INTERNATIONAL COURT OF JUSTICE

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

(CHILE v. BOLIVIA)

WRITTEN STATEMENT OF THE EXPERTS OF THE REPUBLIC OF CHILE

DRS. HOWARD WHEATER AND DENIS PEACH

14 JANUARY 2022

ABOUT THE AUTHORS

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Dr. Howard Wheater is Canada Excellence Research Chair Laureate in Water Security at the University of Saskatchewan, Canada, where he was founding Director of the Global Institute for Water Security, and Emeritus Professor of Hydrology at Imperial College London, where he held a full-time academic appointment for 32 years. A leading expert in hydrological science and modelling, he has published more than 240 refereed articles and 6 books. He is a Fellow of the Royal Society of Canada, the UK's Royal Academy of Engineering and the American Geophysical Union. He was awarded the 2018 International Prize for Water (Dooge Medal) by UNESCO, the World Meteorological Organisation and the International Association for Hydrological Sciences and the 2006 Prince Sultan bin Abdulaziz International Prize for Water. He has initiated and led national and international research programmes in the UK and Canada, and has advised states, provinces and national governments on flood, water resource and water quality issues. He sat on the Court of Arbitration concerning the Indus Waters Treaty and has been instructed by Hungary and Argentina in cases before the International Court of Justice. He was, until 2014, vice-chair of the World Climate Research Programme's Global Energy and Water Cycle Exchange (GEWEX) project and led UNESCO's GWADI arid zone water program. In Canada, he led the Changing Cold Regions Network, focused on the analysis and prediction of hydrological change in western Canada, and the Global Water Futures Program, focused on managing water futures in Canada and other cold regions where global warming is changing landscapes, ecosystems, and the water environment. In 2018 he was the only non-US member of a US National Academies panel that reported on Future Water Priorities for the Nation.

Dr. Denis Peach

Dr. Denis Peach spent nine years as the Manager of the British Geological Survey (BGS) Groundwater Programme, then 6 years as BGS Chief Scientist. He is a hydrogeologist with broad scientific interests and 49 years of experience, which includes work for a UK water authority, overseas work in tropical hydrogeological environments, small island hydrogeology and work for international consultants in arid zone hydrogeology. His particular scientific interests include groundwater modelling which he developed in BGS, arid zone hydrogeology, and Chalk and Karst hydrogeology. He has been a Vice President of the Geological Society of London (GSL), is a Visiting Professor at Imperial College, London and University of Birmingham and he gave the Ineson Distinguished lecture at the Geological Society of London in 2009. He has led numerous national geological and hydrogeological research programmes in the UK and has sat on many national research programme boards and national water resource strategic committees. He currently carries out research with BGS and Imperial College and recently provided advice to the University of Saskatchewan and UK engineering consultants.

TABLE OF CONTENTS

LIST OF FIGURES

1 INTRODUCTION

1.1 Background

We, Drs. Howard Wheater and Denis Peach, have produced this written statement at the request of the International Court of Justice, as expressed in a letter of 15 October 2021 from the Registrar, M. Philippe Gautier, to the Agent of the Republic of Chile, Ms. Ximena Fuentes Torrijo. M. Gautier has asked for a summary of our five reports, previously presented to the Court in Chile's Memorial (CM), Reply (CR) and Additional Pleading (CAP).

In this introduction, we briefly summarise the key areas of agreement and disagreement concerning the expert issues on which we have reported in this case and present the background of our previous submissions to the Court. In section 2, we provide a description of the Silala River and its hydrology and hydrogeology, and in sections 3 and 4 we present the key areas of agreement and disagreement between the experts. Our conclusions are presented in section 5.

1.2 Summary of the key areas of agreement and disagreement

Both sets of experts (i.e., ourselves and Bolivia's consultants, the Danish Hydraulic Institute (DHI)) agree that the Silala River exhibits the properties of an international watercourse. Whether as surface water or as groundwater, the waters of the Silala River flow naturally down-gradient across the international border into Chile.

Channelization works carried out on the Bolivian side of the border in 1928 will have had some limited effect on the flow of the Silala River. The experts disagree as to the magnitude of this impact. We consider that impact to be very small. The DHI experts, by contrast, consider the impact to be an increase in trans-border surface flow in the region of 11% to 33%. However, it is agreed by all the experts that the channelization has not impacted the direction of flow of the Silala River and, apart from the very small effects of channelization on evaporation, any increase in surface flow in the river will be accompanied by a decrease in groundwater flows across the border, and vice versa.

In other words, even though there is disagreement as to the precise impacts of the channelization on surface water flows, it is agreed that notwithstanding the channelization (and subject to the very small effects of channelization on evaporation), all the waters of the Silala River continue to flow down-gradient across the international border into Chile. Thus, the channelization has not, and could not have, materially affected the quantity of water flowing into Chile.

1.3 Our five reports to the Court – background and summary

In the pleadings before the Court, we have set out, in a series of joint reports, the growing scientific evidence concerning the hydrological functioning of the Silala River, together with our independent expert opinion on Bolivia's various submissions to the Court.[1] In these reports we address a series of questions posed to each of us by Chile. The answers to questions addressed to Dr. Wheater have therefore been drafted by Dr. Wheater, as first author, and similarly the answers addressed to Dr. Peach, by Dr. Peach as first author. However, the joint authorship of these reports reflects the fact that they represent our joint opinion.

Together with Chile's Memorial of July 2017 we submitted two reports, namely *The Silala River Today - Functioning of the Fluvial System* ("Wheater and Peach 2017"), which focussed on the hydrological functioning of the river, and *The Evolution of the Silala River, Catchment and Ravine* ("Peach and Wheater, 2017"), which focussed on the geological and geomorphological history of the basin. In both reports, a central question was whether the Silala River satisfies the criteria of an international watercourse, which was answered affirmatively by both Dr. Wheater and Dr. Peach, from a hydrological and a hydrogeological perspective, respectively. In addition, Drs. Wheater and Peach provided a first opinion on the impacts of the historical channelization, namely that the effects on surface flows at the border would be insignificant, no more than 2%.

In Chile's Reply (February 2019) to Bolivia's Counter-Memorial (BCM) we updated the scientific evidence and provided our independent expert opinions on Bolivia's scientific evidence, in particular concerning the modelling by Bolivia's international consultants, DHI, of the impacts of channelization of the Bolivian wetlands on the surface water flow (DHI, 2018a). In *Impacts of Channelization of the Silala River in Bolivia on the Hydrology of the Silala River Basin* ("Wheater and Peach, 2019a"), we summarised the points of technical agreement between the parties and explained our concerns about Bolivia's modelling. In addition to our technical issues with the modelling, we identified Bolivia's erroneous interpretation of the geology and hydrogeology of the Silala River basin, which was addressed in our second report, *Concerning the Geology, Hydrogeology and Hydrochemistry of the Silala River Basin* ("Peach and Wheater, 2019").

Finally, in Chile's Additional Pleading (September 2019), following receipt of Bolivia's digital data and in response to Bolivia's Rejoinder (BR), we reported on our further analysis of Bolivia's modelling of the impacts of the channelization in Bolivia (*Impacts of Channelization of the Silala River System in Bolivia on the Hydrology of the Silala River Basin – an Updated Analysis* ("Wheater and Peach,

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[1] Under the joint direction of the authors of this Written Statement, a team of Chilean experts under the leadership of Dr. José Muñoz, an expert on groundwater hydrology, conducted a series of intensive studies, together with enhanced monitoring, which continues to the present time.

2019b" or "Updated Analysis, 2019"). This Updated Analysis, based on inspection of the data files used to run Bolivia's models, showed further and very significant modelling errors. We also reported an updated analysis of Bolivia's interpretation of the geology and hydrogeology of the Silala River surface and groundwater catchments upon which Bolivia's modelling was based. We concluded that Bolivia's modelling was wholly unreliable and should be disregarded by the Court.

2 THE SILALA RIVER

2.1 Introduction

After initial site reconnaissance and review of existing scientific studies, a substantial program of hydrological and hydrogeological studies was put in place by Chile, on our recommendation, to better understand the hydrological functioning of the Silala River, including surface water-groundwater interactions, and its geological and geomorphological evolution. The groundwater flow regime was investigated with drilling and pump testing, and detailed geological mapping and hydrochemical surveys were carried out. Much of this we reported in our two reports of 2017 (Wheater and Peach, 2017; Peach and Wheater, 2017). However, Bolivia's Counter-Memorial made a number of erroneous claims about the geology and hydrogeology of the Silala River basin and the impacts of channelization on the Bolivian wetlands (the Cajones and Orientales wetlands)[2] from which the Silala River flows originate. As we are unable to observe the Bolivian wetlands directly, we developed detailed studies of a similar wetland in the Silala River basin in Chile, the Quebrada Negra wetland, which allowed us to better understand wetland functioning in the basin and undertake comparative analysis of the Bolivian headwater wetlands based on remote sensing data. This we reported in Chile's Reply, together with a detailed analysis of Bolivia's geological and hydrogeological interpretations. While some uncertainties remain, we now have a much-improved understanding of the basin, which we summarise below.

2.2 Catchment definition and hydrological functioning

The Silala River is a typical groundwater-fed river.[3] The perennial river flows originate in groundwater springs in Bolivia, associated with the Cajones and Orientales wetlands, at more than 4323 metres above sea level (m.a.s.l.), but the river interacts with groundwater along its flow path. It receives substantial inputs from groundwater springs that emerge from the wall of the Silala River ravine that

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[2] Denoted 'Northern' and 'Southern' respectively by Bolivia.

