia within a 20 km radius.

21) Around 1910, the Antofagasta and Bolivia Railway Company Ltd. started piping the outflow from the Silala Wetlands in Bolivia to the railway for use in the steam locomotives. Subsequently, in 1928, the Company constructed a dense network of 6.4 km of drainage canals and pipes inside Bolivian territory. This artificial infrastructure routes the water quickly from each of the many springs in the wetlands to the Chilean border where today it is still collected and piped to supply remote water users.

22) The Silala wetlands are formed by a number of springs at two different locations (termed by DHI as the Southern and the Northern wetlands) where groundwater is discharged to the surface (Figure 3-1). In total, 138 individual springs have been excavated and connected by individual drainage canals or drain pipes to the two main collector canals (the North Canal and the South Canal). From the Southern wetland the South Canal leads the water through a narrow and steep ravine to the confluence point where it joins the North Canal from the Northern wetland. From the confluence point, the main canal conducts the combined outflow from the Northern and Southern wetlands to the border through a steep but wider ravine.

23) Before the channelization, sustained groundwater discharge through springs allowed for the development of the bofedales in the Northern and Southern wetlands and along the ravine bottoms, and significant peatlands developed.

24) Within the arid Andes, experience has shown that extensive bofedal systems often occur in areas of highly fractured rock that can transmit significant groundwater and are connected to regional aquifers that can sustain flows. This is consistent with the observed situation in Bolivia's Silala. It is also well known that bofedales are highly sensitive to relatively small changes in groundwater elevations (Cooper et al., 2019; Cooper et al., 2015; FUNDECO, 2019 RB, Vol. 5, Annex 26). Oyague and Copper (2020) provide a general description of bofedales: "… plant shoots grow so densely packed that they form an almost waterproof dam that limits lateral water movement, and when the cushions touch, they isolate pools which prevents rapid drainage". This explains how natural bofedales can maintain pools of surface water on the wetland surface – even in sloping terrains. It also indicates that the materials that would have been excavated and removed to construct the drainage network must be expected to have been low permeable and therefore possibly restricting the natural outflow through the springs.

25) In Silala, the artificial drainage network lowered the groundwater levels within the wetlands to below the soil surface and dried out the previously saturated soils that had exhibited widespread stagnant or slow flowing water on the surface**.** Consequently, in the present Silala wetlands less water is now available for direct evaporation from the surface and for transpiration[5] than in the un-channelized natural situation (see Figure 3-2). The vegetation in the drained areas is presently dominated by grasses characteristic of upland areas where depth-to-groundwater is greater. The drainage and its elimination of the former widespread stagnant or slow flowing surface water in the wetlands has significantly disturbed the original ecosystem.

26) In addition to the artificial lowering of the groundwater by the constructed drainage system, there is evidence that the springs have also been excavated, and the original densely rooted peat and topsoil, restricting the spring discharge, have been removed. This has increased the groundwater discharge into the wetlands and hence further increased the surface water discharge from the wetlands as a whole.

27) The described changes in the wetlands are evident in the field. The photos at the top of Figure 3-3 compare the current concentrated high velocity flow in the main canal of the Silala (top left) with the braided slow-moving flow across the swampy surface of an un-channelized bofedal 50 km from Silala (top right). Direct evidence that these slow-moving flows and bofedal morphology dominated in the Silala wetlands prior to channelization is found in a small, poorly drained patch of the Northern

[5] Transpiration is the process of evaporation through the leaves of vegetation.

wetland demonstrating the same vegetation and flow pattern as an un-channelized bofedal (Figure 3-3, bottom right). The change in vegetation, as a consequence of the canals, is evident when comparing the artificially drained part of the Northern wetland (Figure 3-3 bottom left), showing dry land dominated by invasive grasses on the banks of the fast flowing canal, with the contrasting naturally and poorly drained portion of the same wetland (Figure 3-3, bottom right).

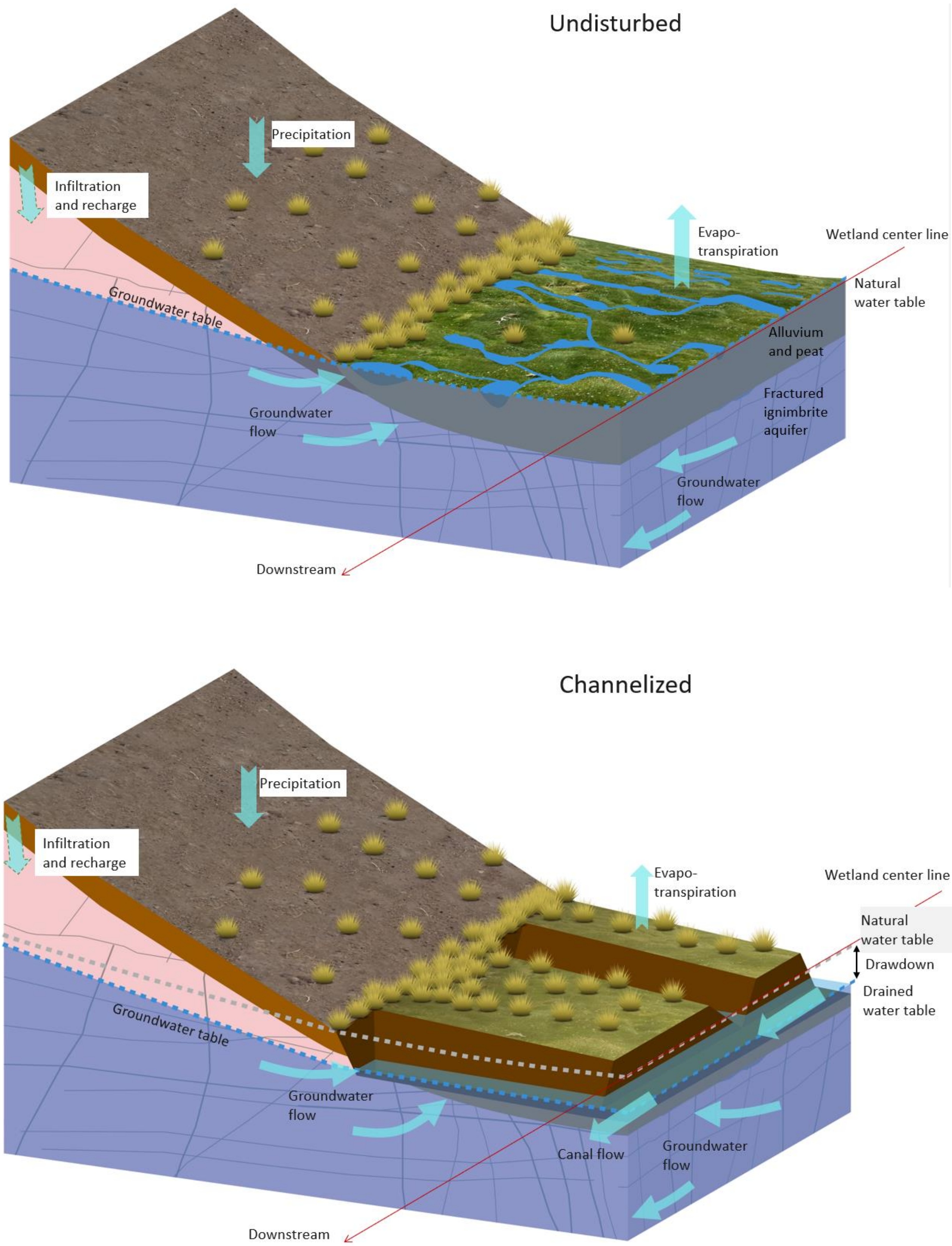

Figure 3-2 Hill slope – wetland element of undisturbed, natural wetland (upper) and a channelised and drained wetland (lower) showing water level and wetland impacts.

28) Irrespective of the impacts of the introduced drainage works on the cross-border surface water and groundwater flows, those works have certainly had large ecological impacts on the wetlands.

29) Measurements of the un-channelized, natural system were made by Engineer Robert Fox, who was in charge of design of the water supply to the Railway Company and studied the quantity and quality of the Silala waters (Fox R. H. 1922). Engineer Fox measured a flow rate of 131 l/s *"with very slight variations"* (18% lower than the present average flow of 160 l/s). The Fox measurements are the only known on-site measurements of the cross-border surface water outflow from the natural Silala prior to the installation of the canal works, and they correspond very well with the assessments made by DHI of the undisturbed flows (11-33% lower than the channelized flows; DHI 4, 2019, RB. Vol. 5, Annex 25).

Figure 3-3 Examples of channel and drainage network impacts. Stone lined narrow canal in Silala with fast flowing water (upper row left) as compared to the wide-spread slowly flowing surface flows in the natural nearby Villamar bofedal (upper right) and in a undisturbed patch of Silala with the original flow pattern (lower right). Lower left: Invasive grasses taking over from the original vegetation in the drained drier section along the main channel of the Northern wetland.

4 DHI'S METHODOLOGY

30) Understanding the combined surface water-groundwater and the hydrologic impacts associated with the dewatering and channelization is a complex task. It is well known that nature is diverse and that slope and altitude of terrain, vegetation, soil properties etc. vary spatially – in some parts of the Silala springs area, it varies within a few meters. Similarly, the thicknesses of the various subsurface geological formations vary spatially as does their ability to store and transmit groundwater. These 'hidden' hydrogeological features are equally important for the understanding of the surface water–groundwater interactions in the area.
Subsurface data collection is significantly more challenging and costly than surface measurements as it requires geophysical surveys, drilling of boreholes to collect rock samples, measuring groundwater

levels and testing wells to determine rock hydraulic properties that govern their ability to store and transmit groundwater.

31) While the presence of groundwater is evidenced by the existence of the springs, the knowledge of the origin and nature of this groundwater was rudimentary at the start of DHI's work in 2017. Therefore, DHI made recommendations and detailed specifications for *an intensive 6-month on-site, field data collection campaign that was subsequently executed by Bolivia with specialized field survey teams supervised by DHI and its subconsultant*. These types of field data collection programs are undertaken to understand the nature of the groundwater flow system and are termed hydrogeological characterization programs. Field work was focused on the Silala Near Field as this is the area that has been most impacted by the canals and drainage of the wetlands, and where model predictions of these impacts will be most sensitive to the water levels and hydraulic parameters measured in the field. A total of 35 monitoring wells or piezometers[6] were installed in 29 boreholes drilled above and along the course of the Silala ravines and wetlands in Bolivia (some to depths of more than one hundred meters) (DHI 1; Annex F pp.1-99, BCM, Annex17). Geologic logging of the rock samples from the boreholes was completed to understand the geologic and hydrogeologic characteristics of the subsurface.

32) Measurements of groundwater elevations were collected from the piezometers to understand the groundwater gradients and flow patterns. Boreholes and wells were tested to quantify the ability of the ignimbrite rock[7] to transmit and store groundwater.

33) An extensive campaign of surface flow measurements was completed along the entire canal network and combined with detailed surveys of the individual springs and drainage canals. These measurements and analyses provide an understanding of where groundwater is discharging to surface water and where surface water is losing water to groundwater, as well as an understanding of the contributions of the various canal reaches[8].

