INTERNATIONAL COURT OF JUSTICE

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

(CHILE v. BOLIVIA)

REPLY OF THE REPUBLIC OF CHILE

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CHAPTER 1
INTRODUCTION

1.1 This Reply is submitted in accordance with the time-limits fixed by the Court in its Order of 15 November 2018, directing the submission of a Reply by the Republic of Chile, limited to the Counter-Claims presented by the Respondent.

A. The dispute before the Court

1.2 In its Memorial of 3 July 2017, Chile noted that the dispute before the Court is straightforward and limited in nature.[1] Chile seeks a declaration from the Court to the effect that the Silala River is an international watercourse (as had been consistently recognized by both Chile and Bolivia for almost a century prior to September 1999 when Bolivia abruptly changed its position),[2] with the rights and obligations for its riparian States that arise as a corollary.[3] Chile decided to request such declaration following Bolivia's President Mr. Evo Morales' public announcement in March 2016 that Chile was "stealing" Silala waters from Bolivia and that Bolivia would present a claim before this Court, and subsequent statements of the Minister of Foreign Affairs of Bolivia that the presentation of such claim would take at least two years.[4]

1.3 Following the lodging of Bolivia's Counter-Memorial (BCM) of 3 September 2018, the dispute has become even more limited. Bolivia

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[1] Chile's Memorial (henceforth "CM"), paras. 1.3 and 1.5.

[2] CM, para. 1.8.

[3] CM, para. 1.2.

[4] CM, paras. 1.8-1.9.

acknowledges (as it had prior to 1999) that the Silala is indeed an international watercourse that flows along the natural topographic gradient from Bolivia to Chile, crossing the border in a natural ravine.[5] Bolivia also acknowledges that both riparian States have rights and obligations with respect to equitable and reasonable utilization of the Silala, prevention of significant harm, cooperation, timely notification of planned measures which may have a significant adverse effect, exchange of data and information and, where appropriate, the conduct of environmental impact assessments.[6]

1.4 The issue that is now left for determination is a new assertion by Bolivia of alleged sovereign rights with respect to a portion of the waters of the Silala which it characterizes as "artificially-flowing Silala waters" (as opposed to the Silala's "natural flow").[7] Bolivia asserts that this "artificial flow" is generated by the channels and drainage systems located in Bolivia's territory, and that it contributes 30-40% of the current transboundary surface flow.[8] Bolivia also contends that customary international law on the use of international watercourses does not apply to what it calls the "artificial" component of the Silala flow,[9] and that the "delivery" of these "artificial" waters to Chile is subject to future agreement between the two States.[10]

1.5 These contentions underpin Bolivia's defence to Chile's claims but also the counter-claims that are the subject of this Reply. In particular, Bolivia claims that it has sovereignty over the artificial flow of Silala waters engineered, enhanced, or produced in its territory (Counter-Claim b)), and that any delivery

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[5] Bolivia's Counter-Memorial (henceforth "BCM"), para. 44.

[6] BCM, paras. 16-18.

[7] BCM, para. 14.

[8] BCM, para. 13.

[9] BCM, para. 14.

[10] BCM, para. 20.

from Bolivia to Chile of such artificially-flowing waters, and the conditions and modalities thereof, including the compensation to be paid for said delivery, are subject to the conclusion of an agreement with Bolivia (Counter-Claim c)).[11] Bolivia's Counter-Claim a), which concerns Bolivia's sovereignty over artificial channels and drainage mechanisms located in its territory,[12] is not contested by Chile, insofar as Bolivia's exercise of sovereignty complies with its obligations regarding the Silala as an international watercourse. Because there is no extant dispute regarding Bolivia's sovereignty over its territory, the Court lacks jurisdiction over Counter-Claim a).[13] In the alternative, Counter-Claim a) is moot.

1.6 Counter-Claims b) and c) (and likewise the parallel defence to Chile's claims) have no foundation in fact or in law.

1.7 As to the facts, there is a very basic point that the Silala rises on Bolivian territory and flows downhill into Chile. Even if it were correct that the works that Bolivia licensed on its territory had a significant impact on surface water flows (it is not), absent such works, the same water would anyway flow down into Chile as groundwater.[14] Bolivia has no case, and can have no case that, absent the works, the so-called "artificial flows" would somehow defy gravity and remain lodged within that part of the Silala system of ground and surface waters that is located on Bolivia's territory.

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[11] BCM, para. 181 b) (henceforth also second Counter-Claim) and c) (henceforth also third Counter-Claim).

[12] BCM, para. 181 a) (henceforth also first Counter-Claim).

[13] *Alleged Violations of Sovereign Rights and Maritime Spaces in the Caribbean Sea (Nicaragua v. Colombia), Counter-Claims, Order of 15 November 2017, I.C.J. Reports 2017*, p. 289, at p. 311, paras. 69-70. Chile considers that this discrete issue of jurisdiction – i.e. the absence of jurisdiction to rule on Counter-Claim a) because there is no dispute between the Parties as required by Article XXXI of the Pact of Bogota – can be decided by the Court together with the merits.

[14] As Bolivia confirms: "Water on the surface and in the subsurface generally flow in a westward direction." BCM, para. 47.

1.8 Indeed, if Bolivia wishes to remove the channels and to restore the wetlands to their pre-1920s state, this is something that Chile would positively encourage:

(a) It is recalled that Chile had no involvement whatsoever in the construction of the channels in Bolivian territory. The works were carried out in 1928 by a British company, The Antofagasta (Chili) and Bolivia Railway Company (the "Railway Company" or "FCAB"), in pursuit of a concession that had been granted by Bolivia in 1908. The 1908 concession was terminated unilaterally by Bolivia in 1997. Since then, nothing has prevented Bolivia from removing or filling up the channels in order to restore the Cajones and Orientales wetlands to their natural state.

(b) Chile encourages Bolivia to take all measures necessary to preserve the wetlands in Bolivia, and if this includes removing the stone-lined channels built in the 1920s, that would meet with no objection at all from Chile. Of course, any restoration of the wetlands would have to be undertaken in a manner not to impair the natural conditions of the Silala water system, i.e. without contravening Bolivia's obligations towards Chile as a riparian state under customary international law and Chile's right to equitable and reasonable utilization of the waters of the Silala River.

1.9 Insofar as it is necessary to look further at the facts (it is not), Chile's experts confirm that Bolivia's estimation of 30-40% "artificially-enhanced flow" defies common sense and is, at best, grossly exaggerated. These estimates are wholly based on a hydrological model developed by Bolivia's consultant, the Danish Hydraulic Institute (DHI), from very limited data.

According to Chile's experts, the modelling has fundamental flaws and uses unacceptable premises, leading to inaccurate and misleading results.

1.10 As to the law, there is no basis for the distinction made by Bolivia between "natural flow" and "artificially-enhanced flow". The principles of the Convention on the Law of Non-Navigational Uses of International Watercourses ("UNWC" or "Convention") apply to international watercourses and the totality of their waters without distinction. The impracticality of Bolivia's theory is underscored by the fact that Bolivia at no point indicates how to separate the "natural" from the "artificial" flows in the Silala River, nor how it purports to "deliver" the "artificial flow" under a supposed future agreement, in circumstances where all the water anyway flows inevitably into Chile due to the topographical gradient. Any increase in surface water flow due to the channelization would result in an almost equivalent decrease in groundwater flow, and the overall cross-boundary flow into Chile would remain practically the same.[15]

1.11 Moreover, the optimization of an international watercourse by upstream States, as for instance by canal lining or more efficient upstream uses, does not set aside the fundamental principle of equitable and reasonable utilization of shared watercourses or give rise to a right to compensation. If such were the case, upstream States could impose a "water tax" on downstream States by optimizing their water usage and letting more water pass through, which is not acceptable under customary international law.