[3] Many major rivers originate in perennial or ephemeral groundwater springs. The River Thames (UK) is a notable example (British Geological Survey, 1996).

crosses the international border (at approximately 4277 m.a.s.l.) and loses water from the flowing channel to an underlying fluvial aquifer (CM, Vol. 1, pp. 135, 168-169). A deeper groundwater system has also been identified, which currently contributes flow to the river in Chile via discharge from an artesian well[4] (CM, Vol. 1, pp. 135, 171-173).

The topography is such that natural drainage will flow from Bolivia to Chile from a topographic catchment, shown in Figure 1. Figure 2 shows the longitudinal profile of the river. The difference in elevation between the spring sources in Bolivia and the river channel at the border is more than 45 metres, and the gradient of the natural river channel is relatively steep (approximately 4-5%). In the vicinity of the border, the river channel flows within a ravine that has been created by fluvial processes. In Peach and Wheater (2017) we showed that the ravine provides evidence that a river has flowed across what is now the international border, at this location, for more than 8,400 years (CM, Vol. 1, pp. 218-223).

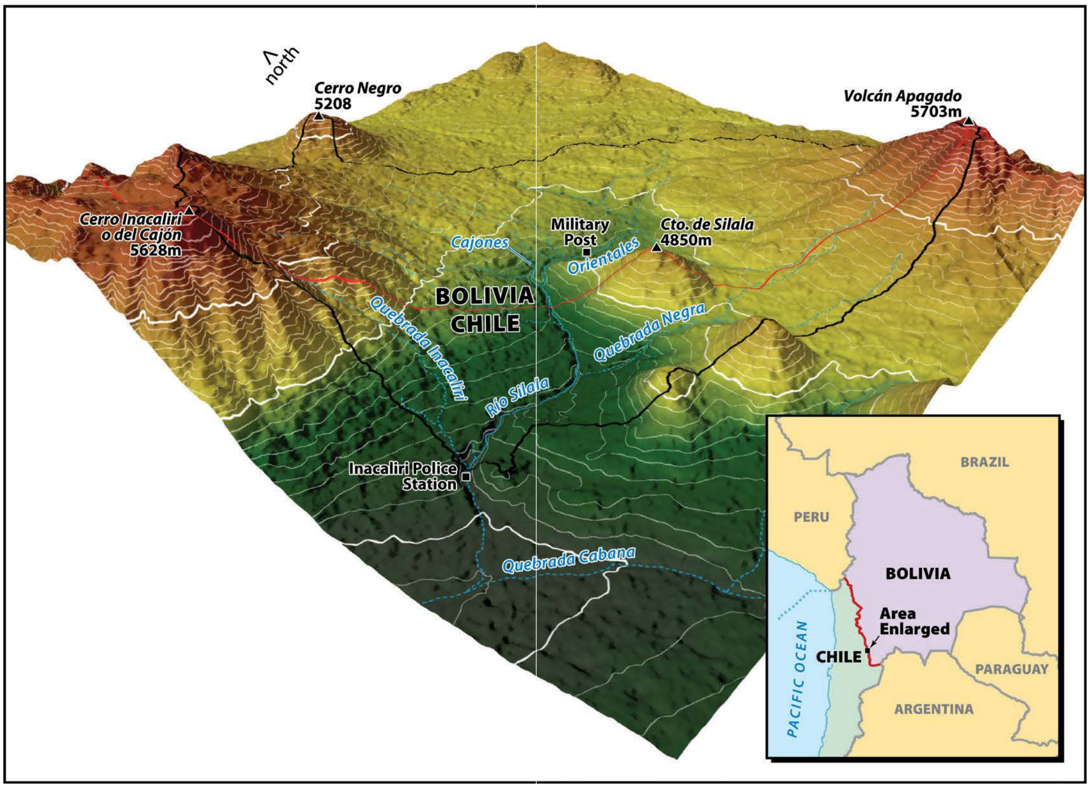

Figure 1. 3D topography with contour lines delimiting the surface water drainage basin of the Silala River basin. International boundary (red line) and watershed boundary (black line) as also shown in Figure 2 (top panel of Muñoz et al., 2017, Figure 3-3, at CM, Vol. 5, p. 182).

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[4] An artesian well is one in which water pressure in the aquifer generates surface flows from the well.

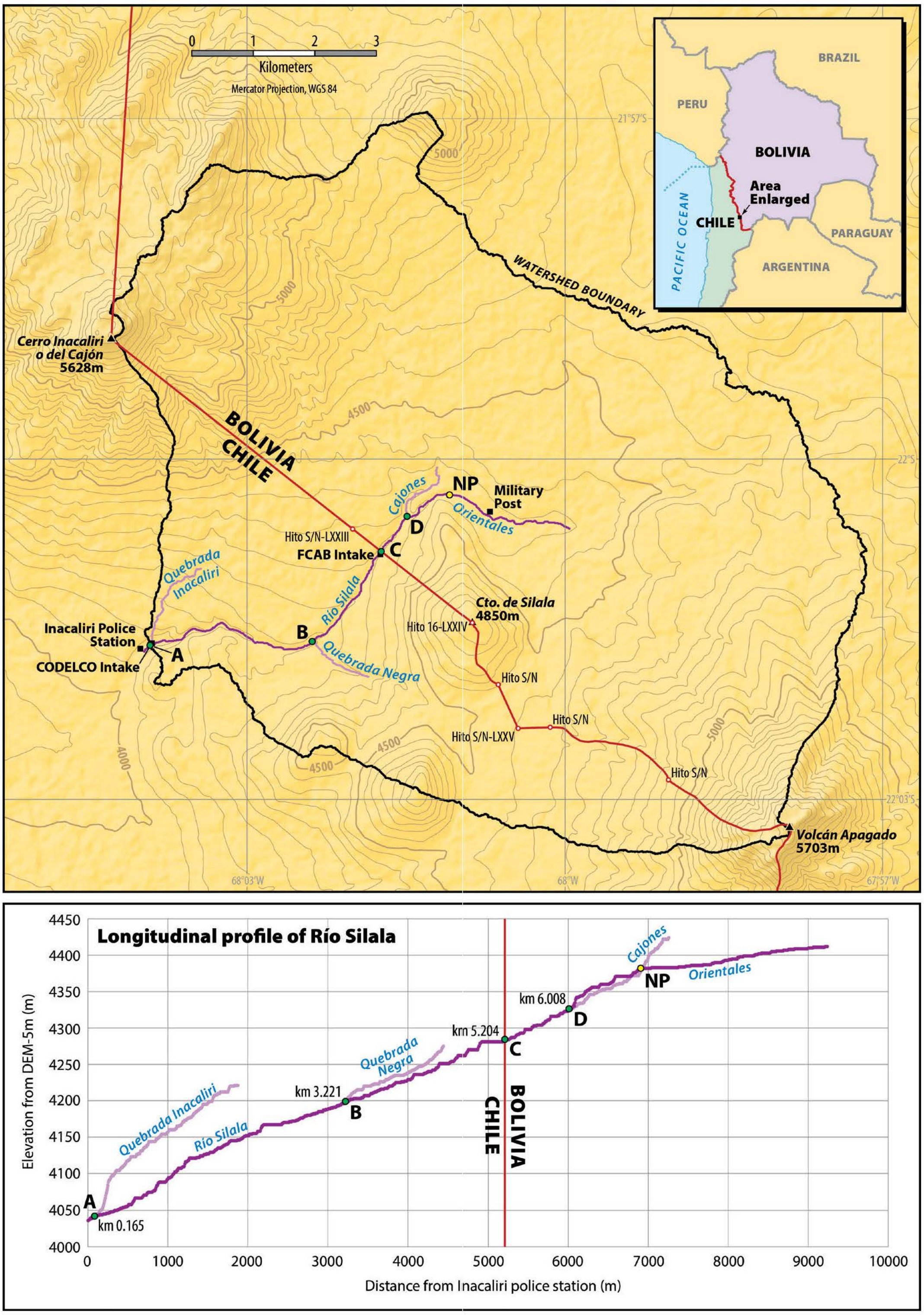

Figure 2. Longitudinal profile of the Silala River and main tributaries (Wheater and Peach, 2017, Figure 4, at CM, Vol. 1, p. 143).

The climate of the basin was described in Wheater and Peach (2017) (CM, Vol. 1, pp. 154-161). Our estimate of average annual precipitation over the topographic basin is 165 mm. In such a dry climate, evaporation (mainly from open water surfaces and plant transpiration) is limited, over most of the area, by the available precipitation. However, for wetland areas, springs provide water that can support high rates of evaporation. We estimated that 78 mm of the annual precipitation is discharged as river flow, and 87 mm is lost as evaporation from the catchment as a whole. Using remote sensing methods, we estimated that the evaporation from Bolivia's wetlands was equivalent to 0.7% of the river flow, but recognizing the considerable uncertainty in this estimate, we suggested that 2% of the average flow was an upper bound to this estimate.

Analysis of the water balance[5] showed that the surface flows in the Silala River cannot be supported by precipitation over the topographic catchment alone. In Bolivia's Counter-Memorial, DHI identified a larger groundwater catchment (BCM, Vol. 2, p. 275, Figure 5), with which we largely agree. Our best estimate of this area is shown in Figure 3.

The groundwater that provides the spring flows that feed the Bolivian Orientales and Cajones wetlands emerges from the Volcanic and Alluvial deposits that underlie these wetlands. Many of these deposits are aquifers, which are supplied with recharge waters derived from the precipitation, less evaporation, over the large groundwater catchment (Figure 3). These aquifers are extensive throughout the catchment in Bolivia and Chile. Hence groundwater will flow down-gradient across the international border from Bolivia to Chile either as surface water, from the springs, or as groundwater within the aquifers (CM, Vol. 1, pp. 167 and 168, Figures 20 and 21).