34) The data from the hydrogeological characterization program was combined with available hydrogeological data from Chile (Arcadis 2017; CM) to form a more complete understanding of the groundwater and surface water conditions.

35) The hydrogeological characterization study has revealed a thick, laterally extensive, highly fractured and heterogenous ignimbrite aquifer that is able to transmit and store large volumes of water. This aquifer is therefore able to sustain the high measured groundwater discharge to springs and surface flows through time. The measured groundwater elevations also indicate that the deeper groundwater is flowing upward in the aquifer towards the Northern and Southern wetlands and that the overall gradient (the slope of the water table) is relatively steep in the direction of Chile. The implication of such a gradient is that groundwater not discharging to surface water or springs will flow across the border.

36) At present, quantification of the cross-border groundwater flow is poorly constrained but is estimated to be in excess of 230 l/s (see details of estimate in DHI 1, 2018, Annex F, p.81; BCM, Vol. 4 Annex 17). Refinement of the estimate of cross-border groundwater flows would have required geophysical surveys, additional deep wells, pumping tests and the detailed geological understanding (i.e. lithology, stratigraphy) that would be acquired by such a wider area characterization program. However, time constraints did not allow for such extension to the already intensive program.

37) The applied scientific methodology follows well-established technical approaches for such studies that emphasize the collection of site-specific hydrologic and hydrogeologic data. The on-site data form the

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[6] A piezometer measures the water level (or piezometric head) of groundwater at a specific location and depth.

[7] Ignimbrite is a rock formed by explosive volcanic eruptions and deposited at high temperature. In Silala, the Ignimbrite form the region's main aquifers (bodies of permeable rock which can contain or transmit groundwater).

[8] A reach of a canal or river is a small section of a canal or river rather than its entire length.

basis for the development of a conceptual model[9] of the hydrogeology in the area, which constitutes the framework for the development of an integrated hydrologic model used for analysing the surface and groundwater flows in Silala for different scenarios.

38) To analyse the impact of the artificial canals on lowering groundwater levels in the Silala wetlands and the related hydrologic impacts on cross-border flow, an integrated hydrologic model of the Near Field was developed by DHI. As illustrated in Figure 4-1, the Near Field model development followed the established best-practices for such models, namely:
1) development of a conceptual and a numerical baseline[10] model[11] consistent with the information derived from the field investigation and from previous studies;
2) calibration of the (baseline) model to reproduce the groundwater elevations and surface flows measured in the field;
3) modification of the calibrated (baseline) model to represent the Silala wetlands in their natural state (i.e., without canals and related infrastructure) to allow for a comparison of the un-channelized flows to those of the baseline model.

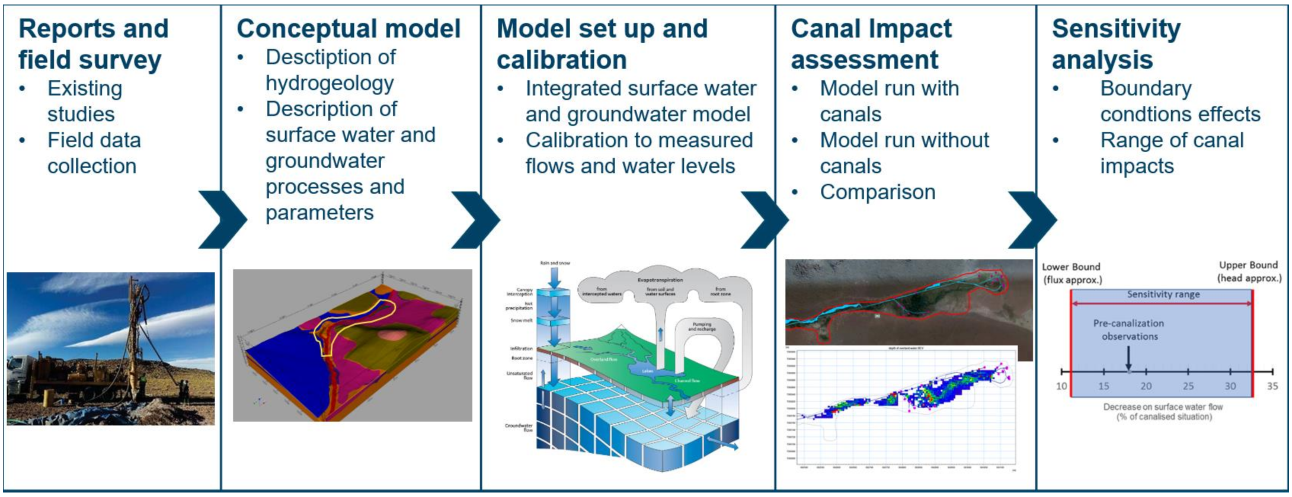

Figure 4-1 Impact assessment methodology

39) Delineation of the Near Field model domain (the area simulated by the model) was based on the extent of the hydrogeological characterization program and limited to where the geology and hydrogeology are reasonably well-constrained.

40) Due to the Near Field model extent, the model boundaries are potentially affected by the canals. The simulations were therefore repeated using different boundaries conditions to evaluate the impact on model predictions. The result of this sensitivity analysis is an upper and a lower bound of the expected impacts on the cross-border flows.

41) It is internationally acknowledged that analyses and quantification of impacts of artificial structures on complex hydrological systems are best done through the application of integrated mathematical models rather than simple analytical hand calculations, as prepared by Chile's experts, that cannot reproduce the complexities of the natural world. Hence, the technical approach taken by DHI in this case is considered common practice for such investigations and is in fact required by environmental regulatory agencies for permitting infrastructure projects throughout the world.

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[9] A conceptual model is a simplified representation of the main processes and characteristics of a system, such as a hydrological system.

[10] The Near Field model is used in different configurations, each representing a scenario to be analysed: Baseline (the present situation); No-canal (similar to Baseline but without the channelization) and Undisturbed (without the Channelization and with restored peat layers).

[11] A numerical model is a mathematical representation of the conceptual model that is typically applied first to simulate the measured and observed states of, for example, an integrated hydrological system, and next to calculate impacts of the changes (scenarios).

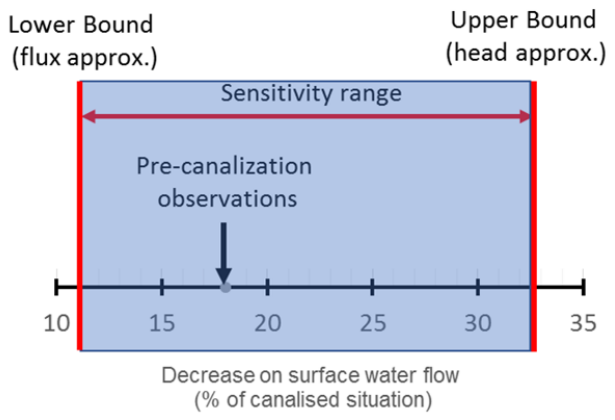

Figure 4-2 Assessed decrease in cross-border surface water if canals are dismantled and wetlands restored

42) Our analyses show that, as a consequence of the artificial channelization of the wetlands and ravines, the surface water flowing across the international border has increased and should be expected to decrease between 11% and 33% from the present situation if the drainage structures are dismantled and the wetlands restored to their original state. This result is confirmed by Eng. Fox's pre-channelization measurements of the surface water outflow from the undisturbed wetlands (Fox, R. H., 1922) which was 18% lower than the recent measured average flow (Figure 4-2).

43) Water chemistry analyses have suggested that the majority of the groundwater discharging to the Silala springs and surface water has had long residence times in the aquifer and potentially infiltrated the soils thousands of years ago (i.e., apparent age from carbon-14 dating[12], see discussion around limitations of these methods in DHI 1, 2018, Annex F; BCM, Vol. 4, Annex 7). A coarser, larger scale model of the Far Field, defined as the best-estimate of the geographic extent of the groundwater catchment of the Silala springs in Bolivia, was developed with the following objectives: 1) evaluate whether the source of water to the Silala springs is likely to be a renewable or a non-renewable resource; and, 2) verify that the simulated groundwater travel times in the aquifer were of the same order of magnitude as the apparent ages[13] determined from carbon-14 analyses. These ages should be similar if the apparent ages are somewhat representative of actual or idealized groundwater age[14] and the conceptual understanding of the groundwater catchment (the Far Field) and recharge areas is correct.

44) The Far Field model results confirm that much of the water discharging to the Silala area is thousands of years old but likely not as old as some of the apparent ages from carbon-14 dating, suggesting there may have been some decrease in carbon-14 associated with chemical processes along the groundwater flow path or potentially inter-basin flow into the Far Field domain or a combination of these two processes. The model also indicates that some of the water discharging to the springs would have smaller average groundwater ages associated with localized recharge and a localized groundwater regime, consistent with the conceptual model (DHI 1, 2018, Annex F, pp.1-99; BCM, Vol. 4, Annex 17). The Far Field model simulations demonstrate that the precipitation over the Far Field catchment can generate average groundwater recharge of 150 l/s to 370 l/s or more[15]. This recharge (also known as the renewable resource) is interpreted to be slightly higher than cross-border surface water measurements (160-170 l/s). However, cross-border groundwater flow must also be considered and is estimated to be 230 l/s or more for a combined cross-border flow in the order of 390 l/s or more. As a result, it cannot be definitively determined whether: (a) the combined cross-border flow corresponds to the average recharge rate for the Far Field (i.e., 150 l/s to more than 370 l/s) and therefore a renewable resource; (b) a portion of the flow originates from a larger groundwater system (i.e., inter-basin flow) or (c) a portion of the flow is non-renewable groundwater that has accumulated during a wetter climate

[12] Carbon-14 dating – The radioactivity of Carbon-14 present in ground water as dissolved inorganic carbon has been used in hydrologic studies to determine the time since recharge of older ground water since the 1960s.

[13] Carbon-14 Apparent age – The apparent age is derived from the Carbon-14 dating and represents the maximum groundwater age of the sample. Because Carbone-14 is not part of the water molecule, its activity and interpreted carbon-14 ages may be affected by reactions between constituents dissolved in groundwater and aquifer materials that may result in apparent ages that are older than an idealized groundwater age.

[14] Groundwater age - Groundwater age is defined as the time between recharge at the water table to the time when groundwater was sampled.

[15] Snowfall is common in the area but is difficult to register in normal rain gauges; therefore, the precipitation and by extension the groundwater recharge may be under-estimated.

period and that is now slowly being discharged from the aquifer, as groundwater elevations adjust to current climatic conditions.

5 POINTS IN WHICH THE EXPERTS OF BOLIVIA AND CHILE AGREE

45) The main source of surface water of the Silala springs is groundwater discharge, and the surface waters (within and outside the canals) interact with the underlying groundwater along their courses (DHI 1, 2018, point 9; BCM, Vol. 2, Annex 17; W&P 5, Vol 1, p.3 point 2).