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[15] Additional loss to evaporation in the no-channel scenario will be no more than 2% of the flow as agreed by both Bolivia's and Chile's experts (Chile's recent evidence suggests that changes are non-existent; Bolivia's wetlands have higher evaporation than an undisturbed wetland in Chile). Other losses of surface water flow due to channelization effects on groundwater recharge have similarly been shown to be small and would in any case flow to Chile as groundwater. See Wheater, H.S. and Peach D.W., *Impacts of Channelization of the Silala River in Bolivia on the Hydrology of the Silala River Basin* (henceforth "**Wheater and Peach (2019)**"), pp. 4-5.

1.12 Take as a hypothetical example, State A, which carries out certain channelization works on the stretch of an international watercourse in its territory, with the result that 20% less water dissipates in its territory and instead flows downstream into the territory of State B. State A does not thereby create sovereign rights and/or some right to compensation with respect to that water. Any contention to the contrary betrays a fundamental misunderstanding of the law relating to international watercourses.

1.13 The inappropriateness of such a scheme is even more evident in the present case, where the construction of the channels that allegedly increased the water flow (although Chile's experts maintain that the effect is negligible) was carried out by a private company and authorized by Bolivia pursuant to a Bolivian concession, without any prior consultation with Chile.

1.14 Chile wishes to reassure Bolivia that it fully recognises Bolivia's sovereignty over the artificial channels and drainage mechanisms in the Silala that are located in its territory, and the right to decide whether and how to maintain them (Counter-Claim a)). Again, Chile encourages Bolivia to restore the wetlands, as it appears in its formulation of Counter-Claim a) that Bolivia wishes to do, in so far as this complies with Bolivia's obligations towards Chile under customary international law.

1.15 In addition, Chile wishes to reassure Bolivia that it does not claim to pre-empt any future uses by Bolivia of the Silala River, to the extent that such uses are consistent with the principle of equitable and reasonable utilization, and provided that Bolivia complies with its obligation under customary international law to prevent the causing of significant harm and related obligations concerning cooperation, notification, exchange of information and, where appropriate, the conduct of environmental impact assessment, in accordance with customary international law. This is important, because Bolivia questions whether Article 11 of the UNWC is part of customary international law and also denies that these related obligations have been engaged in the present circumstances.

1.16 In light of all the above, the dispute before the Court has been very significantly reduced as compared to when Chile decided to lodge its Application in June 2016. Bolivia now recognizes that the Silala River is an international watercourse. Bolivia's defence and Counter-Claims b) and c), building on the notion of an "artificially-enhanced watercourse", are legally and factually untenable. They should be dismissed by the Court.

B. The structure of the Reply

1.17 The structure of this Memorial is as follows: **chapter 2** explains in greater detail the untenable nature of Bolivia's thesis that international law distinguishes between an international watercourse and an "artificially enhanced watercourse". Chile also points out that any "artificially enhanced flow" in the Silala River is attributable to the acts of Bolivia. In **chapter 3** Chile addresses the limited differences between the Parties as to the facts, noting however that these are not dispositive of the case (which is dealt with entirely by chapter 2). It is demonstrated that the percentage of "artificially-enhanced flow", if such flow exists at all, is grossly overstated and the result of a fundamentally flawed hydrological model.

1.18 This Reply is supported by two expert reports by Drs. Howard Wheater and Denis Peach that point out the fundamental flaws in the hydrological model developed by Bolivia's consultant DHI. They also provide additional data to support and/or refine the conclusions reached in their earlier expert reports submitted together with Chile's Memorial (CM) of 3 July 2017. The Wheater and

Peach reports are in turn supported by a number of underlying studies into the Silala River system that are annexed to the Reply.

CHAPTER 2

BOLIVIA'S CLAIMS TO THE "ARTIFICIALLY ENHANCED FLOW" OF THE SILALA RIVER HAVE NO SUPPORT IN INTERNATIONAL LAW AND IGNORE KEY HISTORICAL FACTS

2.1 In its Counter-Memorial, Bolivia reverts to its pre-1999 recognition that the Silala is an international watercourse and that, as such, its use is governed by the rules of international law concerning international watercourses. This acceptance of what is obvious has left Bolivia in a difficulty, given that it has elected to pursue its defence and make a counter-claim: how to assert control and sovereign rights over water that Bolivia is not using, and which international law requires it to share in an equitable and reasonable manner with Chile (which alone is using the water).

2.2 In an effort to escape this difficulty, Bolivia invents a notion unfounded in science or law, namely, that works that Bolivia had authorized in Bolivian territory – chiefly the excavation of earth channels in the wetlands, some of which were lined with stone, and lining of the Silala natural river channel – produced an "artificial flow" over which "Bolivia has sovereignty" and for which Chile must pay compensation.[16] According to Bolivia, the "delivery" of this "artificial flow" from Bolivia to Chile and the conditions and modalities thereof, "including the compensation to be paid" therefor, "are subject to the conclusion of an agreement with Bolivia."[17]

2.3 As is discussed in section A below, Bolivia's thesis finds no support in international law. In section B, Chile points out key omissions in

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[16] BCM, para. 181 b).

[17] BCM, para. 181 c).

Bolivia's account of the historical background relevant to its counter-claims that further undermine its case.

A. The principles reflected in the Convention on the Law of Non-Navigational Uses of International Watercourses apply to international watercourses and the totality of their waters

2.4 Chile will show that there is no basis in international law for distinguishing between natural and "artificial" flows (section 1) and that any such distinction runs counter to the principle of equitable and reasonable utilization of shared watercourses (section 2). Chile will also establish that Bolivia's third Counter-Claim for compensation for the upkeep of unilaterally instituted waterworks in its own territory would be not only unprecedented but also seriously disruptive of existing water governance regimes (section 3). Finally, Chile will show that the case law, State practice and doctrine referred to by Bolivia do not support the existence of a distinct legal regime for "artificially-enhanced" flow (section 4).

1. International law does not recognize the concept of "artificial" water

2.5 Bolivia takes great pains to try to establish that there are two separate flows of water in the Silala that cross the border into Chile: a "natural" flow and an "artificial" or "artificially enhanced" flow.[18] It contends that, while international law governs the "natural" flow, Bolivia "has sovereignty over the artificial flow" and any "delivery" of this "artificial" flow to Chile is subject to the conclusion of an agreement between the two countries.[19]

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[18] BCM, Chapter 2, in particular section C, "Artificial Enhancement of the Silala".

[19] BCM, para. 181.

2.6 This argument amounts to nothing less than a denial of the fact that water flows downhill. All of the natural recharge from precipitation over the Silala groundwater catchment area will cross the international border, either as surface water or groundwater.[20] The so-called "intake mechanism" and "complex system of artificial channels and drainage mechanisms within Bolivian territory near the *bofedales*"[21] that according to Bolivia "produced" the "artificially-enhanced" flow, were constructed by the British private Railway Company FCAB, with the authorization of Bolivia.[22] These small channels (about 0.6 m depth and 0.6 m width)[23] could only have very minor impacts on the flow of the Silala water, which was and always will be down a gradient toward Chile.

2.7 Development of watercourses often takes the form of what the UNWC refers to as "regulation".[24] Many intensively used watercourses are regulated in some way or another, often by straightening their channels to eliminate naturally-occurring meanders and thus facilitate their use for such purposes as navigation and hydroelectric power production.[25] This does not convert the water they carry from being "natural" to being "artificial." Even the bypass canal involved in the *Gabčíkovo-Nagymaros Project* case,[26] which was constructed by Czechoslovakia, runs for 31 km through what is now Slovak

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[20] **Wheater and Peach (2019)**, p. 4.

[21] BCM, para. 63.

[22] Deed of Concession by the State of Bolivia of the Waters of the Siloli (No. 48) to The Antofagasta (Chili) and Bolivia Railway Company Limited, 28 October 1908. **CM, Vol. 3, Annex 41**.

[23] Wheater, H.S. and Peach, D.W., *The Silala River Today – Functioning of the Fluvial System* (**Exp. Rep. 1**), p. 6. CM, Vol. 1, p. 134.