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[5] Simply stated, the difference between precipitation and evaporation provides the water available for surface water and groundwater flows within and leaving the basin (including any abstraction for public or industrial uses), neglecting seasonal and inter-annual changes in storage.

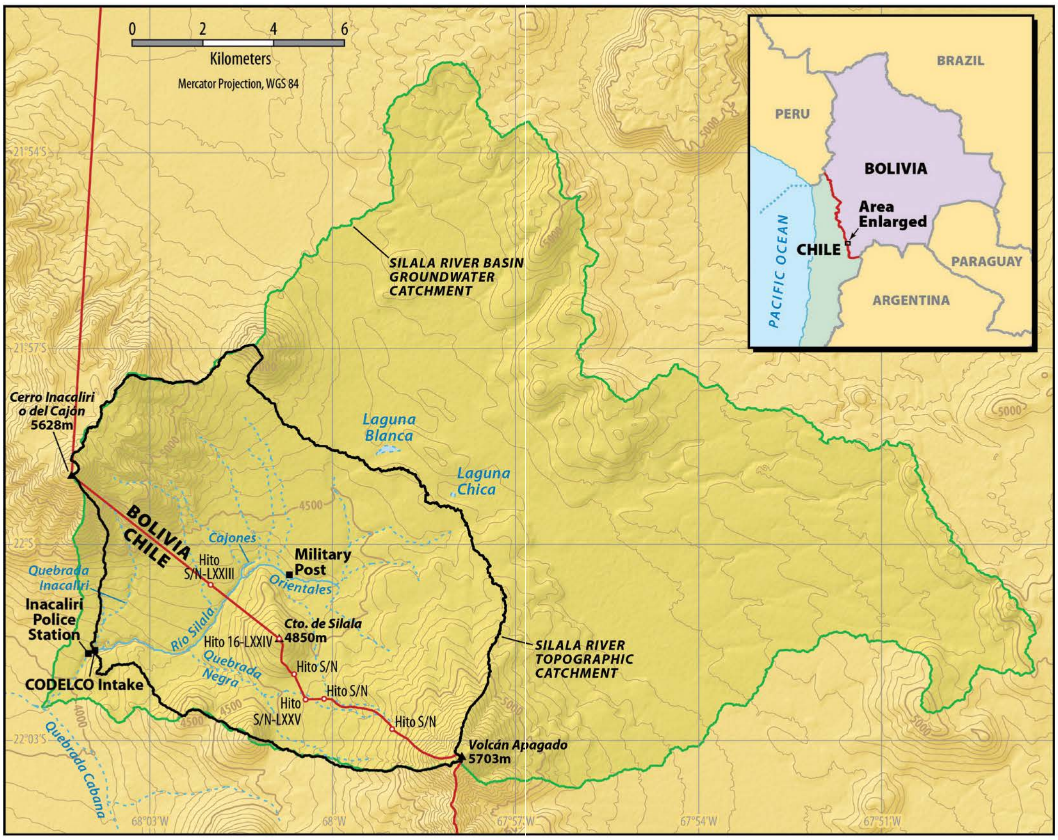

Figure 3. Silala River topographic and groundwater catchments (Wheater and Peach, 2019a, Figure 1, at CR, Vol. 1, p. 105).

As noted above, a central concern of Chile, articulated in its Application to the Court of June 2016, was that the Court should recognize the Silala River as an international watercourse. We concluded in Wheater and Peach (2017) (CM, Vol. 1, pp. 135-137), from our expert point of view, that the Silala River is without doubt 'a system of surface waters and groundwaters constituting by virtue of their physical relationship a unitary whole and normally flowing into a common terminus', and that it is 'a watercourse, parts of which are situated in different states' (which we understand to be the relevant definition from the 1997 UN Watercourses Convention). The natural direction of flow is across the international border, from Bolivia to Chile, and the 'common terminus' element is satisfied by the discharge of Silala waters into the San Pedro River, and ultimately via the Loa River into the Pacific Ocean.

We noted that in Bolivia's Counter-Memorial, DHI agree with this understanding (Wheater and Peach, 2019a, at CR, Vol. 1, pp. 103-106). They confirm that the Silala River is 'a coupled groundwater-surface water system […] extending across the border' (BCM, Vol. 2, p. 266). They also note that numerous additional springs occur downstream of the Orientales wetlands and add to the river flow (BCM, Vol. 2, pp. 368-369). Further they note that 'groundwater level gradients and hydrogeological properties clearly indicate groundwater flow from Bolivia to Chile' (BCM, Vol. 5, p. 84). While the magnitude of cross-border groundwater flow remains uncertain, DHI estimate that 'the groundwater flow across the border is at least of the same order of magnitude as surface water discharge at the border' (BCM, Vol. 5, p. 84).

2.3 Geology and hydrogeology

To understand the functioning of a groundwater-dominated catchment, it is necessary to understand the underlying geology, which determines the hydrogeological characteristics, e.g., the extent and properties of the aquifer systems, as well as their inter-connectedness. Experts from the Chilean Geological Survey, SERNAGEOMIN, working with Dr. Peach, have conducted extensive studies, as reported in Chile's Memorial (SERNAGEOMIN, 2017), Reply (SERNAGEOMIN, 2019a) and Additional Pleading (SERNAGEOMIN, 2019b). In addition, various comments by Bolivia raised a doubt as to the nature and formation of the ravine in which the river flows from Bolivia to Chile (e.g., CM, Vol. 3, p. 375; BCM, Vol. 5, p. 119). Hence studies of the geomorphology of the river were carried out by the Chilean expert team (Mao, 2017; Latorre and Frugone, 2017).

The current geology is a result of a long history of geological activity, summarised below:

i) During the period from about 6 million to about 1.5 million years ago (Ma) the area now occupied by the catchment of the Silala River was subject to episodes of volcanism associated with the collision of the ocean tectonic plate to the west (beneath the Pacific Ocean) and the South American continental tectonic plate. This resulted in volcanic activity that shaped the landscape, including the building of the Cerro Inacaliri, Cerrito de Silala and the Volcán Apagado (CM, Vol. 1, pp. 199-200), which are all dominant features of the catchment morphology (Figure 1).

ii) The foundations of these edifices are formed of largely volcanic domes and lavas dated at around 6.6-5.8 Ma. Upon these older basal rocks, which can be found beneath the Silala River ravine, are deposits called Ignimbrites. These were emplaced by explosive volcanic eruptions extruding flows of rock fragments, molten rock droplets and hot gases, which flowed down the existing topographic gradient at great speed (CM, Vol. 1, pp. 199-200). The first of these (Cabana Ignimbrite, ca 4.12 Ma) was a very extensive and voluminous event affecting a large area of the Chilean Altiplano. This was followed by a first period of fluvial activity, which eroded a valley in the ignimbrite and left fluvial sediments (CR, Vol. 3, pp. 208-209). On top of these early fluvial deposits a further ignimbrite (Silala Ignimbrite ca 1.61 Ma) was deposited, probably filling the valley. Subsequently further volcanism led to a massive lava flow being erupted from the Inacaliri volcano (1.48 Ma) which flowed into the headwater area of the Silala River. This lava flow truncated the then-existing drainage network of the Silala River (CM, Vol. 1, pp. 208-215; CR, Vol. 1, pp. 179-183; SERNAGEOMIN, 2017; SERNAGEOMIN, 2019a).

iii) There appears to have been a hiatus in volcanic activity in the catchment after 1.48 Ma, and the next events to impact the catchment morphology were associated with the glaciation of the high peaks, above 4400 m.a.s.l. There is no evidence of glacial erosion or glacial deposits to be found at the level of the current Silala River ravine or in the ravine. The cutting of the Silala River ravine, as we know it today, was caused by fluvial processes. It began in the period ca 12,000-8,400 years ago and continues today. Radio-carbon dating has shown that there are sediments deposited by the current Silala River system in the ravine that are more than 8,400 years old. The river began cutting the ravine before that, probably as a result of the melting of the glaciers about 12,000 years ago that caused significant runoff and increased flow in the river and continues in a cycle of erosion and deposition in response to climatic regime changes (CM, Vol. 1, pp. 218-223; Latorre and Frugone, 2017).

Features of fluvial erosion are common in the sides of the ravine. There are four water-cut river terrace surfaces and four sedimentary sequences of deposits several metres thick (CM, Vol. 1, pp. 218-223; Arcadis, 2017). These deposits include sands, gravels, silts and organic remains of wetlands. The sides of the ravine contain minor wind erosional features, and there are some windblown sand deposits to be found, but these are minor features, and would have had no significant impact on the ravine formation (CM, Vol. 1, pp. 227-233; SERNAGEOMIN, 2017). Archaeological surveys have found artefacts and shelters or temporary dwellings along the course of the river, mainly on the upper three terraces (CM, Vol. 1, pp. 224-225; McRostie, 2017). These testify to the human use of the river and its course over the past at least 1,500 years. There is no doubt that the geological, geomorphological, and other evidence points definitively to the historical existence of a fluvial system in the Silala River catchment. The modern ravine, created by fluvial action, has existed for more than 8 millennia (CM, Vol. 1, pp. 218-225; Latorre and Frugone, 2017).

These geological processes and events have formed the landscape of the Silala River catchment and ravine as we know it today (a schematic cross-section through the Silala River ravine and Cerro Inacaliri and Volcán Apagado can be found in CR, Vol. 1, p. 190, Figure 3-6). We noted that the hydrological regime is not only a reflection of the climate and meteorology, but of the nature and topography of the land surface and the rocks found in the subsurface. The current topography (Figure 1) and river profile (Figure 2) are a direct result of the interaction of the atmospheric processes, solid earth processes and biological processes and their variability over the last 6 million years. The natural gradients of the landscape topography and the river channel are such that the river must flow naturally from Bolivia to Chile. Similarly, the current groundwater level gradient indicates a natural flow from Bolivia to Chile (CM, Vol. 1, p. 167, Figure 20), as agreed by DHI (BCM, Vol. 2, p. 266).