46) Silala is of a complex nature and comprised of a coupled groundwater-surface water system originating in Bolivian territory (upstream) and extending into Chile (downstream) (DHI 1, 2018, p.2, point 9; BCM, Vol. 2, Annex 17; W&P 5, Vol 1, p.3 point 2).

47) The hydrogeological characterization program has clearly identified geological layers of significant thickness, high hydraulic conductivities[16] and significant groundwater gradients[17] towards Chile (DHI 1, 2018, p.2, point 5-6; BCM, Vol. 2, Annex 17; W&P 5, p.3 point 3).

48) In general, the slopes of both the groundwater table and the terrain are significant, and the construction of the canals cannot possibly have changed the overall direction of flow in surface water or groundwater. Hence, the field data and analyses of the Near Field and Far Field models suggest that the water discharged from the Silala catchment (accounting for the evapotranspiration from soils, wetlands and canals) eventually flows to Chile either as groundwater or as surface water, with or without the canals (DHI 3, 2019, p.11; RB, Vol. 5, Annex 24; W&P 5, p.3).

49) The Experts of the two parties agree that the drainage works of 1928 have affected the surface flows across the border (W&P 3, p.12) and have led to a reduction of the direct loss of water by evapotranspiration and possibly infiltration. Hence, the evapotranspiration from the wetlands will increase if the canals are removed (DHI 3, 2019, p.11, par.5; RB, Vol. 5, Annex 24; W&P 5, p.3 par.3).

50) Chile's experts agree with DHI that the effect of the drainage works in the wetlands has lowered (ground)water tables in the wetlands and ravines of Silala. They also agree that increased hydraulic gradients and reduced hydraulic resistance through springs and the resulting increased spring discharges are plausible effects of the channelization (W&P 3 pp 11-14). Increased discharge through the springs translates into increased cross border surface water flow. We therefore also agree that this flow across the border has increased as a result of the artificial drains and channelization (DHI 1, 2018, p.2, point 10; BCM, Vol. 2, Annex 17; W&P 5, p.3, point 4 and par.2), but disagreement on the magnitude of this increase persists as elaborated upon below.

51) The magnitude of the estimates of increased surface water flow associated with channelization cannot be given as an exact number. There is always uncertainty associated with hydrologic and hydrogeologic predictions (DHI 3, 2019, p.7, par.7; RB, Vol. 5, Annex 24).

52) Chile's experts also agree with DHI that the simple Darcy flow profile hand calculation of the impact of the drainage canals presented by Chile's experts is insufficient to quantitatively assess the magnitude of the canal impact (DHI 3, 2019, p.7 par.8; RB. Vol. 5, Annex 24; W&P 5).

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[16] Hydraulic conductivity is a measure of relative ease with which water can flow through the pore spaces and fractures.

[17] A water level gradient, or slope, or rate of change, describes the water level difference between two points relative to distance.

6 POINTS IN WHICH THE EXPERTS OF BOLIVIA AND CHILE DISAGREE

6.1 The impact of the channelization on the cross-border flows

53) While the technical experts of Chile and Bolivia agree that the surface water flow rates across the border have increased as a result of the drainage of the wetlands, the magnitude of this change is disputed.
Chile's experts assess it to be negligible but have only presented a very simplified analysis to support this - an analysis, which they later admitted does not suffice for impact quantification of this type (W&P 5, p.4). Unlike DHI, Chile's experts carried out *no* field investigations in the Bolivian bofedales. DHI's analyses indicate that channelization has significantly increased the surface flows into Chile. DHI has made several fact finding and data collection missions to the Silala wetlands in Bolivia and bases its estimate on an extensive on-site characterization program, detailed numerical model analyses founded on the on-site data (an approach normally applied for such analyses) *and* on historical and present on-site flow measurements.

54) Chile's experts have stated that the model's original boundary conditions were inappropriate for DHI's conclusions. DHI agrees that due to limitations to the field characterization program the model boundaries are potentially affected by the canals. Accordingly, a number of different model simulations were made to evaluate *how* the boundaries affect the model predictions of the cross-border flows with and without canalization, respectively. The outcome of the analysis is that if the canals are dismantled and the bofedales restored to their natural state, the cross-border surface water flows are expected to decrease by between 11% and 33%.

55) The tested boundary conditions include *both* an upper-bound scenario (constant pressure along the inflow boundaries), that will result in estimated flow differences in the high end (33%), *and* a lower-bound scenario (constant flux boundary), which is considered conservative in the sense that it is likely to underestimate the flow difference (11%). Hence, the correct result must be assumed to be somewhere between the upper and lower bounds.

56) The only discharge observations from the pre-channelized Silala of 131 l/s (Fox 1922) is 18% lower than the average present observations (160 l/s). This is consistent with the range of results from the Near field model (Par. 55).

57) Chile's experts contest Eng. Fox's measurement and question the accuracy and reliability of his measurement arguing that even today, it seems to be difficult to measure the flows. However, Fox seems to have spent a good deal of time studying the conditions and planning for the works, and thus his conclusions should not be dismissed. Moreover, DHI is convinced that most of the problems concerning the Silala flow records stem from problems related to the automatic equipment (now installed at the sites) or poorly trained gauge operators. Fox would likely have used manual methods for his flow measurements. Such methods have been known for many years, and Fox quotes the flow with a three-digit precision[18] and that it is "with very slight variations". This indicates that he made several consistent measurements over a period of time. Also, Fox, as a professional engineer responsible for designing the many kilometres of pipeline, would rely on accurate measurements. He even made rather detailed chemical analyses of the Silala water, which we believe was not standard in the early 20th century. Hence, DHI finds it very unlikely that he would not have made these crucial measurements properly, and their validity must therefore be recognized.

58) Chile's experts also dispute the location at which Fox's measurements were taken. DHI finds his description sufficiently accurate to locate his monitoring location within the ravine close to the present de-siltation chamber approximately 600 m upstream of the border. This location is on a reach of the ravine where, according to the recent measurement (DHI 1, 2018, p. 23, Figure 13; BCM, Vol. 2, Annex 17), the flow does not vary much. The observations can therefore be considered representative

[18] It is good technical practice that the number of digits reflect the assumed accuracy of the measurement.

of the surface flows crossing the border for the natural conditions without the artificial drainage network.

59) Although the predicted range of changes in surface water crossing the border is fully consistent with the flow observations under pre-channelization conditions, the significant change indicated by the analyses and observations has not been accepted by Chile's experts.

60) The Silala wetlands in Bolivia have, to a large extent, been drained, dissected, altered and, as a result, reduced in area. Soils have dried out, peat deposits have been excavated and removed, and native wetland vegetation has been replaced by invasive grasses characteristic of areas with lower moisture contents and deeper depths to groundwater (Figure 3-3, and Figure 6-1). DHI finds that this is a significant change in the *ecological* conditions of the Ramsar wetland.

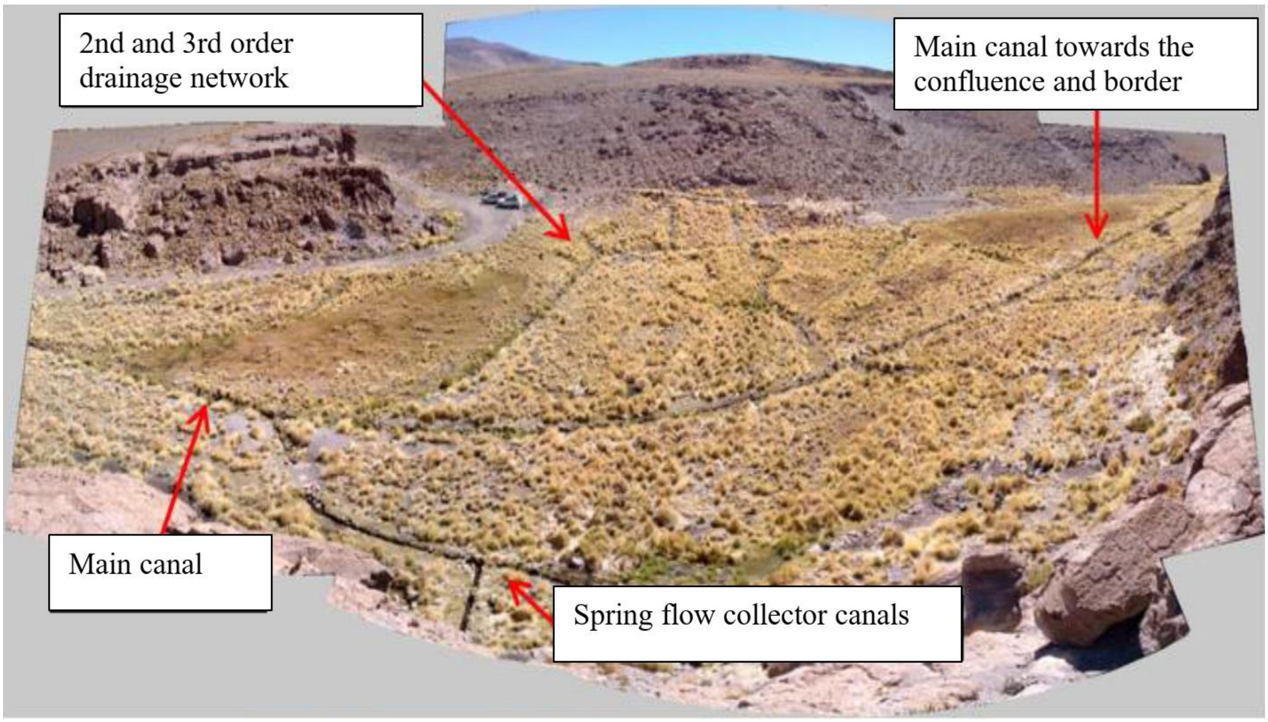


Figure 6-1 Aerial overview photo of the channelization of the Northern wetland.

6.2 Disagreements between Bolivia's and Chile's technical experts about methodologies and results

61) Chile's technical experts compare remote sensing evapotranspiration estimates from the nearby small undisturbed Quebrada Negra wetland on the Chilean side of the border with the two Silala wetlands in Bolivia. Since the estimates (W&P 3, p41) seem to indicate higher evaporation rates in the Bolivian wetlands than in the Chilean, Chile's experts conclude that the channelization in Bolivia "does not seem to have had a significant effect on the evapotranspiration rates". DHI disagrees with this conclusion as it compares three wetlands each with different groundwater (and climate) conditions. The satellites can obviously not observe the original un-channelized conditions in the Silala wetlands in Bolivia many years after the implementation of the channelization. Further, the calculation formula does not seem to account for the evaporation from open water surfaces that would constitute a significant part of the evapotranspiration in the case of the undisturbed Silala wetlands. Finally, the estimated evapotranspiration rates for the undisturbed Quebrada Negra are only around 50% of the quoted potential values (CR Vol 3, p.151, (Muñoz & Suárez 2019, p.61), this is lower that what would be expected in a natural bofedal with abundance of water. However, it is noteworthy that the sub-areas within the wetlands which Chile's experts associate with high evapotranspiration rates (CR Vol 3, p.153, (Muñoz & Suárez 2019A, p. 63) correspond to sub-areas with relatively less drainage and more remaining natural bofedal features. This would contradict the conclusion made by Chile's experts.