[24] Convention on the Law of the Non-Navigational Uses of International Watercourses (henceforth "UNWC"), signed at New York on 21 May 1997, U.N. Doc. A/RES/51/229 (1997), Art. 25. **CM, Vol. 2, Annex 5**.

[25] This is the case, for example, with the Danube. See *Gabčíkovo-Nagymaros Project (Hungary/Slovakia), Judgment, I.C.J. Reports 1997,* p. 7 (henceforth "*Gabčíkovo-Nagymaros Project*").

[26] Ibid.

territory, and is capable of carrying some 80 to 90% of the Danube's flow, was never thought to carry "artificial" flows. Nor of course could any claim have been made by Slovakia for compensation from Hungary for any "artificially enhanced" flows carried by the bypass canal following Hungary's attempted termination of the 1977 treaty involved in the case.

2.8 In addition, domestic courts in disputes involving similar factual situations have not found that a user who has altered a watercourse system to reduce water "loss" to evaporation and evapotranspiration gains a water right in the net gain to the stream of the kind claimed by Bolivia. The facts of the United States case *R.J.A., Inc. v. The Water Users Association of District No. 6, et al.*,[27] are similar to the alleged facts of the present dispute. The case involved property situated in the U.S. State of Colorado at the headwaters of a tributary of the South Platte River. The plaintiff company undertook a "project that will reduce water loss from a marshy mountain meadow by removing the underlying peat moss, thereby eliminating a saturated, seepy condition. This will decrease evaporation from the soil and surface and reduce evapotranspiration from grassy vegetation."[28] The plaintiff asserted a right to the water thus saved – as does Bolivia to the "artificially-enhanced" flows as a result of its channelization and stone lining works.[29]

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[27] *R.J.A., Inc. v. The Water Users Association of District No. 6, et al.*, Supreme Court of Colorado, Sep. 10, 1984, 690, P.2d 823 (1984). Available at: https://casetext.com/case/rja-inc-v-water-users-assoc.

[28] Ibid., p. 824. Specifically, the plaintiff's property "originally included a 27-acre [10.9 hectare] peat moss marsh which was approximately 3000 years old and, thus, was in existence long before any water rights were established on the [relevant] River system. [...] According to the [plaintiff], loss of water to the atmosphere was higher from this peat moss marsh than from a well-drained mountain meadow of equivalent size. [...] In the early 1970s, the [plaintiff] undertook a project to remove the extensive deposits of peat moss underlying the marsh, drain the land, and convert the marsh to a well-drained meadow [...]."

[29] Ibid. Plaintiff claimed that "the drainage of the marsh and elimination of the saturated, seepy condition would reduce the rates of evaporation and evapotranspiration, and thereby would decrease consumptive use of water by 43.3 acre feet [53,409,764.33 liters] per year. Because this

2.9 The Supreme Court of Colorado, in an *en banc* decision,[30] ruled against the plaintiff, holding that "reduction of consumptive use of tributary water cannot provide the basis for a water right that is independent of the system [of water rights] on the stream."[31] The court referred to its jurisprudence distinguishing between "developed" and "salvaged" water. "Developed" water is "new water not previously part of the river system, i.e., it is imported or non-tributary water."[32] "Salvaged" water is "tributary water made available for beneficial use through elimination of waste." The court explained that "[o]nly developed water can be made the basis of a right independent of the [otherwise existing water rights] system,"[33] and made plain that it was not willing to "create a superclass of water rights never before in existence".[34]

2.10 As for this case, to hold –as Bolivia pretends– that the construction of works to optimize the quality of the water, which might also have had a minor effect on the optimization of the flow, would likewise be to "create a superclass of water rights never before in existence" in international law.[35] Such a "superclass" of rights would disrupt established rights and obligations in

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would represent a net gain to the stream, the [plaintiff] asserted that its water right should not be subject to administration under the [applicable water rights] system."

[30] Ibid. An "*en banc*" decision is one by all of the judges of a court rather than the more common case of a hearing and decision by a panel of the court. Cases heard *en banc* are often ones of exceptional public importance.

[31] Ibid., p. 825.

[32] Ibid.

[33] Ibid.

[34] Ibid., p. 827, quoting from *Southeastern Colorado Water Conservancy District v. Shelton Farms, Inc.*, 187 Colo. 181, 190, 529 P.2d 1321, 1326 (1975), the court noted that it had there "concluded that, since the water in question had always been tributary to the stream and was not water new to the river system, the developed water cases were inapposite. [...] 'To hold any other way would be to weaken the [water rights] system, and create a superclass of water rights never before in existence.'"

[35] Ibid.

international watercourses throughout the world and is clearly unacceptable under customary international law.

2.11 Finally, Bolivia appears to be concerned that the channelization of the Silala might qualify as a "canal" and as such be included in the International Law Commission's commentary to its 1994 draft articles on international watercourses, as one of the possible components of a hydrologic system constituting a "watercourse."[36] Thus, Bolivia tries to make good the argument that the International Law Commission (ILC) did not intend to include "artificial diversions" in its definition of a "watercourse".[37]

2.12 Bolivia's contention that the ILC's definition of watercourse does not include "artificial diversions" is misplaced, for several reasons. First, the oral exchange to which Bolivia refers in support of this contention, published in the summary records of the ILC's 1987 session,[38] occurred while the draft articles were still in gestation and does not reflect any concluded position. Second, the exchange related to the definition of the expression "watercourse States," not the term "watercourse." Indeed, the ILC adopted several introductory articles at that session, which were later revised in its draft articles adopted on second reading in 1994, but which did not include a definition of the term "watercourse." The Commission postponed defining that term until work on the entire set of draft articles was otherwise complete. Third, the "personal" view of the special rapporteur referred to by Bolivia[39] was just that, and not necessarily the view of the Commission.[40]

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[36] *Yearbook of the International Law Commission*, 1994, vol. II (Part Two), p. 90, para. 4 of the commentary.

[37] BCM, para. 96.

[38] *Yearbook of the International Law Commission*, 1987, vol. I, p. 220, para. 75.

[39] BCM, para. 96. The opinion in question was that the special rapporteur would be "reluctant to define international watercourse so as to include such man-made diversions as a canal, which

2.13 In seeking to establish that canals are not part of an international watercourse and not subject to the rules of customary international law,[41] Bolivia also quotes selectively from the authorities on which it relies. The quotation from the *Max Planck Encyclopedia of Public International Law*,[42] for example, neglects to include the part of the entry concerning canals and non-navigational uses, the material most applicable to the present case.[43]

2.14 In any event, the waterworks in Bolivia, consisting of the excavation of earth channels in the wetlands and straightening and lining of the natural river channel, do not come close to qualifying as a "canal" as understood in international practice.[44] Thus, Chile does not contend that the water channels

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might take the water of an international watercourse into another drainage basin." *Yearbook of the International Law Commission*, 1987, vol. I, p. 220, para. 75. This provisional view stated orally during the Commission's debate in 1987, in answer to a question, related to a canal used for a specific purpose.

[40] The special rapporteur's personal view was supplanted by the commentaries the ILC adopted in both 1991, on first reading, and in 1994, on second reading, which included "canals" as one of the possible components of a hydrologic system, see *Yearbook of the International Law Commission*, 1994, vol. II (Part Two), p. 90, para. 4 of the Commentary.

[41] BCM, paras. 94-102.

[42] BCM, para. 99.

[43] The relevant passage reads: "When a canal is so constructed as to affect an international watercourse and its water resources, it may be subject to the rules of customary international law governing the non-navigational uses of international watercourses. In the context of the codification of that body of law [...], the International Law Commission (ILC) has defined an international watercourse as a system of surface waters and groundwaters constituting by virtue of their physical relationship a unitary whole, the parts of which are situated in different States, and whose components can include rivers, lakes, aquifers, glaciers, reservoirs and canals. [...] As this definition is also embodied in Art. 2 Convention on the Law of the Non-Navigational Uses of International Watercourses, it follows that the general principles codified therein, and in particular the rule of equitable utilization of shared water resources and the obligation not to cause significant harm to other riparian States, can apply to canals integrated to an international watercourse system and exploited for non-navigational purposes." (Emphasis added) M. Arcari, "Canals", *Max Planck Encyclopaedia of Public International Law*, online version, last updated October 2007, para. 9. Available at: http://opil.ouplaw.com/view/10.1093/law:epil/9780199231690/law-9780199231690-e1013?rskey=GDqdM0&result=1&prd=EPIL.