We also note, based on studies of the fluvial geomorphology (Mao, 2017), that the current fluvial system continues to be geomorphologically active; we have observed size-selective transport of fine and coarse sediments and bed armouring,[6] and the current channel morphology of steps and pools is consistent with that needed to transport the current flow and sediment loads. The river also maintains flourishing populations of fish and invertebrates, an indicator of aquatic ecosystem health (Mao, 2017).

It is clear from our investigations reported in Chile's Memorial and Chile's Reply that the hydrogeology of the groundwater catchment is highly complex, but we have found three distinct aquifer systems that are active in Chile (Arcadis, 2017):

i) A fluvial aquifer that is found beneath the bed of the Silala River and within the ravine (CM, Vol. 1, pp. 166-169). These deposits are composed of sediments laid down by the river and associated riparian wetlands. They support minor groundwater flows but display a distinct groundwater level different from the perched and regional aquifers described in (ii) and (iii) below.

ii) A perched aquifer system that is present in alluvial deposits that overlie the bedrock volcanic formations found in the Silala River basin, as evidenced from geophysical investigations, spring flows into the Silala River, in particular from the northern side of the Silala River ravine (CM, Vol. 1, pp. 168-169), and confirmed by hydrochemical analyses that show the distinctly different nature of the water from deeper groundwaters (Herrera and Aravena, 2017; Herrera and Aravena 2019).

iii) A regional aquifer system that was formed by a succession of ignimbrite deposits of variable permeability, which are interbedded with fluvial deposits (providing high permeability). The groundwater found in this aquifer has a distinctly different hydrochemical signature to those of the perched aquifer (CM, Vol. 1, pp. 171-172). This aquifer is recharged from the extensive groundwater catchment (Arcadis, 2017; BCM, Vol. 2, p. 275, Figure 5) (See Figure 3 above).

It is also clear that recharge to these aquifers in the groundwater catchment, most of which lies in Bolivia, either emerges at the Bolivian wetland springs or the

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[6] Gravel-river beds typically have an 'armoured' layer of coarse grains on the surface, which acts to protect finer particles underneath from erosion.

Chilean springs downstream of the international border, or flows within the regional ignimbrite aquifer down gradient through Chile to the southwest. The vertical variability of permeability in the ignimbrites is demonstrated by the artesian overflowing well, SPW-DQN, and implies a confining, low permeability layer (CR, Vol. 1, p. 216).

The differences in hydrochemistry and carbon isotope content between the Cajones and Orientales wetland spring waters are marked and indicate different origins for the groundwater issuing from the two sets of springs. The Cajones waters are probably derived from recharge more locally and show similarities to the groundwaters emerging from the perched aquifer springs emerging from the ravine wall in Chile. However, the groundwaters emerging from the Orientales springs show close similarity to the groundwater flows found at depth such as those that enter the Silala River from the artesian borehole SPW-DQN (CR, Vol. 1, pp. 201-213; Herrera and Aravena, 2017; Herrera and Aravena, 2019).

Geological mapping by SERNAGEOMIN, in Chile, has found no evidence of the 'Silala fault' as proposed by Bolivia (BCM, Vol. 4, pp. 69-81, and p. 75, Figure 27) in the Silala River ravine, but several faults downstream in Chile indicate that the regional aquifer is only found at depth beneath low permeability Pliocene lavas (CAP, Vol. 2, pp. 214-217), and it is likely that groundwater flow further down-gradient would be limited.

2.4 The historical channelization of the Silala River in Bolivia

Although, as noted above and in Section 3 below, there is agreement between ourselves and Bolivia's experts that the Silala River has the characteristics of an international watercourse, and broad agreement about the nature and functioning of the catchment, including cross-border surface and groundwater flows, there are remaining scientific differences between the experts. Apart from the interpretation of the geology and hydrogeology, discussed above, a key difference is focussed on the effects of historical channelization of the river system in Bolivia, undertaken for sanitary reasons in the context of water supply (CM, Vol. 1, p. 98).

In the context of the social and economic development of a hyper-arid region, the Silala River has historically been an important regional water source for Chile. In 1906 a concession was granted by Chile to a British company, the Antofagasta (Chile) and Bolivia Railway Company Ltd. (FCAB) to supply drinking water to the port city of Antofagasta (CM, Vol. 1, p. 40). Two years later, in 1908, FCAB secured rights to use the waters of the Silala River from Bolivia. We understand that engineering works were constructed during the period 1909-1910 to enable flow diversion into a pipeline from the Silala River in Bolivia. The concession continued until terminated by Bolivia in 1997 (CM, Vol. 1, p. 42). A second intake and pipeline were constructed by FCAB in 1942 on Chilean territory. These points of water withdrawal were just downstream and just upstream of the international border, as shown in Figure 4. The figure also shows the location of a further withdrawal point, some distance downstream of the FCAB pipeline intakes, which was implemented in 1956 by the Chilean state-owned mining company CODELCO, for domestic water supply to one of its copper mines. Further details can be found in Wheater and Peach (2017) (CM, Vol. 1, pp. 145-147).

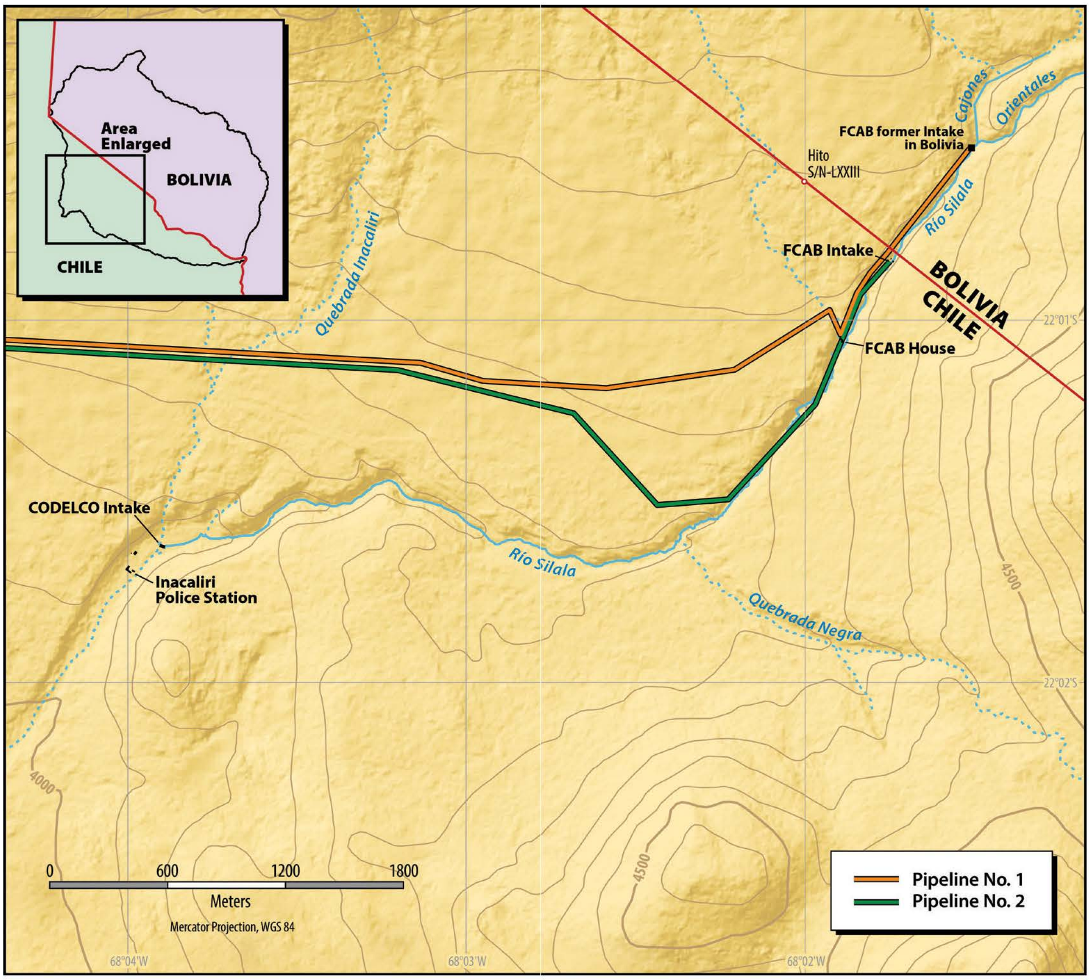

Figure 4. FCAB former Intake in Bolivia, FCAB Intake in Chile and pipelines constructed and used by FCAB. The FCAB former Intake in Bolivia and Pipeline N°1 (orange line) conducted water from Bolivian Territory to the FCAB reservoirs at San Pedro Station (and on to Antofagasta). FCAB Intake and Pipeline N°2 (green line) conducted water from Chilean territory, also to the San Pedro reservoirs (Muñoz et al., 2017; Wheater and Peach, 2017, Figure 6, at CM, Vol. 1, p. 146).

In 1928, FCAB constructed a network of small channels (0.6 m wide x 0.6 m deep) in the Bolivian Orientales and Cajones wetlands, together with some additional channelization of the main river in Bolivia (CM, Vol. 1, p. 42). Constructed as earth channels, and lined with stone, these would act as drains, allowing ingress of water from the wetlands, and loss of water to adjacent soils. The purpose of the channels was to avoid contamination of the water with eggs of green flies that were breeding in the vegetation through which the river was flowing (CM, Vol. 1, p. 98). The history of maintenance of these channels is unclear, though DHI notes (BCM, Vol. 2, pp. 281-282) that in recent years, in parts of the Southern (Orientales) wetland, the canal and drains have been removed, filled in or blocked, in partial attempts at wetland restoration.