62) According to Chile's experts, DHI's Near Field model cannot be used to predict the impact of the artificial drains and canals *because*:

- It does not reflect the hydrogeology (e.g., the model does not incorporate perched aquifers[19] as identified in Chile). DHI disagrees as perched aquifers have not been identified by any of the many hydrogeological boreholes drilled and studied in the model area. Furthermore, DHI maintains that the model is constructed and calibrated using extensive field data *collected on-site* both on the surface and in the subsurface. The model reproduces the observed groundwater flow patterns, hydraulic gradients and discharge rates to the Southern and Northern wetlands and measured surface flows throughout the system in Bolivia.
- The model area is too small covering only a few percent of the catchment area. DHI disagrees: The model domain covers the Near Field, where field data have been collected and, more importantly, where the majority of the hydrologic impacts have occurred. DHI concedes there are some boundary effects[20], but sensitivity analyses were applied to account for the effects resulting in lower and upper bound predictions. As noted, Chile's experts carried out no on-site field studies in the relevant area nor did they develop numerical models to reproduce the hydrologic and hydrogeologic conditions measured in the field.

63) Chile's experts' re-interpretation of hydrogeological conceptual model (W&P 4 2019) deviates from DHI's conceptual model in terms of the lateral extent of the ignimbrite aquifer beyond the immediate area of the Silala ravines and ignores the geological observations and age dating of rock units completed on-site in Bolivia. As a result, the stratigraphy[21] beyond the immediate area of the ravines is disputed. DHI states that the smaller model domain was deliberately constrained to the Near Field areas that could be reasonably well characterized and where the impacts of the channelization are largest. The stratigraphy outside of the model domain is unlikely to materially change model predictions of the hydrologic impacts of the artificial drains and canals. In addition, a fault coincident with the Silala ravine, that was previously included in Chile's conceptual model (Arcadis, 2017), has now been removed without explanation. Furthermore, Chile's experts attempt to extrapolate their findings of perched aquifers in Chile to Bolivia despite the fact that an intensive hydrogeological characterization program did not identify any perched aquifer conditions.

64) DHI's Near Field model is based on field evidence and has been calibrated to reflect the groundwater flow patterns in the field. It reproduces the on-site field data in a reliable manner. An example is the simulation of the surface flow pattern in the Southern wetland which has been partly re-established by blocking some of the canals – a demonstration that the wetlands retain water on the surface when the canals are inactivated (Figure 6-2).

65) Chile's experts question the hydrogeologic framework of the Near Field model, the assigned hydraulic properties, the internal consistency between applied datasets and the appropriateness of the modelling approach adopted in the study. DHI has evaluated, explained and answered the technical issues brought up by Chile's experts and has reached the conclusion that DHI's approach, properties and assumptions are valid. We elaborate on these disagreements in Chapter 7 below.

66) A perfect model does not exist; it is inherently a simplification of the complex natural world, and therefore the predictions have some degree of innate uncertainty. However, DHI has analyzed how key assumptions or model limitations affect the model predictions and reports a range of possible hydrologic impacts based on these analyses. The limitations of models are widely understood, and regulatory agencies frequently request and accept the type of analyses presented by DHI for hydrologic impact assessments.

67) Chile's experts assume that local discrepancies or inaccuracies in the input to the Near Field model translate into severe one-sided errors hampering the results of the model and disqualifying it for use in

[19] A perched aquifer occurs when infiltrating water is intercepted by a low permeability layer or lens resulting in an accumulation of water on top of the low permeability lens above the main water table.

[20] I.e. where the conditions along the boundary of the model affects the results.

[21] Stratigraphy concerns the order and relative position of strata and their relationship to the geological timescale.

impact assessment. In contrast, DHI finds that the calibrated model based on actual field data provides the best basis and, together with Eng. Fox's in-situ observations of the pre-channelized undisturbed surface water flow, remains the best available tool for assessing the impact of the canalization on the surface water flow, regardless of minor inaccuracies or uncertainty inherent to all models.

68) For comparison, Chile's experts have presented a simplified hand calculation to argue that the impact of channelization would be 20 times less than predicted by the integrated model developed by DHI. The calculation used an idealised, uniform groundwater flow profile (in one dimension) that does not reflect the Silala site conditions by any means. In subsequent submittals to the court, Chile's experts explained that such simplified calculation is unfit for impact quantification and that it was meant only for illustration of the effect of boundary conditions (W&P 5, p.4). Nonetheless the factor 20 continues to be quoted by Chile to argue that DHI's impacts are overestimated.

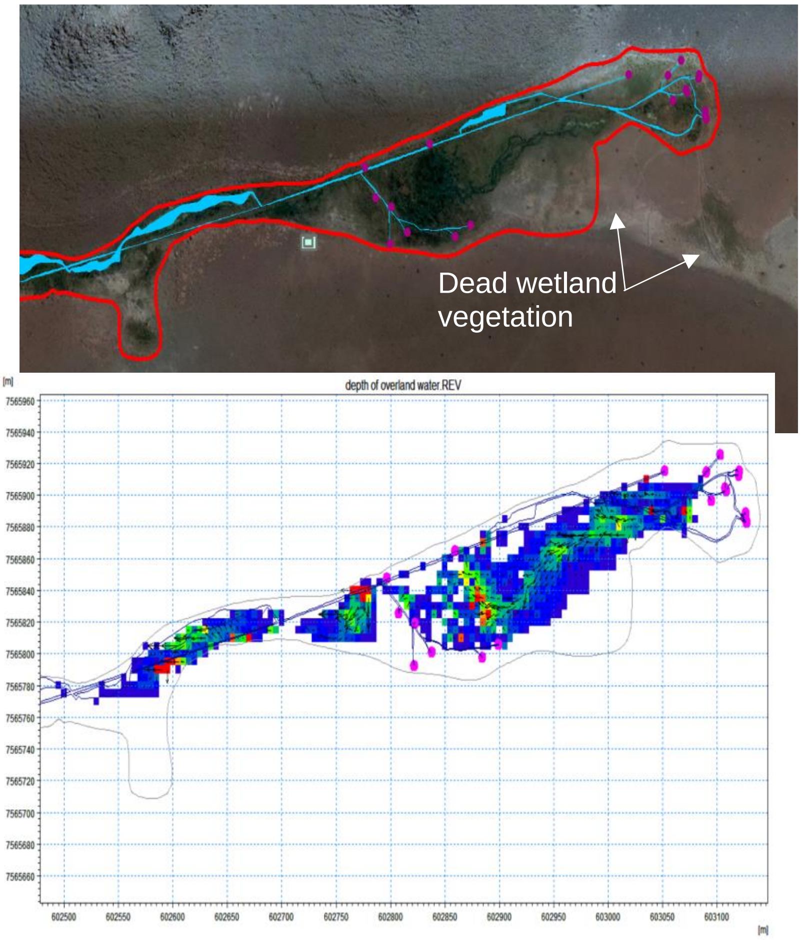


Figure 6-2 Figure showing how the flows and inundation, as simulated by the Near Field model (picture below), reflects the present surface flows in the Southern wetland (shown as dark green areas in the satellite image above). Also, the degraded (dried) patches of the original wetland with dead bofedal vegetation are clearly visible as light grey areas in the satellite image. The image shows the present situation in the Southern wetland, where the flow in a number of the canals has been obstructed. This has caused the water level in the canals (and in the groundwater) to rise, and the wetland has started to transform to its original state with saturated peat soils and slow-moving surface water on top (the dark green areas on the image and on the flow chart below). This flow pattern, generated by blocking the flows in the drain canals, is evidence that drying of the wetland was caused by the artificial drainage structures.

7 DETAILED TECHNICAL ARGUMENTS ON THE DISAGREEMENTS

69) This Chapter contains more technical arguments in relation to Chile's experts' criticism of DHI's analysis and includes more technical language and elaborations that refer to the points of disagreement summarised above.

70) Chile's experts claim that the only effect of the canals is a change in the wetland area and evapotranspiration rates accounting for only a minor change in the channel flow. According to the results of DHI's Near Field model, the change in *total* groundwater and surface water flow across the border may be limited, but the canals have increased the surface water flow and correspondingly reduced the groundwater flows. Hence, the estimated surface water cross-border flow from the natural un-channelized wetlands is assessed to be 11-33 % lower than today (DHI 4, 2019, p.8; RB, Vol. 5, Annex 25). In sections 7.2-7.3 below we further analyse Chile's experts' reservations about the model.

7.1 The water balance – Far Field and Near Field models

71) DHI developed and applied three different models to understand, describe and analyse Silala's hydrology:

a. A Water Balance Model (WBM or Far Field model) for recharge and sustainability analyses;
b. A detailed model of the Confluence–Border Reach for detailed infiltration studies;
c. A Near Field Model (NFM) for canal and drainage network impact assessments.

72) The models are independent and used for different purposes. It is therefore a misunderstanding when Chile's experts assume that they are linked and that boundary conditions are transferred or coincide.

73) The Water Balance Model was established prior to the completion of the detailed hydrogeological Near Field characterisation program. It was therefore based on sparse geological information and preliminary data for the downstream boundary at the Near Field area (DHI 1, 2018, Annex E, p.20; BCM, Vol. 3, Annex 17). These boundary conditions are, however, sufficient for the purpose of establishing the water balances.

74) Chile's experts imply that DHI assumes the simulations of the past 49 years to be representative of the climate variations during the last 5,000 years. This is not the case; we consider them to be representative of the *present* climate. It is the *present* climate that matters when evaluating the flows in the Silala as being a renewable or a non-renewable resource (par.44).

75) It is true, though, that we have used the present climate as the best estimate of the prehistoric climate in order to evaluate if the assumed groundwater catchment (the Far Field) and the coarse hydrogeological information available to this model are consistent with the observed very old age of the spring water. We have calculated the groundwater travel times in the Far Field and found travel times in the order of thousands of years (which we find makes the Far Field a plausible groundwater catchment).

7.2 Extent of the Near Field model area and assigned boundary conditions

76) Chile's experts have questioned the limited spatial extent of the Near Field model. Nevertheless, the modelled area (the Near Field) includes all the wetlands, canals and drainage networks. The canal impacts are simulated by the hydrological processes in this model area. Chile's experts continue to claim that the area is too small for impact assessment (W&P 5, p.40).

77) The size of the Near Field model was selected as the area for which it was possible to collect sufficient hydrogeological information to form a proper basis for the hydrogeological modelling, given the temporal constraints. Both our conceptual hydrogeological model and the Near Field model are based on data from an intensive drilling and field-testing campaign (including 35 piezometers) in the Silala Near Field (analyzing stratigraphy, hydraulic characteristics, groundwater heads and gradients).

78) As for all groundwater models, the boundary conditions for the Near Field model are an approximation. A unique delineation of the exact extent of open versus closed boundary segments is not possible, but the boundaries are generally outlined with respect to the potential head data. Wherever the groundwater gradient is parallel to a model boundary, groundwater will flow parallel to the boundary, and it may in such situations be regarded as closed (as opposed to open boundaries). In the Near Field model, closed boundaries have been introduced where this is approximately the case.