[44] In international practice the term "canal" is normally used to refer to a means of water conveyance that is separate from the bed of a river. The Rhine-Main-Danube canal, which was completed in 1992 and links two major international drainage basins, those of the Rhine and the Danube, is an example. It would be considered to be part of an international watercourse although

in Bolivia constitute one or more "canals". However, the ILC's inclusion of canals as a possible component of a watercourse means that, *a fortiori*, the stone lining of a stream would not in any way impact upon its character as a "watercourse." It is therefore plainly wrong that, as Bolivia contends, "the evidence indicates that the accepted norm is to exclude artificial conveyance mechanisms like canals and drainage mechanisms from the scope of customary international law applicable to transboundary watercourses."[45]

2. The principle of equitable and reasonable utilization is fully compatible with efforts to optimize international watercourses

2.15 Bolivia's argument that optimization of the flow of the Silala creates "artificially-enhanced" water flows that are not governed by the customary international law principle of equitable and reasonable utilization runs counter both to that principle and to State practice.

2.16 Article 5 of the UNWC, after setting forth the principle of equitable and reasonable utilization, states as follows:

> "In particular, an international watercourse shall be used and developed by watercourse States with a view to attaining optimal and sustainable utilization thereof and benefits therefrom, taking into account the interests of the watercourse States concerned, consistent with adequate protection of the watercourse."[46] (Emphasis added)

2.17 The ILC's commentary to Article 5 explains that the attainment of "optimal utilization" of an international watercourse "implies attaining maximum possible benefits for all watercourse States and achieving the greatest possible

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it is called a "canal." Information available at: https://www.britannica.com/topic/Main-Danube-Canal.

[45] BCM, para. 101.

[46] UNWC, Article 5(1). **CM, Vol. 2, Annex 5**.

satisfaction of all their needs, while minimizing the detriment to, or unmet needs of, each."[47] This is to be done in a manner that is "consistent with adequate protection of the watercourse."[48]

2.18 As the ILC's commentary to Article 25 states, "Regulation of the flow of watercourses is often necessary […] to maximize the benefits that may be obtained from the watercourse."[49] As stated two decades earlier by the Indian Krishna Water Disputes Tribunal: "Needless waste of water should be prevented and efficient utilisation encouraged".[50]

2.19 Article 25(3) of the Convention defines "regulation" to mean "the use of hydraulic works or any other continuing measure to alter, vary or otherwise control the flow of the waters of an international watercourse."[51] This definition readily encompasses the minor hydraulic works installed by the Railway Company in Bolivia that were designed to preserve the quality of the Silala River waters.[52] The fact that this form of development of a watercourse is recognized in the Convention as a form of use by States that is governed by international law is in itself a sufficient answer to Bolivia's claim that the regulatory works on the Silala in its territory are "artificial conveyance mechanisms like canals and drainage mechanisms [that are excluded] from the

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[47] *Yearbook of the International Law Commission*, 1994, vol. II (Part Two), p. 97, para. (3) of commentary to Article 5.

[48] UNWC, Article 5(1). **CM, Vol. 2, Annex 5**.

[49] *Yearbook of the International Law Commission*, 1994, vol. II (Part Two), p. 126, para. (1) of commentary to Article 25.

[50] Krishna Water Disputes Tribunal, Decision of 24 December 1973, para. 310. Available at: http://cwc.gov.in/main/downloads/KWDT%201volume1.pdf.

[51] UNWC, Article 25(3). **CM, Vol. 2, Annex 5**.

[52] As Chile has demonstrated, the channelization was carried out for sanitary reasons, not to increase the flows, see CM para. 4.61. Moreover, the channelization counted with Bolivia's authorization under the 1908 Bolivian concession, see **CM, Vol. 3, Annex 41**.

scope of customary international law applicable to transboundary watercourses."[53]

2.20 Even if it were the case, as Bolivia suggests, that "[t]he channelization system was installed to improve the transport of Silala water into Chile […] necessary to create a more consistent and voluminous flow of water from the Silala springs in Bolivia, through the dense *bofedales*, and across the border into Chile",[54] these purposes are covered by the concept of regulation, an activity recognized by the UNWC as being governed by international law and consistent with the principle of equitable and reasonable utilization. Hence, the works by the Railway Company in Bolivia, designed as they were to preserve the quality of the Silala waters, are in conformity with the requirements of Article 5 of the Convention.

3. *There is no justification whatsoever for upstream States to demand compensation for the construction or maintenance of works unilaterally implemented within their territory*

2.21 In its third Counter-Claim, Bolivia states:

> "c) Any delivery from Bolivia to Chile of artificially-flowing waters of the Silala, and the conditions and modalities thereof, including the compensation to be paid for said delivery, are subject to the conclusion of an agreement with Bolivia."[55]

2.22 It has been shown in section 1 above that international law does not recognize the concept of "artificially flowing waters" and, in section 2, that there can be no legal basis for Bolivia's contention that it has "sovereignty" over an

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[53] BCM, para. 101.

[54] BCM, para. 53.

[55] BCM, para. 181 c).

alleged "artificial" flow.[56] Nonetheless, Bolivia goes on to demand in its third Counter-Claim that Chile conclude an agreement as a precondition to the "delivery" by Bolivia of the "artificially-flowing waters of the Silala".[57] This section will address Bolivia's third Counter-Claim.

a. Bolivia's third Counter-Claim in effect asserts a right of veto over Chile's right to receive Silala waters

2.23 Through this Counter-Claim, Bolivia asserts that it has the right to effect the "delivery" of the so-called "artificial flow" of Silala waters to Chile pursuant to terms that are ultimately subject to Bolivia's agreement. Included as one of these terms is "the compensation to be paid [by Chile to Bolivia] for said delivery."[58]

2.24 This assertion has no basis in reason or law. In the well-known *Lake Lanoux Arbitration*,[59] Spain asserted that France's right to develop the Carol River, which flows from France into Spain, was subject to the prior agreement, or consent, of Spain. The arbitral tribunal disagreed. It stated:

> "[T]o evaluate in its essence the need for a [prior] agreement, it is necessary to adopt the hypothesis that the States concerned cannot arrive at an agreement. In that case, it would have to be admitted that a State which ordinarily is competent has lost the right to act alone as a consequence of the unconditional and discretionary opposition of another State. This is to admit a 'right of consent', a 'right of veto',

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[56] BCM, paras. 180 and 181 b).

[57] BCM, para. 181 c). See also Submission 2 c), BCM, p. 106.

[58] BCM, para. 165.

[59] *Affaire du Lac Lanoux (Spain v. France)*, Award of 16 November 1957, Reports of International Arbitration Awards, Vol. XII, p. 281. English translations in 24 ILR p. 101 (1961); 53 AJIL p. 156 (1959); and *Yearbook of the International Law Commission*, 1974, vol. II (Part Two), p. 194.