Bolivia's experts agree with us that the channelling of flow on Bolivian territory has not influenced the river flow direction, which follows the natural topographic gradients (BCM, Vol. 2, p. 267). Flow across the border in the present ravine has occurred for at least the last 8,400 years and long predated the concessions to FCAB and the later construction of a system of small channels. However, it can reasonably be expected that the channelization will have had some limited effect on the generation of surface flows in Bolivia's wetlands, with potential effects on the extent and health of the wetland vegetation, and on the downstream transmission of surface flows in channelized sections of the river. It should be noted, however, that any effects on surface flow, other than by increased or decreased evaporation would be accompanied by a compensating effect on groundwater flows down-gradient to Chile. In lay terms, whether as surface or as groundwater, all the waters of the Silala River inevitably flow downhill from Bolivia into Chile. Any increase in surface water flow, whether minor (according to us) or significant (according to DHI) could not somehow lead to a material increase in the overall quantity of water flowing into Chile.

The principal hydrological effect of the drainage channels is to reduce the elevation of the groundwater water table in the vicinity of the channels. Instead of groundwater emerging at the wetland surface, it will flow into the drain. This means that at the drain location, the water table will be drawn down to just above the base of the drainage channels (0.6 m), instead of at the ground surface. With increasing lateral distance from the channel, the water table will of course have a higher elevation.[7] Evaporation of water from an open water surface will typically be higher than water transpired by vegetation. However, since in the wetlands the water table, even at a depth of 0.6 m, is relatively close to the surface, evapotranspiration rates are expected to be close to those from open water, and hence any differences in evaporation will be small.

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[7] Bolivia's soils data show water table depths ranging from 0.1 to 0.4 m in the Northern wetland and from 0.15 to 0.45 in the Southern wetland (BCM, Vol. 3, pp. 12-13).

Our preliminary calculations (Wheater and Peach, 2017, at CM, Vol. 1, pp. 161-164) showed that even under the most conservative assumptions, evaporation from these wetlands is a very small component of the water balance of the Silala River.[8] From remote sensing data, we estimated this to be equivalent to 0.7% (1.3 l/s) of the river flow at the border but, recognizing the uncertainty in this estimate, we suggested an upper limit of 2% (3.4 l/s) of the river flow at the border. Clearly, even if some reduction of this evaporation had occurred due to channelization (it should be noted that we show in later reports that that has not been the case), minor changes to this very small element of the catchment water balance would have had no significant effect on flows at the border. Further, the channels, as we understand, have (until very recently) not been maintained since 1997 (CM, Vol. 1, p. 42), and we see no evidence of a change in flow regime at the border. In fact, satellite data shows the wetland extent to be dominated by large natural seasonal and inter-annual variability (CAP, Vol. 1, pp. 137-140).

In Bolivia's Counter Memorial, Bolivia's consultants, DHI, raised further possible effects of the channelization. They agreed with us that changes in evaporation could be expected due to drainage of the wetlands, but also suggested (BCM, Vol. 2, p. 276) that the channels would increase surface water discharge 'due to lowering of the hydraulic head loss by removal of peat or constraining rock cover'. It was stated that at the spring discharge points, 'the soil and any underlying layers of coarser material or rocks have been completely removed' (BCM, Vol. 2, p. 276). These effects were conceptualised for modelling using two scenarios, one in which the channels were removed (the 'No Canals' scenario), and a second (the 'Wetland Restoration' scenario) in which assumed long-term peat accumulation was simulated. They also suggested that the channelization would affect the interactions between flowing surface water and groundwater, reducing seepage losses from the channels to underlying groundwater.

We agreed (Wheater and Peach, 2019a, at CR, Vol. 1, pp.106-109) that the reduction of water table elevation due to the installation of drainage will increase the gradient of groundwater spring flow to the stream, and hence increase the groundwater discharge to the river, and that further accumulation of peat, which has a relatively low hydraulic conductivity, could, in the long term, produce an additional resistance to groundwater flow due to the peat cover, thereby reducing the surface flow. We also agreed that there could be changes to stream-groundwater interactions. However, as we stated in Wheater and Peach (2019a) in our opinion, any changes in surface flow due to these effects will be very small. We return to these issues in section 4, below.

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[8] Although wetland evaporation rates are high, they are associated with relatively small areas.

3 KEY AREAS OF AGREEMENT

We, and Bolivia's experts, agree on several key points concerning the nature and functioning of the Silala River. In summary, these are:

i) 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 (BCM, Vol. 2, p. 266; CM, Vol. 1, p. 177).

ii) The river is primarily fed by groundwater and interacts with groundwater along its course to the border and beyond (BCM, Vol. 2, pp. 368-369; CM, Vol. 1, p. 177).

iii) In addition, there are substantial groundwater flows from Bolivia to Chile, possibly of an equivalent magnitude to the surface water flows (BCM, Vol. 2, p. 266; CR, Vol. 1, p. 104).

iv) In summary, the Silala River is a coupled groundwater-surface water system, extending across the border (BCM, Vol. 2, p. 266; CM, Vol. 1, p. 177) and hence it appears to be accepted that it is an international watercourse.

v) Construction of the channels in the 1920s on Bolivian territory has not influenced the river flow direction, which follows the natural topographic gradients (BCM, Vol. 2, p. 267; CM, Vol. 1, p. 178).

vi) This channelization will have had some effect on the surface water flow of the Silala River. An increase in river flow due to these works would be expected (BCM, Vol. 2, p. 266; CM, Vol. 1, p. 178). (As discussed further in section 4 below, we consider that this impact will be very small).

vii) Some impact of the drainage channels on evaporation from the wetlands would be expected but is small (BCM, Vol. 2, p. 303; CM, Vol. 1, p. 178). (As discussed further in section 4 below, we consider that this impact will be very small).

viii) Apart from the effects of channelization on evaporation, any increase in surface flow in the river will be accompanied by a decrease in groundwater flows across the border, and vice versa (BR, Vol. 5, p. 30; CR, Vol. 1, p. 108).

4 KEY AREAS OF DISAGREEMENT

4.1 Introduction

There is one over-riding point of disagreement between ourselves and DHI, which has been a central issue for Bolivia in its Pleadings before the Court. This concerns the magnitude of impacts of channelization on surface water flows.

We had noted (Wheater and Peach, 2017, at CM, Vol. 1, p. 134) that the channelization in Bolivia could have an effect in reducing evaporation, and hence increasing surface water flows across the border, but calculated that this effect would be very small. DHI agreed, both that this was a likely effect, and that it would be small.[9]

We agreed (Wheater and Peach, 2019a, at CR, Vol. 1, pp. 106-109) that the installation of drainage will increase the gradient of groundwater spring flow to the stream, and hence increase the groundwater discharge to the river, and that further accumulation of peat could, in the long term, produce additional resistance to groundwater flow, thereby reducing the surface flow. We also agreed that there could be changes to stream-groundwater interactions. However, as stated in Wheater and Peach (2019a), in our opinion, any changes in surface flow due to these effects will be very small.

DHI's surprising conclusion was that the overall effects of channelization on surface flows would be large. DHI stated in Bolivia's Counter-Memorial (BCM, Vol. 2, pp. 266-267), 'Without canals […] [a] reduction of surface flows of **30-40%** is estimated compared to current conditions'.[10] Following our critique of their modelling in Wheater and Peach (2019a), DHI revised their estimates in Bolivia's Rejoinder, but nevertheless continued to assert very large effects: '….the simulated range of decrease in transborder surface flow when removing the canals is **11%-33%**' (BR, Vol. 5, p. 56).[11] We have consistently stated that these estimates are wholly implausible and that, given the relatively small reductions in groundwater table depths associated with the channelization of the wetlands and of the main river, any effects will be very small.

Most importantly, both we and DHI agree that any increase in surface flows due to the channelization would have been accompanied by a decrease in groundwater flows from Bolivia to Chile, and vice versa (CR, Vol. 1, p. 107-108). In later pleadings, Bolivia agreed that 'with no canals, less water enters the surface water system and more enters the groundwater' (BR, Vol. 5, p. 30). Recharge to the groundwater system occurs over the large catchment shown in Figure 3 and is not affected by changes in downstream surface or groundwater flows. Since the groundwater flows from Bolivia to Chile, any difference in the combined flows of surface water and groundwater from Bolivia to Chile will be mainly due to the difference in wetland evaporation losses,[12] which as noted above, both sides have agreed is small.

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[9] Our original best estimate was a maximum increase of 1.3 l/s in surface water flow (CM, Vol. 1, p. 161), with an upper bound of 3.4 l/s (CM, Vol. 1, p. 164). DHI estimated this effect to be equivalent to 2-3 l/s of river flow (BCM, Vol. 2, p. 303).

[10] 30% is the effect of a scenario of channels removed, 40% of a scenario of channels removed and an assumed regrowth of peat soils.

[11] 33% and 11% are DHI's upper and lower bounds for channel removal only, with no assumed peat regrowth.

[12] Other changes to evaporation may arise due to the channelization of the main river channel, and the associated interconnection between surface water and groundwater, but these will be minor.

Bolivia's estimates depend on simulations carried out by DHI using a widely used and respected series of models. The question thus arose for us – how could these models produce such unrealistic effects? In Wheater and Peach (2019a), based on the limited information provided in Bolivia's Counter-Memorial, we noted errors in the modelling, some associated with technical issues, particularly the small scale of the simulations and the associated model boundary conditions, and others concerning the underlying geology on which the model was based. Subsequently, we were provided with the digital data used by DHI to run their models, and were able to see multiple errors and unexplained assumptions.