79) Chile's experts point out that along a segment of these boundaries, the groundwater flow may be almost parallel to the boundary. We still find the approximation quite reasonable, also bearing in mind that the segment on the southern boundary questioned is associated with low permeabilities, i.e., limited flow.

80) To explore the potential effects of the model area and the boundary conditions, DHI has carried out a sensitivity analysis. We note that Chile's experts agree that the approach used in the sensitivity analysis represents the upper and lower bounds of impact assessment (W&P 5, p.42).

7.2.1 The Near Field model's surface flow representation

81) The differences between the two flow patterns have been documented above (Figure 3-3). As the soil moisture and evaporation conditions are different in the two situations, the model must reflect these differences. The integrated surface water-groundwater modelling approach to assessing canal impacts is straightforward. The current Silala springs system is first modelled with the existing man-made canals (Baseline) and then without the canals (No-canal). The model setup is changed by removing the one-dimensional canal flow component (since there are no canals in the natural state), and the differences between the flows simulated in the Baseline and the No-canal scenarios are compared. Chile's experts argue that different models are used for the canal versus no canal scenarios and that by leaving out the canal flow model they are "not directly comparable". It seems rather obvious that hydrologic impacts associated with the canals are described as the difference between model scenario runs with and without the canal. Criticising this approach is somewhat surprising and contradictory.

82) DHI's modelling framework and modelling approach reflect the task at hand, i.e., evaluating the impacts of removing the canals causing a change in the flow regime as groundwater flow and two-dimensional overland flow become more dominant. Consequently, the model approach has been chosen carefully to serve the intended purpose.

83) Chile's experts claim that the model does not describe 'reality' (W&P 5, p.47). DHI asserts that it describes reality as observed, measured and described by the conceptual and numerical model. That said, the model *is* a simplification with respect to spatial resolution and the physical processes of the system. This is true of all models, and like for all models, there will be some degree of uncertainty with respect to input data and model parameter which translate into predictive uncertainty. This, however, is always the case for any model and, thus, does not disqualify it as an impact assessment tool.

84) Even an advanced computer model is a simplification compared to the natural system (e.g., small-scale variability) and yet, by utilizing data of the comprehensive field data collection program, it provides the best available quantitative assessment tool superior to hand calculations lacking site-specific data.

7.3 Topographical differences between canal and terrain

85) Chile´s experts describe topographical differences between terrain and canals, and between the terrain in model scenarios. To explain how data are used and represented in the integrated model, it is necessary to explain how the widely used modelling software (MIKE SHE-MIKE11) combines surface and canal elevation data.

86) Summarising the detailed description available in the software manuals, MIKE SHE does indeed use different resolutions in the topographical data for the canal flow component and the overland flow component. In the case of the Silala Near Field model, the MIKE SHE model resolves the canals in the order of tens of centimetres and the overland flow over a 10 m x 10 m grid, which is common in numerical modelling and referred to as discretization[22].

87) The exchange between water in the canals and the water on the surface is performed numerically at the grid cell boundaries (Figure 7-1). That is to say that even if the canal is located in the middle of the cell, the exchange of water occurs at the cell boundary, a simplification that is necessary in all MIKE-SHE models.

[22] In numerical models, discretization is the process of transferring continuous data into discrete elements (model grid) to make it suitable for numerical solution by computers.

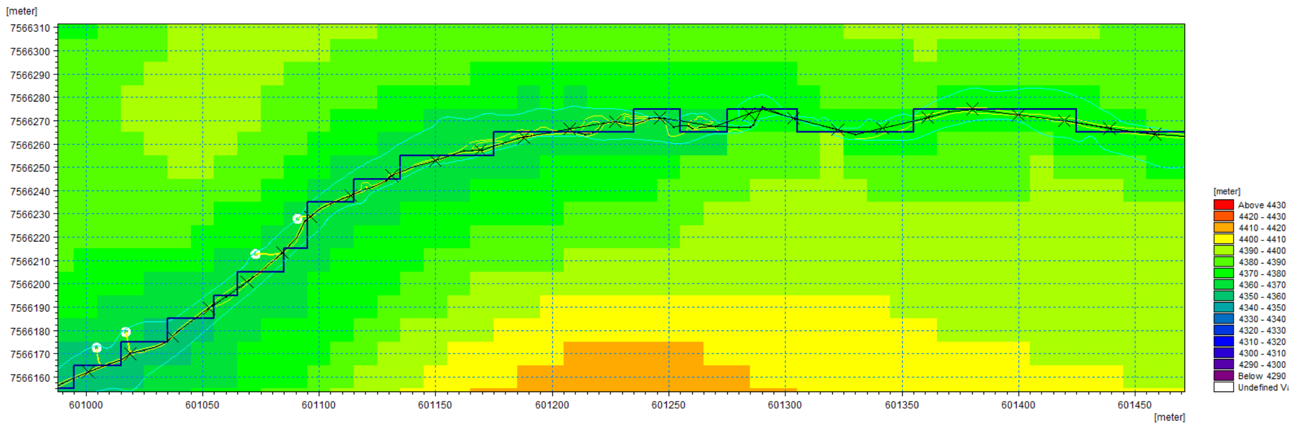


Figure 7-1 Silala zoom-in of the MIKE SHE method of mapping of catchment topography and canal network to the model grid elements with canal links aligning grid cells. The canal network is mapped onto the grid cell edges as canal links. The geometry of these links is interpolated from the canal network onto the canal links.

88) Figure 7-2 shows the relation between the topography used in MIKE SHE overland flow component and the topography used in the canal flow component of MIKE SHE, MIKE 11. The topography used in MIKE SHE for two-dimensional overland flow grid (10 m x 10 m) is indicated by the two horizontal black lines.

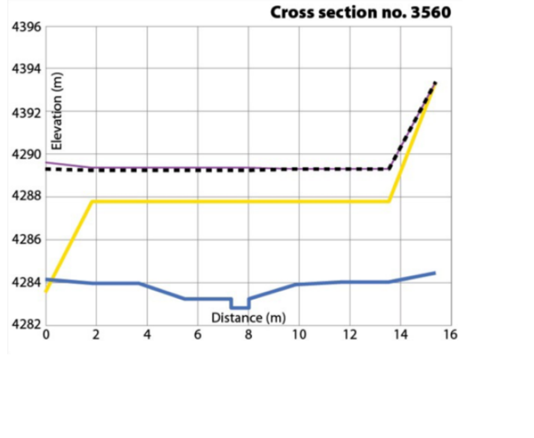
89) The topographical information used in channel flow calculation is contained in the cross-section (blue line). For illustration, the closest canal cross-section is shown with the elevations of the two cells adjacent to a canal link which is included in the flow transfer calculations. Within the numerical model, canal geometry at each edge is interpolated from the actual cross-sections.

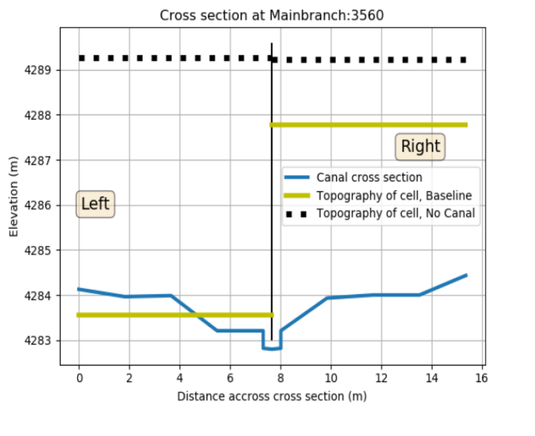
90) The exchange of flow from the canal to the surface depends on the water level within the canal. As the water level rises in the canal, water will spill from the canal onto the adjacent overland cell when the canal water level exceeds the highest level of either the canal bank levels or surface cell levels. If, as in the case shown in Figure 7-2, the surface topography is higher than channel bank levels, then water will first flow out of the channel onto the surface when the water level reaches the lowest of two cells on either side of the canal link. Consequently, the canal will spill to the lowest of the two canal banks (the left or the right) which Chile's figures fail to show.

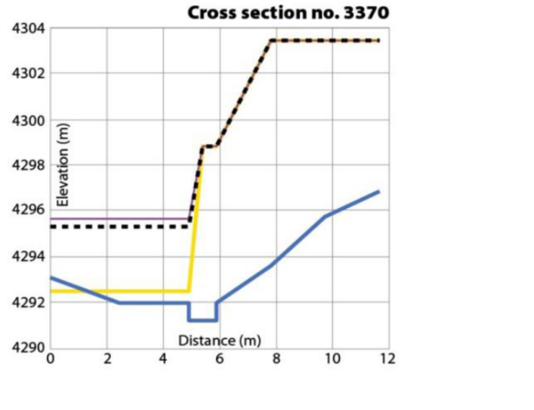
91) Chile's experts claim that the topography used in the No-canal and the Undisturbed scenarios is too different from the one used in the Baseline to give reliable results, and they have selected four examples to illustrate this. However, the examples reveal some misunderstandings regarding the processing of the topography by the model. The differences are far smaller than those reported by Chile. It is common for finite difference models, and not specific to neither the Silala model setup nor the MIKE SHE modelling software, to represent the topographic inputs in a spatial resolution represented by the grid cell size (i.e., topography is averaged for each 10-m x 10-m grid cell).

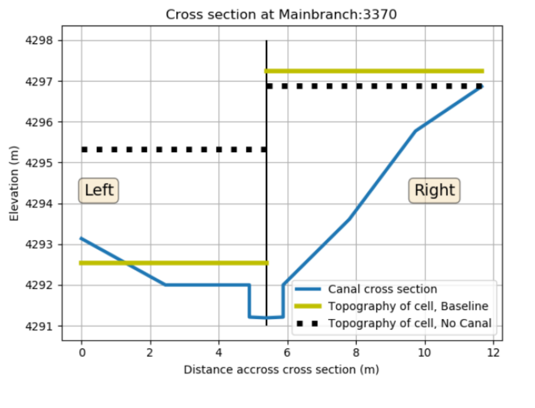
92) The elevation is an average across the grid cell which means that elevations of the topography are generally expected to be higher than the canal cross section elevations derived from the finer scale digital elevation model. Chile compares the topographical level at a single grid cell node to canal elevations. The model, however, connects a canal segment via canal links along the edge of two neighbouring grid cells. These two neighbouring cells (right-hand side and left-hand side) have different topographical levels. This means that the apparent elevation differences drawn in the figures by Chile are exaggerated and not representative for how the model works.

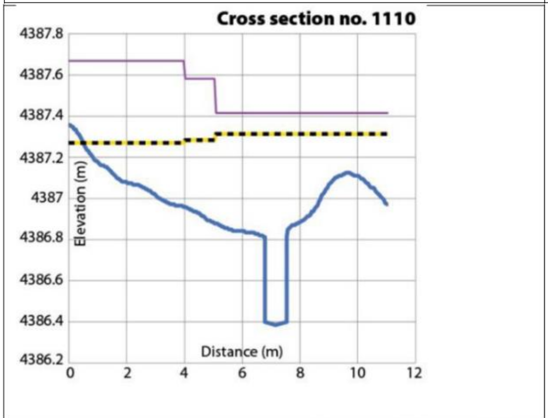
Chiles interpretation	Correct interpretation.