> which at the discretion of one State paralyses another State's exercise of its territorial competence."[60]

2.25 In the present case it is the upstream State, Bolivia, that is claiming a right of consent to the "delivery" into Chile of what Bolivia calls the "artificially-enhanced" flow of the Silala. But the effect is the same: Bolivia is claiming "a 'right of veto', which at [Bolivia's] discretion [...] paralyses [Chile's] exercise of its territorial competence" in accordance with international law. Such a claim is unsustainable for the reasons expressed in the *Lake Lanoux* award. If the claim were upheld, it would free upstream States to assert a right of prior consent to downstream States' use of a shared watercourse and demand compensation for the release of water into downstream States on the pretext that the upstream State had created an "artificially-enhanced" flow of that water. This would be contrary to established principle and would destabilize water relations around the world.

b. The concept of territorial sovereignty is inapplicable to a shared natural resource

2.26 Bolivia's claims regarding Silala flows passing through the works in its territory are premised on Bolivia's assertion that it "has sovereignty over the artificial flow of Silala waters [...] and Chile has no right to that artificial flow; [...]."[61]

2.27 The notion that a State can have exclusive sovereignty over something that it shares with another State, here freshwater resources, is not supported by State practice, including the sources cited by Bolivia, as will be shown in section 4 below. Chile does not dispute Bolivia's Counter-Claim a) that it "has sovereignty over the artificial channels and drainage mechanisms in the

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[60] *Yearbook of the International Law Commission*, 1994, vol. II (Part Two), p. 197, para. 1065.

[61] BCM, para. 181 b).

Silala that are located in its territory and therefore has the right to decide whether and how to maintain them."[62] This is in essence a claim that Bolivia has sovereignty over its territory. Of course Bolivia does, but this is without prejudice to Chile's rights as downstream riparian to the equitable and reasonable use of the waters of the Silala, the prevention of significant harm principle, and Bolivia's procedural obligations under customary international law. It follows that Chile does not contest Counter-Claim a), although there are two important points to be made.

2.28 First, there is a major difference, and a legally dispositive one, between the physical works in Bolivia on the one hand, and the waters of the Silala, on the other. It is impossible for a State to have exclusive sovereignty over a resource that is shared with another State without doing violence to the concept of sovereignty.

2.29 That a State does not have exclusive sovereignty over the portion of an international watercourse within its borders is the basis of the law of international watercourses, by which Bolivia accepts that it is bound in relation to the Silala.[63] The most fundamental principle in that field of law, equitable and reasonable utilization,[64] is the negation of the notion of exclusive sovereignty over a portion of an international watercourse within a State's territory. As established by the Krishna Water Disputes Tribunal: "No State has a proprietary interest in a particular volume of water of an inter-State river on the basis of its contribution [...]."[65] Even if, *quod non*, any portion of the flow of the Silala is

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[62] BCM, para. 181 a).

[63] BCM, paras. 14-16.

[64] The Court referred to this principle a conferring a "basic right" on Hungary at co-riparian with Slovakia of the Danube. *Gabčíkovo-Nagymaros Project*, at p. 54, para. 78.

[65] Krishna Water Disputes Tribunal, Decision of 24 December 1973, para. 308.

"enhanced" as Bolivia contends, that is still part of the Silala system of waters, a system that Bolivia shares with Chile.[66]

2.30 The special meaning of sovereignty in the law of international watercourses is informed by the Permanent Court's judgment in the *River Oder* case.[67] In addressing whether the principle of freedom of navigation provided downstream States with access to portions of tributaries situated wholly in upstream States, that Court emphasized the existence of a "community of interest of riparian States", rather than fall back on the notion of sovereignty:

> "when consideration is given to the manner in which States have regarded the concrete situations arising out of the fact that a single waterway traverses or separates the territory of more than one State, and the possibility of fulfilling the requirements of justice and the considerations of utility which this fact places in relief, it is at once seen that a solution of the problem has been sought not in the idea of a right of passage in favour of upstream States, but in that of a community of interest of riparian States. This community of interest in a navigable river becomes the basis of a common legal right, the essential features of which are the perfect equality of all riparian States in the user of the whole course of the river and the exclusion of any preferential privilege of any one riparian State in relation to the others."[68]

2.31 In the *Gabčíkovo-Nagymaros Project* case the Court, after quoting this passage, stated:

> "Modern development of international law has strengthened this principle for non-navigational uses of international watercourses as well, as evidenced by the adoption of the Convention of 21 May 1997

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[66] CM, paras. 2.3-2.6.

[67] *Case relating to the Territorial Jurisdiction of the International Commission of the River Oder (Czechoslovakia, Denmark, France, Germany, Great Britain, and Sweden/Poland)*, 1929, P.C.I.J., (Ser. A) No. 23 (Sept. 10), p. 5.

[68] Ibid., p. 27.

on the Law of the Non-Navigational Uses of International Watercourses by the United Nations General Assembly."[69]

2.32 There is thus a community of interest among the riparian States, Bolivia and Chile, in the shared freshwater resources of the Silala River. Bolivia must therefore respect Chile's right to the reasonable and equitable use of Silala waters – all Silala waters, including any that may allegedly have been "saved" by the works constructed in Bolivia.

2.33 Second, and as part of the above, Bolivia is obliged to provide timely notification and consult Chile with respect of planned measures on the Silala watercourse that may be adversely affected by them.[70] Bolivia has indicated that it accepts this obligation in general terms,[71] although its understanding of what is required does not accord with that of Chile.

2.34 It is not the function of this Reply to respond to Bolivia's inadequate defence to Chile's claims concerning Bolivia's failure to comply with its obligations of notification and consultation with respect to a number of past projects.[72] However, in response to Bolivia's Counter-Claims b) and c), Chile notes that it is not tenable to contend that the procedural obligations to notify and

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[69] *Gabčíkovo-Nagymaros Project*, at p. 56, para. 85. The concept of "community of interest" has also been invoked by States in disputes before the Court. See, e.g., the Court's 2006 Provisional Measures Order in the *Pulp Mills* case, p. 122, para. 39, and p. 130, para. 64. *Pulp Mills on the River Uruguay (Argentina v. Uruguay), Provisional Measures, Order of 13 July 2006, I.C.J. Reports 2006*, p. 113.

[70] Part III of the UNWC, "Planned Measures," sets forth procedures aimed at preventing transboundary harm, "assist[ing] watercourse States in maintaining an equitable balance between their respective uses of an international watercourse" and thus "help[ing] to avoid disputes relating to new uses of watercourses." *Yearbook of the International Law Commission*, 1994, vol. II (Part Two), p. 111, para. (1) of commentary to Article 12.

[71] BCM, para. 153.

[72] Three projects were announced by the Governor of the Department of Potosí in 2011, namely, the construction of a fish farm, a small dam and a mineral water bottling plant. See Note N° 199/39 from the General Consulate of Chile in La Paz to the Ministry of Foreign Affairs of Bolivia, 7 May 2012. **CM, Vol. 2, Annex 34**. The Bolivian Military Post was constructed in 2006 and ten houses near the Military Post were constructed in 2016.

consult are only applicable to the naturally-flowing Silala waters and not to the "artificially-enhanced" flows of the Silala,[73] and likewise that Article 11 of the UNWC, "Information concerning planned measures," does not reflect customary international law and is not applicable in the present case.[74] Article 11 is the *chapeau* to Part Three of the Convention, Planned Measures, which is "introduce[d]"[75] by Article 12, "Notification concerning planned measures with possible adverse effects," that Bolivia does accept as customary international law. It follows that Bolivia's position is also internally inconsistent.

2.35 Bolivia's sovereignty as asserted in its Counter-Claim a) is of course subject to the procedural obligations it has accepted, as well as the suite of related obligations recognized by the Court. Bolivia acknowledges the Court's finding that "the obligation to notify is 'an essential part of the process leading the parties to consult in order to assess the risks of the plan and to negotiate possible changes which may eliminate those risks or minimize their effects.'"[76] With respect to any work Bolivia may undertake on the Silala to "modify the artificial channels and drainage mechanisms which are located in its territory in order to fulfil [the] goal" of maintaining the natural ecology,[77] it would be incumbent upon Bolivia to follow this finding by the Court. Bolivia would equally be bound to follow the process outlined by the Court in the *Certain Activities* and *Road* cases in order to comply with its obligation of harm-prevention:

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[73] BCM, para. 148.

[74] BCM, paras. 153-155.

[75] *Yearbook of the International Law Commission*, 1994, vol. II (Part Two), p. 111, para. 1 of commentary to Article 12.