In the sections below we first introduce DHI's models, and then explain why DHI's simulations are incorrect. We summarise the series of very serious errors we found in the modelling, including errors in the geology, and address incorrect assertions made by Bolivia concerning wetland shrinkage and degradation. We also include a short comment on Bolivia's unfounded assertions concerning the use of explosives to increase the yields of the Bolivian springs.

4.2 DHI's Water Balance and Near Field models

Bolivia's experts established a suite of models to simulate the Silala River system (CAP, Vol. 1, pp. 89-91) (Figure 5). A Water Balance Model was used, based on the MIKE-SHE hydrological modelling software, to simulate the water balance of the topographic catchment and a larger groundwater catchment, estimated to be 234.2 km^2. However, the modelling results used to estimate the effects of channelization and peat accumulation were based on the simulation of a very small area (2.56 km^2) around the river and wetland spring areas in Bolivia, named by DHI as the Near Field. This Near Field modelling was carried out using a combination of two models: (i) the MIKE-SHE hydrological model was used alone for the two scenarios without channelization ('No Canals', and 'Wetland Restoration', as discussed above), and (ii) for the scenario representing channelization (the 'Baseline' scenario), the MIKE-SHE hydrological model was linked to the MIKE-11 hydraulic model, which represented the detail of flow in the river channels (BCM, Vol. 5, p. 11).

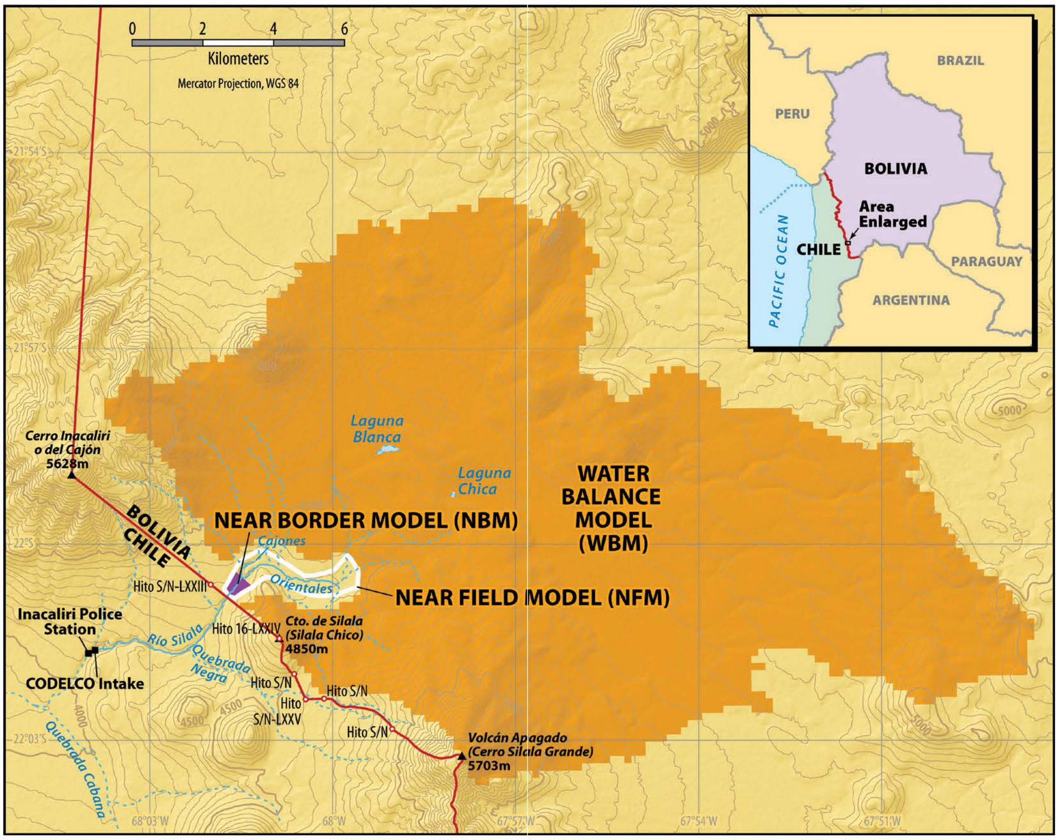

Figure 5. Domains covered by the different DHI models (Muñoz et al., 2019; Wheater and Peach, 2019a, Figure 2, at CAP, Vol. 1, p. 91).

It is relevant to note that the results of the Water Balance Model (BCM, Vol. 3, Annex E), which calculated recharge from the natural input variables of rainfall less evaporation, were not used in the Near Field Model (BCM, Vol. 5, Annexes G and H). Rather, assumptions were made by DHI concerning the groundwater elevations and/or flows at the boundaries of the Near Field Model (known as the model boundary conditions), as discussed below. We note that the recharge calculated using the resulting flow into the Near Field Model was different from the Water Balance Model results, and that the different Near Field Model scenarios had different recharge values (see section 4.3.1 below). That cannot, of course, be the case. In reality, all the recharge to the Ignimbrite aquifer(s) from the extended groundwater catchment flows into the Near Field Area.[13] The precipitation and groundwater catchment areas are essentially unchanged between scenarios, and any changes to evaporation are acknowledged by DHI to be small.

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[13] DHI's incorrect interpretation of the geology (see CR, Vol. 1, pp. 179- 201, in particular Figures 3-6 and 3-7) allows groundwater flows to bypass the Near Field, thereby providing DHI with an erroneous justification for the changing inflows (BR, Vol. 5, pp. 28-30).

4.3 Key areas of disagreement

4.3.1 Near Field Model boundary conditions

The choice to model such a small part of the catchment area of the river system as the Near Field means that the modelled flows will be mainly determined by the assumed boundary conditions for the model: the assumed boundary conditions used by DHI were inappropriate. In particular, water table conditions at the model upslope boundary were fixed, whereas in reality, water table conditions are not at all fixed. The changes due to the removal of channels and the hypothetical long-term accumulation of peat cover that were proposed by DHI to have such large effects on the groundwater discharge to the stream would also affect the conditions at the model boundary, given its close proximity to the stream.

One obvious effect of the inappropriate boundary conditions is that the inflows to the model changed significantly for the different scenarios investigated by DHI. And clearly, because the inflows to the model change, the model outputs change, too. The inflow to the Near Field Model was 253 l/s for the Baseline (with channelization) scenario, but 216 l/s for the Restored wetlands scenario with channels removed and assumed peat regrowth (BCM, Vol. 5, p. 67, Table 1). A difference in combined surface water and groundwater outflows of 49 l/s was reported for the different scenarios, of which 37 l/s was generated solely by inappropriate changes to boundary inflows. As noted above, in reality, the recharge from the groundwater catchment will be essentially unchanged for the three scenarios and can only flow to Chile – either as surface water or as groundwater.

In Wheater and Peach (2019a) (CR, Vol. 1, pp. 114-125), we demonstrated, using simple calculations as an example, that the erroneous boundary assumption will exaggerate the effects of water table rise and peat cover, and perhaps explain DHI's exaggerated estimates. In our opinion, in the context of the very large groundwater elevation differences that determine the groundwater flow (150 metres, according to DHI's modelling (BCM, Vol. 3, p. 488, Figure 11)), the effects of lowering the water table by less than 0.6 metres and long term growth of peat cover (assumed by DHI to be up to 0.6 metres (BCM, Vol. 5, p. 70)) will be minor, a few per cent at most of the cross-border surface flow. We estimated the order of magnitude of these combined effects to be a 1.2% change in river flow (CR, Vol. 1, p. 124). Although based on a major simplification of reality (a 2-dimensional hillslope segment), this analysis nevertheless indicated the likely order of magnitude of the effects.

Also importantly, as noted above, any increase in surface water flow would be accompanied by a corresponding decrease in groundwater flow, the former flowing down the topographic gradient, and the latter down the groundwater hydraulic gradient to Chile.

In their report (DHI, 2019) attached to the Bolivian Rejoinder (15 May 2019), DHI accepted our criticism of the model boundary conditions used to simulate the effects of channelization and accepted that its calculations had overestimated the effects (BR, Vol. 5, p. 55).

DHI presented revised results, in which the previous results were described as an upper limit. A different approach was taken to the Near Field boundary condition to define a lower limit, and hence a new range of impacts was specified for the effect of channelization. It was said: 'if the channels and drainage mechanisms were removed, cross-border surface flows in the Silala River would decrease by 11% to 33% of current conditions […] evapotranspiration from wetlands without canals will increase by 28% to 34% of the reference values, i.e. between 2.8 and 3.4 l/s, while groundwater flows across the […] border will increase between 4% and 10% as compared to current conditions' (BR, Vol. 1, p. 35). However, even the lower limit (an 11% decrease in surface water flows) gave an implausibly high estimate of the effect of channelization in our opinion. We reiterate that recharge into the groundwater catchment has remained the same and losses to cross-border flows are confined to the effects of increased evaporation, so these new DHI numbers are impossible. It therefore seemed that other errors were likely to be present in DHI's modelling.

We noted a further point on our concern for the boundary conditions in Wheater and Peach (2019a) (CR, Vol. 1, p. 125). The field observations reported by DHI (BCM, Vol. 5, p. 49, Figure 35) were inconsistent with the assumed Near Field Model lateral boundary conditions. This was consistent with other concerns for the accuracy of the geology used by DHI to define their Near Field Model, which we explain in section 4.3.3 below.