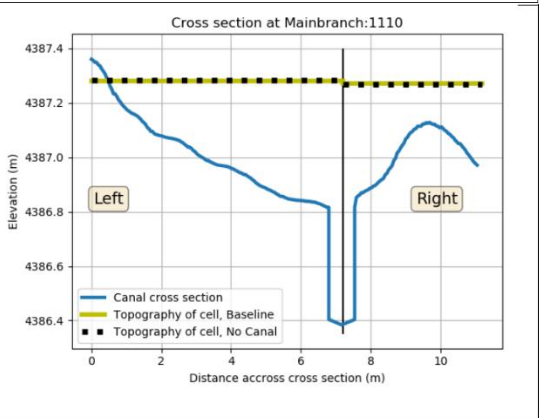


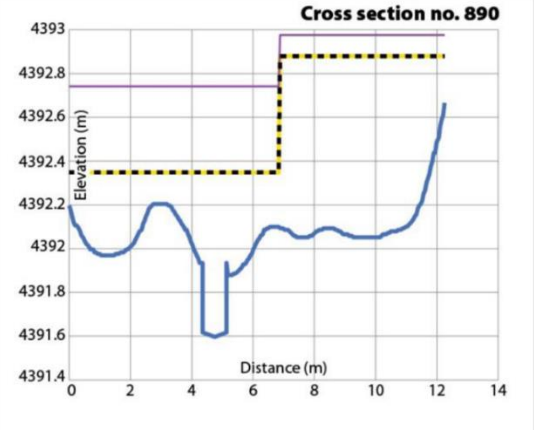












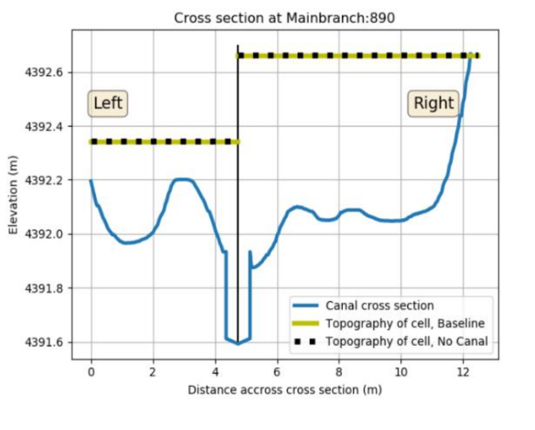


Figure 7-2 Cross section figures showing Chile's interpretation to the left and the correct comparison to the right

93) Figure 7-2 shows differences presented by Chile's experts on the left and the correct representation according to the MIKE SHE modelling software on the right. Any difference in topography must be assessed by the lowest level of the two cells since that determines where overland flow first occurs when water spills onto the floodplain from the canal as described above. Looking at only one cell is misleading, and the right-hand side column of Figure 7-2 shows that, when comparing to the lowest point, differences are much smaller. In addition, when looking across the entire model, the average difference between topography elevation and canal bed elevations is less than 1 m.

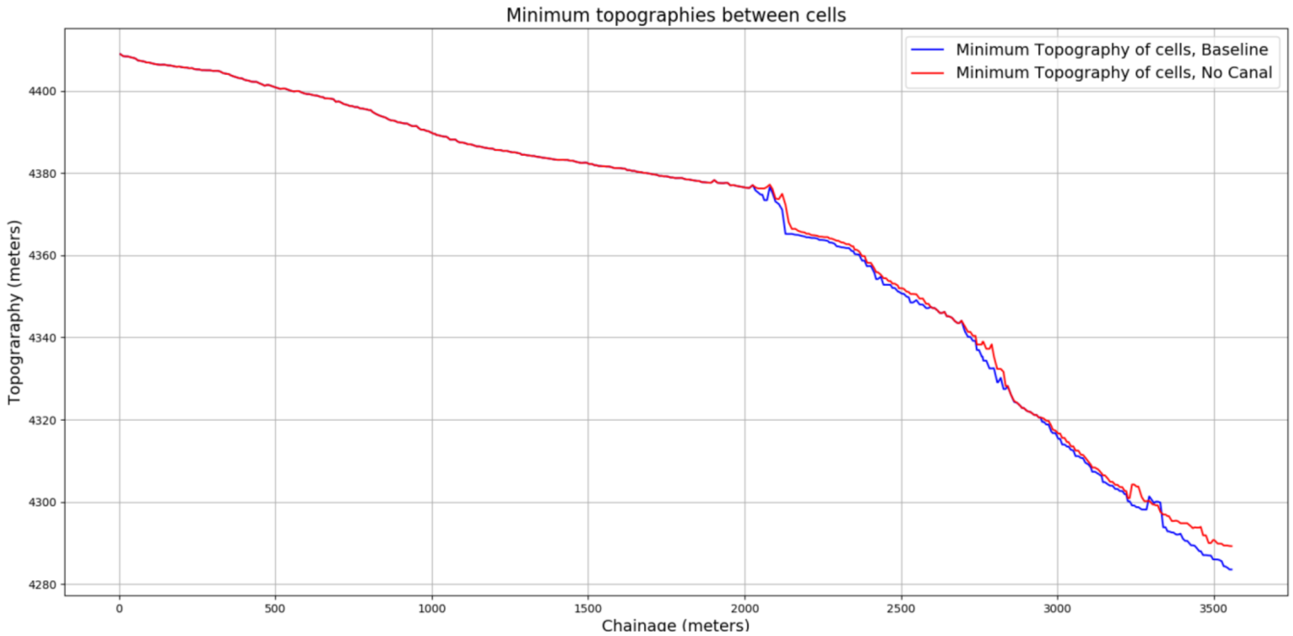


Figure 7-3 Longitudinal profile of topography along the flow path from the Southern wetland to the border for the Baseline and the No-canal scenarios. The topographic levels refer to the elevation of the lowest point at the specific locations.

94) Figure 7-3 shows differences in topography relative to the general slope. With and without adjustments to canal cross section elevations, localised moderate differences can be seen, mainly immediately upstream of the border where finer and coarser topographical models are merged. According to measurements and model results, the canal flow does not change significantly from the canal confluence to the Chilean border, and topographical differences do not change the overall canal slope or flow direction.

95) Chile's experts have pointed to different file names for the topographical input to the model applied in the Baseline and in the No-canal scenarios respectively. We appreciate drawing our attention to this. The differences in topography are minor and restricted to a small area close to the border.

7.3.1 Stationary model runs reaching equilibrium

96) Chile's experts claim that there is a difference in the initial conditions of the groundwater heads between scenarios and that the groundwater levels have not completely reached equilibrium by the end of the baseline simulation. Figure 7-4 shows the subsurface storage development together with the development in the surface flow at the border. It is clear that after 3 months, both curves are independent on the initial conditions. It is true that the groundwater storage is still changing slightly corresponding to approximately 3 l/s after 3 months. More importantly, the flow at the border is in equilibrium. Nevertheless, to double check these results, the very same simulation was prolonged to one year. The results shown in Figure 7-4 demonstrate clearly that the surface flow at the border by the end of the simulation is unchanged compared to the result after 3 months and that the subsurface storage change approaches zero (0.6 l/s). The storage change after three months is already included in the error term in the result table, and since the surface flow at the border is in balance, the results are still valid.

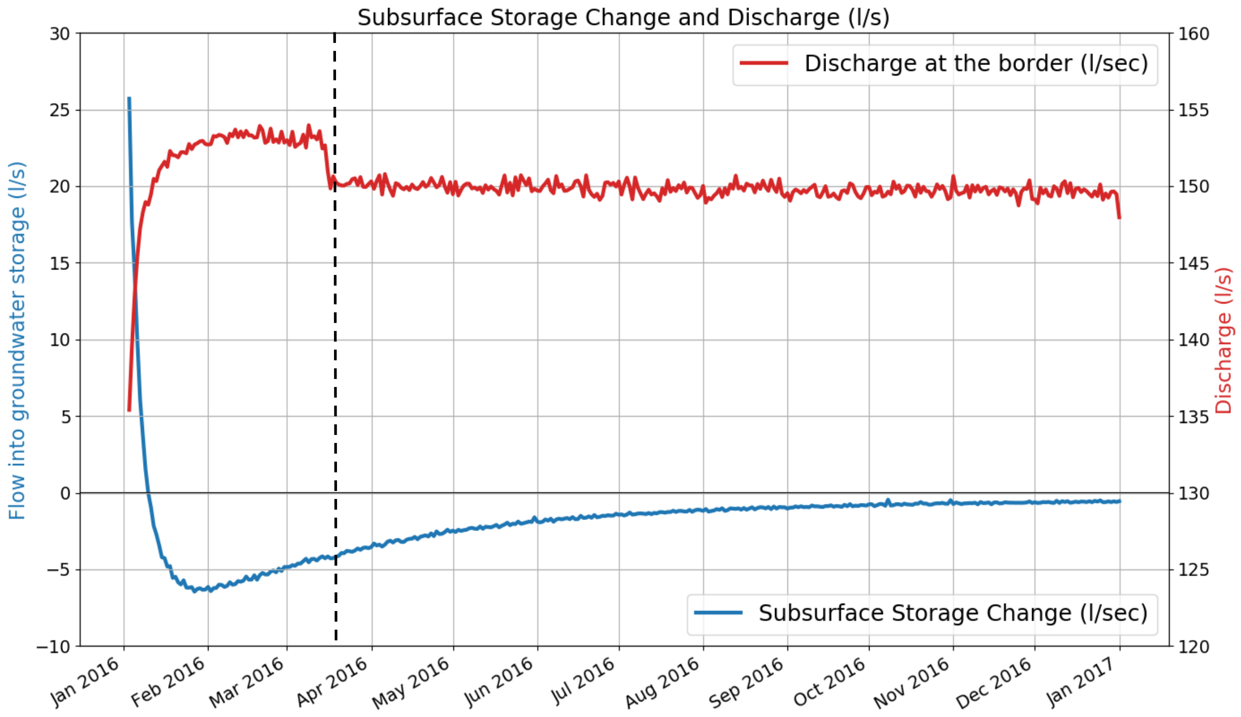


Figure 7-4 Output of the same baseline model simulation but prolonged to one year. Plot of subsurface storage change and discharge at the border after 12 months.

7.3.2 Canal roughness parameters applied

97) The resistance to flow or effective roughness of the channel is commonly represented by a parameter known as the Manning's coefficient (n). Chile's experts argue, referring to Muñoz et al. (2019B), that DHI has "used unrealistically large values for this parameter, way beyond feasible literature values for the types of channel represented here". This is not correct as the additional effects of large-scale roughness, bed irregularities and pool and riffle sequences must be accounted for.