[76] BCM, para. 156, quoting *Pulp Mills on the River Uruguay (Argentina v. Uruguay) Judgment, I.C.J. Reports 2010*, p. 14 (henceforth "*Pulp Mills*"), at p. 59, para. 115.

[77] BCM, para. 180.

> “[T]o fulfil its obligation to exercise due diligence in preventing significant transboundary environmental harm, a State must, before embarking on an activity having the potential adversely to affect the environment of another State, ascertain if there is a risk of significant transboundary harm, which would trigger the requirement to carry out an environmental impact assessment.”[78]

2.36 The Court had found in *Pulp Mills* case that “it may now be considered a requirement under general international law to undertake an environmental impact assessment where there is a risk that the proposed industrial activity may have a significant adverse impact in a transboundary context, in particular, on a shared resource.”[79] Thus Bolivia would be under an obligation to prepare an environmental impact assessment in respect of any work on the Silala River that meets these conditions. Article 18(1) of the UNWC establishes a process to be followed if Bolivia fails to observe these obligations:

> “1. If a watercourse State has reasonable grounds to believe that another watercourse State is planning measures that may have a significant adverse effect upon it, the former Sate may request the latter to apply the provisions of article 12. The request shall be accompanied by a documented explanation setting forth its grounds.”[80]

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[78] *Certain Activities Carried Out by Nicaragua in the Border Area (Costa Rica v. Nicaragua)* and *Construction of a Road in Costa Rica along the San Juan River (Nicaragua v. Costa Rica), Judgment, I.C.J. Reports 2015*, p. 665, at p. 706, para. 104.

[79] *Pulp Mills*, at p. 83, para. 204. The Court found in its judgment in *Certain Activities* and *Construction of a Road* cases that “Although the Court’s statement in the *Pulp Mills* case refers to industrial activities, the underlying principle applies generally to proposed activities which may have a significant adverse impact in a transboundary context.” *Certain Activities Carried Out by Nicaragua in the Border Area (Costa Rica v. Nicaragua)* and *Construction of a Road in Costa Rica along the San Juan River (Nicaragua v. Costa Rica), Judgment, I.C.J. Reports 2015*, p. 665, at p. 706, para. 104.

[79] *Pulp Mills*, at p. 83, para. 204.

[80] UNWC, Article 18, para. 1. **CM, Vol. 2, Annex 5**.

2.37 If, as has happened in the past,[81] Bolivia responds to Chile's request by refusing to provide any information on the projects, the remainder of Article 18 sets forth the procedure to be followed:

> "2. In the event that the State planning the measures nevertheless finds that it is not under an obligation to provide a notification under article 12, it shall so inform the other State, providing a documented explanation setting forth the reasons for such finding. If this finding does not satisfy the other State, the two States shall, at the request of that other State, promptly enter into consultations and negotiations in the manner indicated in paragraphs 1 and 2 of article 17.[82]
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> 3. During the course of the consultations and negotiations, the State planning the measures shall, if so requested by the other State at the time it requests the initiation of consultations and negotiations, refrain from implementing or permitting the implementation of those measures for a period of six months unless otherwise agreed."[83]

2.38 This process has not eventuated in respect of past projects, due to Bolivia's refusal to provide information concerning them. With regard to any

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[81] Bolivia claims to have responded to Chile's repeated requests for information by Notes of 7 May 2012 and 9 October 2012. See **CM, Vol. 2, Annexes 34 and 35**, and also BCM, paras. 143-147. However, Bolivia's Note of 24 May 2012, cited by Bolivia in this context, did not provide any information on the projects that had been announced by the Governor of Potosí, and on which Chile had requested information. Rather, it insisted that the Silala cannot be considered an international river and that Chile's past use of the waters should be economically compensated. See Note N° VRE-DGRB-UAM-009901/2012 from the Ministry of Foreign Affairs of Bolivia to the General Consulate of Chile in La Paz, 24 May 2012, **BCM, Vol. 2, Annex 12**. In the same vein, Note N° VRE-DGRB-UAM-020663/2012 from the Ministry of Foreign Affairs of Bolivia to the General Consulate of Chile in La Paz, 25 October 2012, **CM, Vol. 2, Annex 36**, also cited by Bolivia in this context (BCM, para. 144). All further Notes referred by Bolivia in BCM, p. 89, footnote 208, dated between 17 January 2013 and 10 April 2014, equally fail to provide any of the information requested by Chile and affirm that Bolivia's decision to use the waters of Silala is an expression of its exercise of full sovereignty. See **CM, Vol. 2, Annexes 37.2, 37.4, 37.6, 37.8, 37.10, 37.12 and 38.2**.

[82] Paragraphs 1 and 2 of Article 17 of the UNWC set forth procedures to be followed in the case of a reply to a notification regarding planned measures indicating the notified State's belief that implementation of planned measures would be inconsistent with Articles 5 or 7, which reflect the obligations of equitable utilization and prevention of significant harm, respectively. **CM, Vol. 2, Annex 5**.

[83] UNWC, Article 18, paras. 2 and 3. **CM, Vol. 2, Annex 5**.

future work on the Silala, relative to artificial channels and drainage mechanisms in the exercise of its sovereignty, Bolivia is bound by the rules of international law set forth above to cooperate with Chile and to provide timely notification of planned measures that may have an adverse effect on shared water resources, to exchange data and information and to conduct where appropriate an environmental impact assessment with respect to such planned work.

2.39 Thus, Bolivia's first Counter-Claim, that it has the right to decide whether and how to maintain the channels in its territory, while not disputed by Chile and therefore outside the jurisdiction of the Court, must be understood in accordance with Bolivia's obligation of equitable and reasonable utilization of Silala waters and the prevention of significant harm, as well as the procedural obligations set forth above, covered by submissions d) and e) of Chile's Memorial.

c. Bolivia's demand for compensation is unjustified

2.40 It follows from what has been said that Bolivia's demand for compensation for any "delivery" to Chile of what Bolivia incorrectly terms "artificially-flowing waters of the Silala"[84] is untenable.

2.41 Bolivia's demand for compensation is all the more surprising in view of the fact that it was Bolivia itself, through its authorization of private company, the FCAB, that unilaterally made the improvements which supposedly produced an "artificially-enhanced flow." This demand flies in the face of the principle that a State is not required to provide compensation for a service that was not requested or agreed to or, *a fortiori*, for the results of that service.[85] And

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[84] BCM, paras. 180 and 181 c).

[85] This principle has in common the basic reasoning behind those of *res inter alios acta alteri nocere non debet* and *pacta tertiis nec nocent nec prosunt*: one is not bound to something to which one is not a party. The principle as it applies to treaties is expressed in Article 34 of the Vienna Convention on the Law of Treaties, 23 May 1969, U.N. Doc. A/CONF.39/27. See generally the

conversely, an individual or a State providing such an unsolicited service is not entitled to be compensated for it.

4. The case law, State practice and doctrine referred by Bolivia do not support the existence of a distinct legal regime for "artificially-enhanced flow" and are irrelevant to Bolivia's case

2.42 In Chapter 6 of its Counter-Memorial, "Counter-Claims," Bolivia states: "Bolivia's Counter-Claims are based on the factual and legal conclusions drawn in the previous Chapters of this Counter-Memorial."[86] The present subsection will show that the legal bases presented by Bolivia in support of its contentions concerning "artificially-enhanced flows" are inapposite and in fact provide no support at all to Bolivia's claims.

2.43 Bolivia's second and third Counter-Claims are based on its argument that States' obligations to each other in relation to international watercourses are limited to the "natural flow" of the waters. In support of this contention Bolivia cites the works of publicists as well as both case and treaty law. A brief examination of these authorities is all that is necessary to demonstrate that they are of no help to Bolivia.

2.44 Bolivia first quotes from highly respected authorities in the field of Public International Law, *Oppenheim* (Jennings and Watts)[87] and Max Huber.[88]

Separate Opinion of Judge Owada in *Question of the Delimitation of the Continental Shelf Between Nicaragua and Colombia Beyond 200 Nautical Miles from the Nicaragua Coast (Nicaragua v. Colombia) Preliminary Objections, Judgment, 17 March 2016*, *I.C.J. Reports 2016*, p. 100, at pp. 174-176.