4.3.2 Model inconsistencies, inaccuracies, and instabilities

In Wheater and Peach (2019a), we noted various other inconsistencies in DHI's Counter-Memorial results (CR, Vol. 1, pp. 126-127). However, the digital data provided by Bolivia in February 2019 (after a repeated request) allowed more detailed evaluation of DHI's modelling. Analysis of model configurations, parameters, input data and simulation results showed that there were many aspects of the modelling that gave rise to serious concern for the reliability of the results, in particular, for the modelling of the 2.56 km^2 Near Field area on which Bolivia's estimates of the effects of channelization were based.

Inspection of the digital data by Chilean hydrologists (Muñoz et al., 2019) revealed many unreported differences between the DHI models used for the inter-comparison of scenarios, and in the MIKE-SHE model's boundary conditions and initial conditions. These unreported differences were compounded by unexplained methodology, and incorrect assumptions. We mention a few of these below; a more comprehensive explanation can be found in Muñoz et al. (2019) and Wheater and Peach (2019b), at CAP, Vol. 1, pp. 100-118.

i) Perhaps of greatest impact was the fact that we found that different topographies had been used for modelling the different scenarios, including different topographies used in the Baseline Scenario for the modelling of catchment processes (the MIKE-SHE model) and the modelling of channel flow (the MIKE-11 model). These differences in topography, of up to 7 metres, were far greater than the small changes in channel depth and peat growth that the models were being used to evaluate, and in themselves would generate large differences between the scenarios (CAP, Vol. 1, pp. 103-104, Figures 5 and 6). It follows that the differences in topography used were clearly not warranted.

ii) We also found unexplained additions of water. In a physically-based model of the Near Field area, we would expect the groundwater inputs to reflect the physical reality that the springs are fed from groundwater inflows at the model boundaries. However, from the DHI model files it was clear that, in addition to the boundary groundwater inflows, extra water had been introduced into the model as an external input, with no explanation or justification. Some 42 l/s was introduced to the Baseline Scenario (i.e., the situation with channelization) as so-called 'spring recharge', whereas only 31 l/s was input to the two scenarios representing no channelization. Clearly a difference of 11 l/s had been introduced into the scenario comparisons, an amount that accounts for more than half of the DHI reported simulated changes in surface flows due to the channelization (CAP, Vol. 1, pp. 110-111). These introductions of unaccounted-for water amount to the invention of that water, with no physical justification. By introducing this invented water, DHI artificially increased the simulated effect of the channelization.

iii) Very large differences were also found in the assumed initial conditions, i.e., the initial groundwater elevations, for the different scenarios. The differences varied between -18 m and +16.5m (CAP, Vol. 1, p. 110, Figure 9). The Near Field Model is a dynamic (time-varying) model, and while it was run to approximate a steady-state condition, the model shows large transient instabilities, so that such large differences in initial conditions would be expected to affect the simulation results.

iv) The results reported to the Court were exaggerated due to instabilities in the DHI model outputs, illustrated in Wheater and Peach (2019b) (CAP, Vol. 1, p. 115, Figure 12). These instabilities were mainly associated with the MIKE-11 model and arose partly due to numerical errors in the DHI modelling, and partly due to inconsistencies in DHI's representation of channel topography.

v) Additionally, very high channel roughness values were used by DHI in the hydraulic modelling, which gave rise to slower velocities than expected, and

> larger flow depths, which is perhaps why the model erroneously simulated water flows outside the main channel in places (CAP, Vol. 1, p. 111).

While the *reported* model errors and inaccuracies for the Near Field Model were of a similar magnitude to the effects being simulated, which in itself casts doubt on the validity of the conclusions from the modelling, we conclude that the large effects proposed by DHI are mainly an artefact of these *unreported* differences between the modelled scenarios. We note that the largest numerical errors were associated with the MIKE-11 hydraulic model, and that different topographies were used for the MIKE-SHE and MIKE-11 modelling for the same scenarios. The fact that MIKE-11 was used for the Baseline simulation (i.e., with channels), but not for the 'No Channel' and 'Restored Wetland' scenarios adds a further major inconsistency to the scenario inter-comparisons. Indeed, we have subsequently observed that, when the DHI models are run with more realistic data with respect to topography, and when the numerical errors in the MIKE-11 model are addressed and the two models are used consistently for all scenarios, the results are in line with our estimates.

4.3.3 Errors in geological and hydrogeological interpretation

A large number of errors and inconsistencies have been found in Bolivia's geological mapping and structural geology analysis (SERNAGEOMIN 2019a; SERNAGEOMIN, 2019b). These were incorporated by DHI in their own conceptual understanding of the hydrogeology and hence in the Near Field Model. Consequently, DHI's interpretation of the hydrogeology and its implementation in the Near Field Model contains many errors, as has been detailed in Wheater and Peach (2019b), at CAP, Vol. 1, pp. 119-137, the most important of which are listed below:

i) An error in the assignment of a radiometric date to establish the age range of the Ignimbritas Silala (Bolivian name) leading to an incorrect interpretation of the stratigraphy (the rock layering). This has important impacts on aquifer geometry and the distribution of permeability in the Near Field Model, the ignimbrite aquifer having a much more restricted areal extent than proposed by Bolivia (CAP, Vol. 1, pp. 122-128).

ii) Bolivia has ignored the existence of the Silala and Cabana Ignimbrites in their establishment of the Ignimbrite stratigraphy. The Silala Ignimbrite is highly welded, and outcrops unconformably over much older Ignimbrites in the Orientales wetland. The Cabana Ignimbrite is highly permeable. Both have a limited lateral extent and are constrained between two hills of Miocene low permeability volcanics in Bolivia, which limits the flow of groundwater through this region. This impacts on the Near Field Model parameterization and the aquifer geometry incorporated into the Near Field Model (CAP, Vol. 1, pp. 122-128). This means, for example, that DHI's incorrect interpretation of the geology allows groundwater to bypass the Near Field, whereas in reality it must all flow through this area.

iii) The Silala Fault, invoked as a high-permeability groundwater pathway by DHI, does not exist, could not be related to tectonic events that took place millions of years before the ignimbrites or the Miocene Volcanics were deposited and cannot be used to specify narrow high-permeability zones running down the Cajones, Orientales and Silala River ravines in an impossible sinuous manner (CAP, Vol. 1, pp. 128-130; CAP, Vol. 2, pp. 214-221).

iv) The Bolivian structural analysis is flawed. This has led to erroneous interpretations in the structural geology, which has then led to the false assumption of the presence and location of open fractures able to conduct groundwater, so there is a likelihood of incorrect assignment of aquifer properties in both conceptual and numerical modelling. (CAP, Vol. 2, pp. 212-235).

v) DHI has ignored Chilean evidence of a shallow aquifer system, which is supported by geophysical and hydrochemical evidence. Although DHI has acknowledged two sources of groundwater supplying the Bolivian wetland springs, these have been ignored in the construction of the Near Field Model, leading to incorrect interpretation of the groundwater water table distribution and groundwater flowpaths (CAP, Vol. 1, pp. 132-133; Peach and Wheater, 2019; Arcadis, 2017; SERNAGEOMIN, 2019a; Herrera and Aravena, 2017; Herrera and Aravena, 2019).

vi) The DHI conceptual model of groundwater flow and potentiometric contours used for the Near Field Model (BCM, Vol. 4, p. 97) are in conflict and represent different interpretations of the groundwater flow regime (Wheater and Peach, 2019b, at CAP, Vol. 1, p. 108, Figure 8).

All of these listed issues affect the representation of groundwater/surface water interaction in the Near Field Model and in turn affect the estimation of the impact of the channelization on surface and groundwater flows.

This list is disturbing and leads to the conclusion that the modelling which has been used to support and justify the DHI estimates of the impact of channelization on the surface and groundwater flows from the Bolivian wetlands at the headwaters of the Silala River is highly flawed. In short, the Near Field Model models developed by DHI as Bolivia's expert advisors are based on an incorrect understanding of the geology and hydrogeology of the Silala River surface and groundwater catchments.

4.3.4 Wetland degradation

Studies by Bolivia's experts, including two reports by FUNDECO (BR, Vol. 3, Annexes 23.3 and 23.4), considered the effect of historical channelization on observed changes in the wetlands. Bolivia's studies shed light on some of the changes that have taken place in the wetlands, but they are flawed in several important respects, as discussed by us in Wheater and Peach (2019b) (CAP, Vol. 1, pp. 137-140), and by Bolivia's own consultant (DHI, 2018b) in Bolivia's Rejoinder (BR, Vol. 2, pp. 65-122).

Bolivia repeats a very serious error in the reporting of current wetland areas (as 0.6 ha), which DHI note is flawed.[14] Bolivia also asserts that large reductions in wetland area are solely due to the historical channelization.[15] However, this is based on their FUNDECO (2018) report, in which, using geochemical evidence, they state that wetland desiccation '…began around 1908, which is a clear sign of the effects that canalization had on the Silala springs' (BR, Vol. 3, p. 142), and note, from pollen analysis, 'From 1908 onwards, a gradual desiccation process took place' (BR, Vol. 3, p. 142). It follows that, on Bolivia's evidence, this desiccation predates the construction of the channelization (installed in 1928) by some 20 years. They also note that 'this desiccation process reached its climax around 1950…' (BR, Vol. 3, p. 142), which to our knowledge does not coincide with any channel changes. Other strands of their evidence, from soil analysis, indicated major changes between 680 and 862 years ago, and between 1960 and 1980 (BR, Vol. 3, p. 155). Given that the dates of reported changes bear no relationship to the date of channelization, it must be concluded that other factors are playing a significant role. We agree with Bolivia's experts, DHI, that climate changes could have been the cause of some of these changes (BR, Vol. 2, p. 99).