98) The general approach for estimating n values in mountainous streams (Jarret, 1985) consists of the selection of a base roughness value for a straight, uniform, smooth channel in the materials involved. Then, through a consideration of various factors, modifying values are added to the base n value to obtain the n value for the channel under consideration (Chow, 1959; Cowan, 1956). Additive values account for cross-section irregularity, variations of the channel, effect of obstructions, density of vegetation and the degree of meandering

99) DHI agrees that one-dimensional models like MIKE 11 are useful tools for predicting flow in streams. We also agree, as recognised in the literature (Jarret, 1984; Bathurst, 1985; Aguirre-Pe and Fuentes, 1990), that the application of such models to streams like Silala can be challenging because "in addition to small scale bed roughness, the effects of large-scale roughness, irregularity in bed geometry, and pool and riffle sequences have to be taken into account at a spatially averaged scale" (Meier and Reichert, 2005).

100) According to Jarret (1985), a first estimate of the roughness for the Silala canals would be in the range of [0.071- 0.12] and that 'Extremely' rough conditions may need larger adjustments. Thus, the value of 0.2 used in the Silala canal model is by no means unrealistic.

7.3.3 Accuracy of canal cross-sections

101) In general, the cross-sections in the model are consistent with the topography and the measured channel dimensions. However, Chile's experts have pointed to some inaccuracies in smaller parts of the reach from the confluence to the border. In the downstream section of the model, a digital terrain model has been used, which is coarser than the one available for the rest of the Silala. Over a smaller distance (300 m) in the lowest part of the ravine reach, the canal has not been correctly located but has

apparently been slightly displaced (a few meters from the canal centre line). As a result, the water in the model follows the lowest part of the ravine (where the physical canal is actually located) but using in this stretch a slightly differently shaped flow area than the canal would dictate. Correcting for this discrepancy, however, would be expected to lower the flow resistance as the flow area would become more rectangular. This may, in principle, lower the simulated canal water levels and increase the net groundwater inflow (slightly), which would generate more surface water flow in the Baseline scenario but not affect the other two scenarios. In DHI's view this would tend to *increase* the estimated impacts of the channelization.

102) A similar effect is expected if the furthest downstream cross-section in the model was lowered slightly. This might be more correct and could also lead to slightly lower water levels at the border; water levels that Chile disputes.

7.4 DHI's hydrogeological model is valid

103) In this section we demonstrate that DHI's hydrogeological interpretations and conceptual models are based on an extensive hydrogeological characterization program and in many aspects are consistent with the Chilean Memorial hydrogeological study (Arcadis, 2017) in terms of key findings such as: the spatial and vertical distribution of the ignimbrite aquifer south of the ravines; that tectonism and faulting are likely to have enhanced the degree of fracturing in the ignimbrites along the Silala ravine; that the ignimbrite aquifer has a high permeability, and that groundwater flow within the ignimbrite predominately occurs through fractures. The modifications to the conceptual model developed by Chile's experts (W&P 4) have been made without additional on-site geophysical or hydrogeologic drilling and testing work. Changes to the interpretations made by their experts of the stratigraphy conflict with Bolivian radiometric age dates for the rock units in question and the removal of the fault coincident with the Silala ravine contradict prior reports by Chile's experts (Arcadis, 2017).

104) The geology of the area is largely a result of Upper Miocene volcanic activity that resulted in emplacement of the volcanic centres and domes of the area. Explosive volcanic eruptions during this period led to the deposition of a regionally extensive ignimbrite deposit termed the Silala Ignimbrite.

105) Faulting, fracturing and jointing of the ignimbrite in the Silala area exert a strong control over the number of springs, their spatial distribution and the magnitude of the spring discharge within the Silala wetlands (SERGEOMIN, 2017; DHI 2, 2019; RB, Vol. 4, Annex 23.5).

Figure 7-5 Example of fracturing in the ignimbrite that is coincident with spring discharge, and represents transmission of groundwater to the surface

106) A detailed structural survey of the fractures and faults, inclusive of site-specific mapping completed by (SERGEOMIN, 2017; DHI 2, 2019; RB, Vol. 4, Annex 23.5), indicates that the fracture networks control the majority of the groundwater flow in the ignimbrite. The highest fracture densities were measured in the area of the Silala springs where open fractures within the ignimbrite can be observed to transmit groundwater to the surface and are coincident with spring locations (Figure 7-5).

107) Hydrogeologic studies of the Silala Near Field support the premise that most groundwater flow occurs within fractures in the ignimbrite and weathered zones of rubblized rock fragments. The sustained and relatively steady discharge of the Silala springs and the site-specific testing of the hydraulic properties of the ignimbrite indicate that the system of fractures associated with the Silala springs is connected over large volumes of rock and spatial extents.

108) In general, measured groundwater gradients indicate that groundwater, that does not discharge to the Silala bofedales or artificial canals, flows to the west-southwest towards Chile (DHI 1, 2018; Annex F; BCM, Vol. 4, Annex 17). Fracture mapping and hydraulic testing results (DHI 1, 2018; Annex F, Figure 40; BCM, Vol. 4, Annex 17) suggest that this flow occurs preferentially near the Silala ravine, where rock permeability is greater and the permeable ignimbrite aquifer has been proven to extend to at least 117-m below ground surface (i.e., the lower limit of the ignimbrite extends much deeper in this area). Measurements indicate that the groundwater system discharges to surface water both along the northern and southern reaches of the canals above their confluence, and the surface water loses a modest quantity of water to the groundwater system from just southwest of the confluence to the Chilean border (DHI 1, 2018; Annex F, Figure 42 and Table 15; BCM, Vol. 4, Annex 17). The measured groundwater elevations in combination with the high permeability and spatial and vertical extent of the ignimbrite aquifer suggest that there is significant cross-border groundwater flow into Chile (DHI 1, 2018; Annex F; BCM, Vol. 4, Annex 17).

109) Both the surface water flow measurements (DHI 1, 2018; Annex C; BCM, Vol. 2, Annex 17) and the hydro-chemical mixing ratios suggest that the majority (60-70%) of the groundwater that discharges to the Silala spring and canal originates from groundwater with a deeper regional provenance. The remaining 30-40-percent is interpreted to originate from more localised flow regimes closer to the Silala Near Field. The statement "clearly concluded that it is likely that there are two primary and distinct sources of groundwater discharging to the Silala springs" in DHI's hydrogeology report (DHI 1, 2018; Annex F; BCM, Vol. 4, Annex 17) has been mischaracterised in W&P 5 (2019) to mean two separate aquifers, which is not correct. Groundwater flow in both cases is within the ignimbrite aquifer that includes both localized and regional flow paths with a certain degree of mixing between the two flow regimes.

7.4.1 Existence and role of the Silala Fault on hydrogeological processes and groundwater-surface water interactions

110) Extensive evidence has been provided to the court to support the existence of a fault approximately coincident with the Silala ravines, termed the Silala Fault Zone (DHI 1, 2018; Annex F; BCM, Vol. 4, Annex 17; SERGEOMIN, 2017; DHI 2, 2019, RB, Vol. 4, Annex 23.5). The fault has been mapped as an extension of the Uyuni-Khenayani Fault System (UKFS) in Bolivia by numerous investigators (Sempere et al., 1988; Martínez et al., 1994; Elger et al., 2005).

111) However, the existence of this fault is now disputed, as noted in the following excerpts from the Chilean Pleadings (Chile, 2019) related to the Silala Fault:

a. *"In the words of Chile's experts, its existence is "so unlikely that we believe it impossible""* (W&P 4, p.45).
b. Chile also claims that the Uyuni-Khenayani Fault System, with which the Silala Fault is associated, cannot be responsible for the fracturing or faulting of the ignimbrites in the Silala area because the "major fault system lies 31 km ENE of the Silala River" and it has not been active since 10 Ma[23] and therefore cannot be responsible for the "*high-permeability zone running down the Bofedales Norte (Cajones), Bofedales Sur (Orientales) and Silala River ravine"* (W&P 5; p.135).

112) These statements dispute the role of the Silala Fault in increasing the degree of fracturing and permeability of the ignimbrite aquifer. Chile's experts, however, document the existence of a thrust fault coincident with the Silala ravine and further note that it was an active post-deposition of the ignimbrites:
"The geology of the Silala River basin is dominated by a series of volcanic episodes interspersed with periods of sedimentary activity, during a time of active tectonics, over the last ca. 6 Ma." (Arcadis, 2017, p.12; Annex 2, Vol. 4, MC, 2017); "Subsequently during the late Pliocene and early Pleistocene (ca. 2.6 Ma - 1.5 Ma) the Silala River basin was subject to local compressive faulting which exposed and tilted the Cabana Ignimbrite deposits" (Arcadis, 2017, p.12, Annex 2, Vol. 4, MC, 2017); and "The rock quality of HU3 along the Silala ravine is very heterogeneous, with zones of fractures/faults and

[23] Ma: Million years ago.

zones that are strongly weathered, where the rock is very friable and permeable." (Arcadis, 2017, p.6; Annex 2, Vol. 4, MC, 2017).

113) Numerous other references to faulting along the ravines and intersected fault gouge in core samples from drilling are also made throughout the Chilean Memorial (Arcadis, 2017, Annex 2, Vol. 4, MC, 2017), including presentation of the fault in diagrams of the geologic evolution and stratigraphy of the area (Figure 7-6). However, the fault coincident with the Silala Ravine (shown in black in Figure 7-6) has been removed from Chile's revised cross-section (Figure 7-7) without discussion, explanation or new geologic evidence or hydrogeologic study.

114) Chile's experts now conclude that the existence of the fault is "so unlikely that we believe it impossible". This is in spite of technical evidence, including mapping of the faults by SERGEOMIN (2017; DHI 2, 2019, RB, Vol. 4, Annex 23.5), higher measured fracture densities along mapped fault trends (SERGEOMIN, 2017; DHI 2, 2019, RB, Vol. 4, Annex 23.5), measurements of the principal fracture network trend indicating consistency with the trend of the regional Uyuni-Khenayani fault system (SERGEOMIN, 2017; DHI 2, 2019, RB, Vol. 4, Annex 23.5) and pumping tests with high hydraulic conductivity (DHI 1, 2018; Annex F, p.81; BCM, Vol. 4, Annex 17) along the ravine (including tests completed within Chile), all of which support rather than refute the existence of a fault zone in this area. The relatively small displacement in the ignimbrite at the border is also noted by Chile as evidence against faulting (W&P 4, 2019; p.52). However, faults frequently have variable displacement along strike, and ignimbrites are known to conceal faults by accommodating strain incrementally in each fracture over a wide area (Wohletz, 2006).