[86] BCM, para. 173.

[87] R. Jennings and A. Watts (eds.), *Oppenheim's International Law* (Longman, 9th ed., 1996), p. 585.

The quotations use the terms “natural” and “naturally” in reference to conditions of States’ territories, and flow, respectively, but not in contrast to “artificial” conditions.[89] They add no support to Bolivia’s case, and Chile does not disagree with them.[90]

2.45 Bolivia next seeks support for its artificial flow theory, upon which its second and third Counter-Claims are built, in three decisions, the *Lake Lanoux* arbitration,[91] the *Donauversinkung* case[92] and the *Gabčíkovo-Nagymaros Project* case.[93] These cases are cited in support of the proposition that “[i]nternational

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[88] M. Huber, *Ein Beitrag zur Lehre von der Gebietshoheit an Grenzflüssen*, Zeitschrift für Völkerrecht und Bundesstaatsrecht, 1907, pp. 29 ff. and 159 ff., translated in S. McCaffrey, *The Law of International Watercourses*, Oxford University Press, 2007, p. 132.

[89] BCM, para. 80.

[90] Bolivia also refers to an article on the present dispute, stating that “[a] manufactured river, in the form of canals or other man-made systems, would not fall within the rubric of international water law, since, by definition, such water bodies are proprietary and subject to the agreements that created them.” BCM, para. 80. The reference given is: “B. Mulligan and G. Eckstein, ‘The Silala/Siloli Watershed: Dispute Over the Most Vulnerable Basin in South America,’ *International Journal of Water Resources Development*, Vol. 27(3), 2011, pp. 595-606.” While confessing some puzzlement as to exactly what is intended by the authors (the quote seems to refer to a water conveyance system that is entirely constructed by humans), Chile does not believe the language in question has anything to do with the Silala watercourse system. The quotation therefore provides no support for Bolivia’s case.

[91] *Affaire du Lac Lanoux (Spain v. France)*, Award of 16 November 1957, Reports of International Arbitration Awards, Vol. XII, p. 281. *Lake Lanoux* involved inter-basin transfers of water, using tunnels and canals, from the Carol River basin to the Ariège River, an equivalent quantity of which was then transferred back from the Ariège to the Carol, from which the water flowed into Spain. This was thus hardly a case involving a river’s “natural” flow, at least as Bolivia seems to define the term.

[92] *Württemberg and Prussia v. Baden (The Donauversinkung Case)*, German *Staatsgerichtshof*, 18 June 1927. The facts of the case have little in common with those of the Silala, involving as they do the passage of Danube water through the banks and bed of the river during certain periods of the year, emerging as the source of the Aach River in the Lake Constance/Rhine basin. The Court found that the resulting “sinking” of the Danube was a natural phenomenon. No “artificial” flow was involved. Indeed, no works of any kind were involved in the case.

[93] *Gabčíkovo-Nagymaros Project*. It is true that the words “natural flow” appear in the passage quoted by Bolivia, but Bolivia does not explain how this advances its case. Hungary’s assertion of a right to 50 per cent of “the natural flow of the Danube” was based on the 1976 Convention cited by Bolivia, not the judgment in the case. Convention on Regulation of Water Management Issues of Boundary Waters (Czechoslovakia and Hungary), 31 May 1976, Articles 1-2. Furthermore,

and domestic judicial decisions […] recognize the legal relevance of the distinction between the existence of natural and artificial flows."[94] However, none of these cases involves "artificial" flows, nor uses the term "artificial." In addition, none of these cases says anything about, or that could be construed to support, "the legal relevance of the distinction between the existence of natural and artificial flows."[95]

2.46 Bolivia then attempts to demonstrate that State practice in the form of treaties shows that at least some agreements "limit their application to the natural flow of a shared watercourse."[96] For all of the watercourses named (the Mahakali, Mekong, and Columbia rivers), the scope of the treaties includes waters affected by substantial dams and other artificial works. Yet none of the treaties contains the expression "artificial" flows or draws a distinction between "natural" and "artificial" flows, much less permits an upstream State to demand compensation for the benefits of its works from downstream States or authorizes it to assert sovereignty over "artificial" flows. The expression "artificial flows" instead seems to have been created by Bolivia for the purposes of this case.

2.47 It is therefore not surprising that the State practice on which Bolivia relies does not differentiate between "artificial" and "natural" flows.[97] Bolivia incorrectly assumes that the presence of the expression "natural flows" in

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Bolivia omits mention of the fact that the scope of application of the treaty in question includes artificial works.

[94] BCM, para. 81.

[95] BCM, para. 81.

[96] BCM, para. 82.

[97] BCM, para. 82, citing the Treaty Concerning the Integrated Development of the Mahakali River, India-Nepal, signed on 12 February 1996, 36 I.L.M. 531; Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin, signed on 5 April 1995, 2069 U.N.T.S. 3; Treaty Between Canada and the United States of America Relating to Cooperative Development of the Water Resources of the Columbia River Basin, signed on 17 January 1961, 542 U.N.T.S. 246; and Treaty Relating to Boundary Waters, and Questions Arising Along the Border between the United States and Canada, signed on 11 January 1909, 36 Stat. 2448, T.S. No. 548.

State practice necessarily implies the existence of, what it calls “artificial flows.”[98]

2.48 The examples cited by Bolivia that refer to “natural flows” do not provide for a preferential right to “artificial flows” that is separate from the regime of international watercourse law. The examples recognize, in some variation, a right to be protected from significant harm by a reduction, alteration or obstruction of the “natural flow,” within the context of human development of an international watercourse. This is true of the Treaty Concerning the Integrated Development of the Mahakali River Including Sarada Barrage, Tanakpur Barrage and Pancheshwar Project,[99] the Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin,[100] the Columbia River Treaty,[101] and the Boundary Waters Treaty.[102]

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[98] BCM, paras. 81-82.

[99] BCM, para. 82. Treaty Concerning the Integrated Development of the Mahakali River, India-Nepal, signed on 12 February 1996, 36 I.L.M. 531. This treaty provides protection against works that would “adversely affect” (Art. 7) the “natural flow and level” but does not provide for any preferential ownership of any “artificial flow”. The scope of this treaty also includes the regulation of the watercourse based on the many artificial works situated on it, as evidenced in the name of the treaty itself.

[100] Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin, signed on 5 April 1995, 2069 U.N.T.S. 3, Article 6, cited by Bolivia at BCM, para. 82.

[101] Treaty Between Canada and the United States of America Relating to Cooperative Development of the Water Resources of the Columbia River Basin, signed on 17 January 1961, 542 U.N.T.S. 246, referred to by Bolivia at BCM, para. 82. Article XIII provides: “Except as provided in this Article neither Canada nor the United States of America shall, without the consent of the other evidenced by an exchange of notes, divert for any use, other than consumptive use, any water from its natural channel in a way that alters the flow of any water as it crosses the Canada-United States of America boundary within the Columbia River Basin.”

[102] Treaty Relating to Boundary Waters, and Questions Arising Along the Border between the United States and Canada, signed on 11 January 1909, 36 Stat. 2448, T.S. No. 548. Article II of the Boundary Waters Treaty does not, as Bolivia states (BCM, para. 82) limit its applicability to “natural channels” but rather to “waters on [each Party’s] own side of the line which in their natural channels would flow across the boundary or into boundary waters” and provides remedies for those affected by changes in the natural channel. The treaty also contemplates the construction of further works by the parties (Art. III). Thus, regulation of boundary waters is clearly envisaged in the treaty, which says nothing about “artificial” flows.