In Wheater and Peach (2019a) (CR, Vol. 1, pp. 127-138), we reported on detailed monitoring of an undisturbed Chilean wetland within the Silala River basin, coupled with high resolution remote sensing data of the Bolivian wetlands, to investigate whether there was evidence of degradation of the Bolivian wetlands. Bolivia had asserted that 'the artificial channels and drainage network of the Silala River substantially affected and degraded the *bofedales* and caused the wetlands to recede and decline' (BCM, Vol. 1, p. 102). Our results showed that both the Bolivian and Chilean wetlands continue to fully occupy the valley floor, and seasonally extend up the base of adjacent hillslopes (CR, Vol. 1, pp. 132-136). It therefore appears that channelization in Bolivia has not affected the area of active wetland in the valley floors, where the drainage channels are located.

The hydrometeorological functioning of the wetland vegetation, as indicated by remote sensing, is similar in all three wetlands, and associated estimates of actual evaporation suggest that the highest evaporation rates are observed from Bolivia's Cajones and Orientales wetlands, some 10% greater than that of the undisturbed

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[14] 'It seems that the areas in the Ramsar report are not reflecting the full wetland' (BR, Vol. 5, p. 41).

[15] 'The scientific evidence shows that the hydraulic works generated the fragmentation of the bofedals' (BR, Vol. 1, p. 50).

Quebrada Negra wetland (CR, Vol. 1, p. 137). This indicates that, with respect to evaporation, the Bolivian wetlands are functioning at least as well as the undisturbed Chilean wetland. Thus, from the satellite data, it appears that there has been no significant reduction in evaporation associated with the channelization of the Bolivian wetlands, and the small reductions in water table elevations associated with the drainage of the Bolivian wetlands have not inhibited evaporation from the wetland vegetation.

The important conclusion, that no effects of channelization on wetland evaporation have been detectable, has significant implications. As discussed above, changes to wetland evaporation losses are seen by both ourselves and DHI to be the primary cause of potential changes in the *total* cross border flow of water from Bolivia to Chile, as both surface water and groundwater flow from Bolivia into Chile (BR, Vol. 5, p. 30; CR, Vol. 1, p. 108).

We note in passing that Bolivia's confusion concerning the wetlands extends to their criticism of our analysis of high-resolution remote sensing data of wetland extent (BR, Vol. 1, p. 46). Our analysis showed strong seasonal variability in the spatial extent of active wetland vegetation, which according to Bolivia 'reveals flawed calculation that cannot be reasonably accepted'. Bolivia thus ignores the evidence of its own experts, Torrez Soria et al. (2017) (BCM, Vol. 3, p. 73) and Castel (2017), who also confirm a large expansion and contraction of areas of active wetland vegetation as the seasons progress.

4.3.5 Could the flow from groundwater fed springs in the Cajones and Orientales springs have been significantly enhanced by the use of explosives?

It was suggested (BCM, Vol. 1, p. 47) that the groundwater-fed springs of the Cajones and Orientales wetland had been enhanced by explosives. However, as we discussed in Peach and Wheater (2019), the evidence for this is very flimsy and a reference cited by Bolivia concerning development of deep borehole yields from very low permeability rocks by explosive methods is inapplicable. The BCM cites Driscoll (1978) (BCM, Vol. 1, p. 47) as evidence that blasting can enhance water flows by a factor of 6 to 20. However, this article is in no way applicable to Bolivia's situation. Firstly, it concerns the development of deep (over 100 metres depth) borehole water supplies, not springs. Secondly the boreholes were located in poorly fractured granites, quartzites and slates. These rocks are metamorphic, have undergone considerable changes due to very high temperatures and pressures, and hence are normally very poorly permeable, unlike the permeable rocks feeding Bolivia's springs. Thirdly, the deep boreholes were plugged with sand to direct the blast horizontally, which is clearly inapplicable to Bolivia's situation. Bolivia's springs could not have been developed significantly to increase yields by the explosive methods they suggest (CR, Vol. 1, pp. 217-218).

4.4 Summary discussion

In short, the basic reasons for the disagreement between Bolivia's experts, DHI, and ourselves concerning the impacts of historical channelization concern the poor use of well-established modelling software by DHI and inaccurate understanding of geology. Our initial concerns with respect to the DHI modelling associated with errors in boundary conditions were acknowledged by DHI, but when DHI's digital data were made available, further very serious errors and unexplained assumptions became apparent. In our opinion, the effects of channelization are primarily due to changes in wetland evaporation. However, DHI and we agree that these will, at most, account for a very small (< 2%) increase in the river's surface water flow, and our remote sensing analysis shows no material difference in wetland evaporation when an undisturbed wetland in Chile is compared to the channelized wetland in Bolivia.

DHI has proposed additional effects, arising from changes in groundwater elevation gradient due to channelization and increased hydraulic resistance to groundwater flow associated with hypothetical peat accumulation. While we accept that these effects are feasible, our own analysis showed that these effects were very small (a result that has subsequently been confirmed when the DHI models were run by us with errors partially corrected).

We noted in our Updated Analysis (Wheater and Peach, 2019b at CAP, Vol. 1, p. 142) that DHI refer to a historical estimate of flow, made in 1922 prior to the channelization, to support their simulations and conclusions. However, in our opinion, a single estimate, made at a location that is uncertain, and in a difficult environment where contemporary measurements have had large errors, cannot be considered reliable. DHI (BR, Vol. 5, p. 56) reported that the single historical flow measurement was 18% lower than current flows (at a location that they assumed), but noted (BCM, Vol. 2, p. 392) that even under nearly ideal flow gauging conditions, based on a specially-constructed flume, errors in flow rate measurement in the Silala River can be expected to be of the order of 25-30%.

Bolivia's claims of wetland shrinkage and degradation are not supported by our remote sensing and ground-based data, and are disputed by their own consultants, DHI. Similarly, Bolivia's assertion that wetland degradation has been proved to be due to channelization have been shown to be incorrect by ourselves and by DHI. And Bolivia's claims concerning the use of explosives are implausible and unsupported by any reliable evidence.

5 CONCLUSIONS

It has been encouraging to note that there is general agreement between Bolivia's consultants, DHI, and ourselves concerning the hydrological functioning of the

Silala River basin. The Silala River flows from Bolivia to Chile and is a system of surface waters and groundwaters constituting a unitary whole and flowing as both surface water and groundwater across the international border. It is therefore unequivocally an international watercourse.

Important differences remain concerning the interpretation of the hydrogeology, but of most significance for the case is the continued assertion by Bolivia, based on advice from its consultants, DHI, that there are large effects on the surface water river flows associated with the historical channelization of the Bolivian wetlands, when in our opinion, these are very small. In our reports accompanying Chile's Reply, we showed that there were errors in the geology used in DHI's modelling and a fundamental flaw in the treatment of the associated model boundary conditions. In our Updated Analysis attached to Chile's Additional Pleading, we further demonstrated that much of Bolivia's geological interpretation was wrong. In addition, with access to the digital data used for the modelling, we showed conclusively that DHI's modelling was fatally flawed. As explained above, the large, simulated effects were in large part artefacts of DHI modelling errors.

In our opinion, the potential effect of the channelization is mainly a reduction in evaporation from the wetlands. Such a reduction could increase the water available for surface flow across the border. However, both DHI and we agree that such an effect would be very small, at maximum 2% of the annual flow. In fact, our remote sensing analysis of Bolivia's wetlands suggests that their lateral extent and seasonal dynamics have not been significantly affected by the channelization, nor has their evaporation been significantly reduced.

Bolivia's consultants, DHI, invoke additional mechanisms to explain their large, modelled effects, represented in their scenarios that compare the 'Baseline' (channelized) situation with a 'No Canals' and a 'Restored Wetland' scenario. Our simplified calculation, while approximate, suggested that these mechanisms might generate a 1% change in surface flows. Additionally, it is important to note that any increase in surface flows will be accompanied by a corresponding decrease in groundwater flows across the border and vice versa. Any net change in water flow across the border will primarily be due to change in wetland evaporation, which DHI agree is small, and our remote sensing analysis suggests is negligible.

In conclusion, Bolivia's modelling of the impacts of channelization has been shown to be flawed in many respects. It is wholly unreliable and should not be relied on by the Court. We have consistently stated our expert opinion that these impacts will be small. Indeed, the effects of the historic channelization on flows across the border from Bolivia to Chile are so small that they are unlikely to be detectable.

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Statement of Independence and Truth

1. The opinions I have expressed in my Reports and Written Statement represent my true and independent professional opinion. Where I have relied on the observational and monitoring studies under my supervision by the Chilean scientific experts, or data supplied to me by the Republic of Chile, I have noted that in my Reports and Written Statement.

2. I understand that my overriding duty is to the Court, both in preparing the Expert Reports that accompany the written presentations of the Republic of Chile, this Written Statement and in giving oral evidence, if required to give such evidence. I have complied and will continue to comply with that duty.

3. I have done my best, in preparing the Written Statement, to be accurate and complete in answering the request of the International Court, as expressed in a letter of 15 October 2021 from the Registrar of the Court to the Agent of the Republic of Chile. I consider that all the matters on which I have expressed an opinion are within my field of expertise.

4. In preparing my Reports and Written Statement, I am not aware of any conflict of interest actual or potential which might impact upon my ability to provide an independent expert opinion.

5. I confirm that I have not entered into any arrangement where the amount or payment of my fees is in any way dependent on the outcome of this proceeding.

6. In respect of facts referred to which are not within my personal knowledge, I have indicated the source of such information.

7. I have not, without forming an independent view, included anything which has been suggested to me by others, including the technical team and those instructing me.

Dr. Howard Wheater
Hydrological Engineer

10 January 2022

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Dr. Denis Peach
Hydrogeologist

10 January 2022