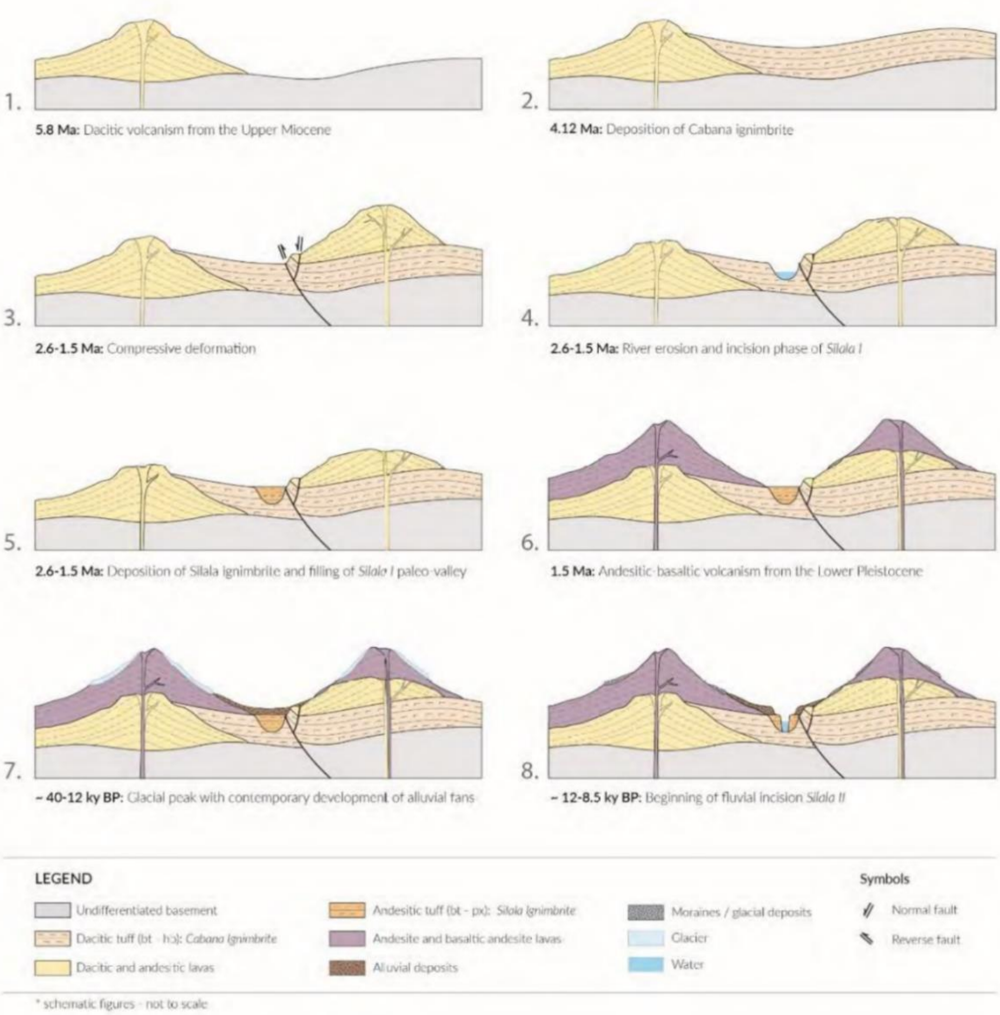


Figure 7-6 SERNAGEOMIN conceptualisation of the Silala ravine showing a thrust fault coincident with the ravine (diagram included in Chile's memorial) and laterally expansive ignimbrite aquifer.

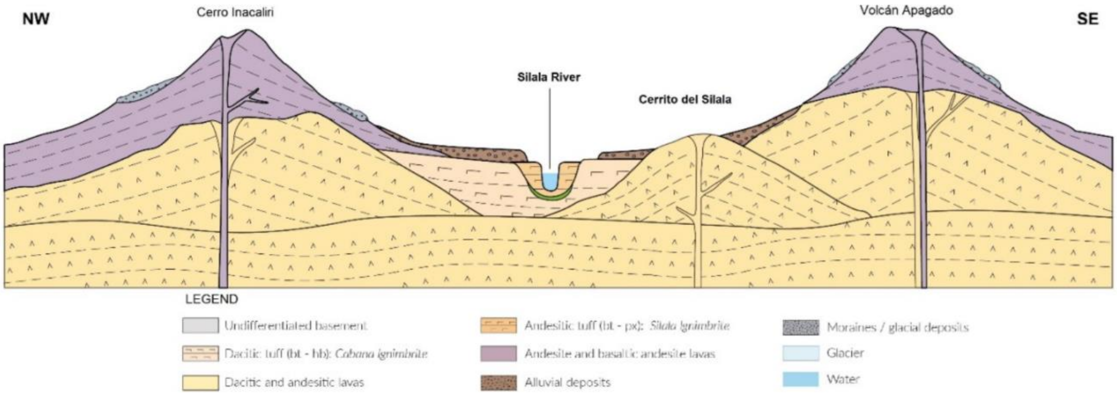


Figure 7-7 Chile's updated conceptualisation of the Silala ravine – note the absence of any faults and the changes to the extent of the ignimbrite aquifer. (W&P 4, 2019)

115) Perhaps more importantly, the Chilean pleadings misrepresent the level of importance assigned to the Silala Fault Zone from a hydrogeological perspective. The measured hydrogeological properties and hydraulic gradients of the Silala Near Field and along the transects of the mapped faults are defined and not in dispute, and these properties are what ultimately control the groundwater flow and groundwater-surface interactions. The hydraulic conductivity values presented are consistent with pumping tests within and near the Silala ravine both in Bolivia and Chile and demonstrate that the fractured ignimbrite aquifer is highly permeable with hydraulic conductivity test results between 2.8 and 17 m/d in Chile (Arcadis, 2017) and 13.8 m/d and 138.2 m/d in Bolivia (DHI 1, 2018; Annex F; BCM, Vol. 4, Annex 17). The origins of the higher degree of fracturing and permeability of the ignimbrite aquifer in the area of the Silala ravine are immaterial.

116) We agree with Chile's experts that much of the fracturing associated with the ignimbrites is related to cooling. What is postulated in DHI 1 2018 (Annex F, p.81; BCM, Vol. 4, Annex 17) is that tectonism has likely affected the fracture density and, thus, the hydraulic properties (i.e., hydraulic conductivity, specific yield, specific storage) approximately coincident with the mapped faults and the ravines themselves. However, explanations for the presence of a higher degree of fracturing, and by extension permeability, near the mapped fault transects coincident with the ravines, do not require tectonic movement post-deposition of the ignimbrite.

7.4.2 Geologic ages of stratigraphic units and lateral extent of ignimbrites in the revised Chilean hydrogeological conceptual model

117) There are conflicting radiometric age dates of the ignimbrite rock that forms the dominant aquifers of the Silala area (see detailed summary in W&P 4, 2019; Table 1). The ages of the ignimbrites relative to the Miocene Volcanics are important because they provide key insights as to the potential spatial and vertical extent of the ignimbrite aquifer, which is a principal factor in determining groundwater flow patterns, spring discharge and cross-border flows to Chile.

118) The age dating determines whether the ignimbrites were deposited prior to or after surrounding volcanics such as those associated with the Inacaliri and Silala Chico volcanoes. The implications for the stratigraphic interpretation are substantial. This can be illustrated using the example of the subsurface interpretations beneath Silala Chico, wherein Chile has proposed a conceptual model in 2017 (Arcadis, 2017; Annex II, Vol.4) and revised the interpretation in 2019 (W&P 4, 2019) as shown in Figure 7-6 and Figure 7-7. As conveyed in Figure 7-6, if the ignimbrite pre-dates the Miocene Volcanics, the ignimbrite would be expected to be present over a much larger area and depths. If the Miocene Volcanics pre-date the ignimbrite deposits, the ignimbrite may be much less laterally and vertically expansive.

119) Conceptually, both alternative conceptual models are plausible depending on which rock age dating and corresponding stratigraphic sequence is accepted as correct. Chile's experts dismiss the Bolivian samples and rely on samples collected in Chile for their interpretations of the stratigraphic sequence in Bolivia. DHI concludes that it is essential to consider the samples collected on-site in Bolivia for the interpretation of the stratigraphy in Bolivia and relies upon these ages in the conceptual interpretation.

120) However, the three-dimensional geometry of the ignimbrite aquifer in both Chile and Bolivia can only be resolved through a geophysical and borehole testing program and will remain uncertain until such a program has been implemented. Collaborative studies on age dating of the ignimbrite could, however, lead to a unified interpretation of the stratigraphy and conceptual model.

121) The primary implications of these two competing conceptual models are potentially different rates of cross-border groundwater flow into Chile and different local groundwater flow patterns depending on whether the ignimbrite aquifer is more (DHI 1, 2018; Annex F, pp.1-99; BCM, Vol. 4, Annex 17; Arcadis, 2017, Annex II, Vol.4) or less (Figure 7-7) spatially and vertically expansive. There is no subsurface lithology data or measured groundwater levels in the area of Silala Chico, which means that such interpretations are by their nature uncertain.

122) Uncertainties in the hydrogeological conditions identified by W&P 4, 2019, located beyond the areas characterized by boreholes and piezometers, support the approach of constraining the Near Field model to regions were the aquifer geometry and hydraulic properties have been characterised.

123) Chile's experts assert that perched aquifers have been observed in Chile (W&P 4, 2019; Arcadis, 2017; SERNAGEOMIN, 2019a; Herrera and Aravena, 2017) and that these also exist in Bolivia and, thus, should have been included in the numerical model due to differing piezometric level distributions.

Figure 7-8 Fracturing within ignimbrite walls of the Silala ravine - note the vertical fracture crossing through the section inclusive of varying degrees of welding and lithological variations

124) The presence of a perched aquifer in Chile is neither accepted nor refuted, though it is entirely possible that such a system exists. However, within Bolivia, no perched aquifer has been observed or documented during an expansive hydrogeologic characterisation program including more than 30 boreholes. The pumping data indicates that the vertical hydraulic conductivity may be somewhat lower than the horizontal hydraulic conductivity as a result of lithological layering within the ignimbrite. As a result, the numerical model also incorporates a vertical hydraulic conductivity that is lower than the horizontal value. As is typical of many ignimbrites, extensive vertical fracturing is evident throughout the Silala ravine (Figure 7-8), and vertical fractures create conduits for vertical flow between various ignimbrite lithologies or stratigraphic layers, reducing the potential for widespread perched groundwater. Within the southern and northern bofedales, upward vertical gradients have generally been measured in the ignimbrite aquifer (DHI 1, 2018; Annex F, p.91, Table 15; BCM, Vol. 4, Annex 17) indicative of deeper groundwater flowing upwards and ultimately discharging to surface water and springs.

125) The argument for perched aquifer conditions in Bolivia masks the fact that both parties have interpreted a localized flow regime with a closer recharge source based on differing water chemistry. Within Bolivia, this localized flow regime has been identified in saturated portions of the shallow ignimbrite aquifer. In contrast to Chile's experts' assertion, the Near Field model boundary formulation north of the Northern wetlands is not influenced by perched water at the alluvial-ignimbrite contact as proven by wells DS-25 and DS-27-II (DHI 1, 2018; Annex F; BCM, Vol. 4, Annex 17). These monitoring wells are completed within the saturated ignimbrite aquifer, and groundwater elevations from these wells control the interpolated groundwater levels in the area north of the Northern wetlands used in the Near Field model setup.

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