2.49 Bolivia then refers to Article 26 of the UNWC, titled "Installations," as support for the propositions that there is "no obligation to install or to maintain infrastructures for the purposes of increasing the flow and enhancing the use of transboundary waters. There is no right for a State to require another State to install or maintain such infrastructures for its benefit."[103] These are unremarkable propositions, and Chile does not disagree with them. They are also wholly irrelevant to the circumstances of the case, where Chile never requested Bolivia to install channels or "enhance" the flow of the Silala River.

2.50 Unable to find any authority in the field of international watercourses to support its concept of "artificial flows," Bolivia turns to the law of the sea. There it finds the term "artificial," but used in contexts that have nothing to do with international watercourses, either directly or by analogy. Instead, the authority in this field cited by Bolivia concerns artificial islands and maritime delimitation.[104] It offers no support for Bolivia's "artificial flows" concept.[105]

2.51 In sum, Bolivia's second and third Counter-Claims assume that under international law there is a distinct legal regime relating to an "artificially enhanced flow" of an international watercourse; Bolivia however, has failed to

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[103] BCM, para. 83.

[104] BCM, paras. 85-90.

[105] Unsurprisingly, the United Nations Convention on the Law of the Sea (UNCLOS) treats artificial structures and natural features differently. For example, artificial islands, installations and structures in the exclusive economic zone "have no territorial sea of their own […]." United Nations Convention on the Law of the Sea, 3 December 1982, 1833 U.N.T.S. 3, Article 60, para. 8. Bolivia's reliance on the *South China Sea Arbitration (The Republic of Philippines v. The People's Republic of China)*, PCA Case No. 2013-19, Award of 12 July 2016; *Maritime Delimitation in the Black Sea (Romania v. Ukraine), Judgment, I.C.J. Reports 2009*, p. 61; *Maritime Delimitation and Territorial Questions between Qatar and Bahrain, Merits, Judgment, I.C.J. Reports 2001*, p. 40; *Fisheries case (United Kingdom v. Norway), Judgment, I.C.J. Reports 1951*, p. 116; and *Land and Maritime Boundary between Cameroon and Nigeria (Cameroon v. Nigeria: Equatorial Guinea intervening), Judgment, I.C.J. Reports 2002*, p. 303, is equally unavailing. Indeed, Bolivia fails to explain how they are relevant, or apposite, to the present case.

cite any relevant authority supporting the existence of such a regime. The doctrine, treaty practice and case law Bolivia refers to fail entirely to address the topic. The fact that Bolivia's theory is without precedent and unsupported by any source of international law leads to the unavoidable conclusion that Bolivia's theory, upon which its counter-claims are constructed, is just that, and has no legal value.

B. The historical background relevant to Bolivia's counter-claims: key omissions by Bolivia

2.52 In formulating its counter-claims, Bolivia has elected to pass over a series of key facts. First, it ignores its own century-long practice recognising the Silala River as a transboundary watercourse, a practice that was not accompanied by any statements as to there being a distinction between "natural" and "artificial" flow. This omission is considered further in section 1 below. Second, as detailed in section 2, Bolivia passes over the fact that the waters of the Silala River in Chilean territory were licensed by Chile in 1906 to the British private company FCAB prior even to the Bolivian concession of 1908, and likewise the fact that the construction of the channels in Bolivia took place in the late-1920s to improve the quality, not quantity, of the water. These are important (but omitted) facts because they show how the flow of the waters of the Silala into Chile was not, and is not, dependent on the excavated earth channels and lining developed by FCAB on which Bolivia has now chosen to build a case. For many years, the waters were considered capable of exploitation, and were exploited, without the FCAB's channels.

2.53 This section is completed by examining two further key omissions by Bolivia: its failure to identify that the channels now at issue were constructed on Bolivian territory with Bolivian authorization, and are therefore a consequence of Bolivia's own sovereign acts (section 3); and the absence of any explanation by Bolivia of why it has not simply removed the channels and restored the wetlands in Bolivia (section 4).

1. Bolivia ignores almost 100 years of joint Bolivian-Chilean recognition of the Silala as a river without distinguishing "natural" from "artificial" flow

2.54 In its Memorial, Chile demonstrated the almost century long recognition by both States of the Silala as a natural river and transboundary watercourse.[106] See, for example:

(a) The depiction of the Silala River on Chilean and Bolivian cartography, including the Map appended to the 1904 Treaty of Peace and Amity signed by the representatives of both States.[107] As recently as 1997, the Silala River was depicted on the Geological Map of Bolivia by the Bolivian Geological Survey (SERGEOMIN)[108] and on the official Map of the area prepared by the Bolivian Military Geographical Institute (I.G.M.).[109] During all this time, Bolivia never referred to, or distinguished between, "artificial" and "natural" flows.

(b) The consistent recognition of the Silala River by the Chilean and Bolivian members of the various Mixed Commissions in charge of the demarcation and revision of the international

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[106] CM, paras. 4.13-4.35.

[107] Map Appended to the Treaty of Peace and Amity, 20 October 1904. **CM, Vol. 6, Annex 82**.

[108] Bolivian Geology and Mining Survey (SERGEOMIN)*, Geological Map of Bolivia, Sheet 5927-6027 Silala-Sanabria,* ed. March 1997. **CM, Vol. 6, Annex 89**.

[109] Bolivian Military Geographical Institute (I.G.M.), *Map of South America (Bolivia) Volcán Juriques*, 1st ed., reissued May 1997. **CM, Vol. 6, Annex 90**.

boundary, from 1906 until the late 1990s.[110] Even after Bolivia's abrupt change of position in 1999, Bolivian domestic legislation and its submissions before the Secretariat of the Ramsar Convention continued to refer to the Silala as a river.[111] Again, no reference was ever made to "natural" versus "artificial" flows.

2.55 Bolivia has made no attempt to engage with this evidence. It asserts that "Chile's Memorial relies on inaccurate interpretations of Bolivian cartography, minutes, and statements regarding the Silala waters".[112] Yet no explanation is given for the numerous representations and descriptions of the Silala River by the Bolivian authorities. Bolivia also asserts that, at the time the multiple documents were produced, "both States lacked sufficient scientific evidence to accurately determine the nature of the Silala waters."[113] This is an irrelevance, and also incorrect:

(a) No scientific evidence is necessary to confirm that the Silala is a transboundary watercourse, whose waters flow naturally from Bolivia into Chile. In the words of Bolivia's Chair of the Bolivian Boundary Commission and President of the Mixed Boundary Commission in 1996, who visited the area many times together with his Chilean counterpart:

> "It rises from two main springs and receives additional waters from other minor springs. The narrow riverbed that is formed, called Silala, runs approximately two kilometers through Bolivian territory before it crosses the

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[110] CM, paras. 4.36-4.55.

[111] CM, paras. 4.62-4.66.

[112] BCM, para. 25.

[113] BCM, para. 25.

> boundary at a point of the east-west slope of the glen between Cerro Inacaliri and Cerro Silala. The inclination of the terrain has been established by experts to be around 30% [sic, more likely 3%], its river bed is narrow and its crystalline waters follow the course that, due to the force of gravity, goes downhill into Chilean territory."[114]

(b) Following Bolivia's change of position in 1999, Chile did agree (in 2004) to form a Technical Commission and conduct joint technical and scientific studies on the Silala River, but this was not because it lacked scientific evidence, as Bolivia suggests.[115] Rather, Chile acted in the reasonable expectation that Bolivia, once faced with the incontrovertible facts, would revert to its pre-1999 position of acknowledging the Silala as an international river, as it has now done.

2.56 Bolivia also contends that the expert reports submitted by both Parties confirm Bolivia's position that the Silala constitutes an "artificially-enhanced watercourse".[116] This is incorrect. Neither Chile's nor Bolivia's experts make any mention of an "artificially-enhanced watercourse" or distinguish "artificial" from "natural" flows. These are concepts of Bolivia's own invention.

2.57 In short, in defence to the counter-claims, Chile reiterates the evidence presented in its Memorial, not addressed by Bolivia, demonstrating Bolivia's century-long recognition of the Silala River as an international watercourse, without making any distinction between "natural" and "artificial" flows.

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[114] Presencia, "*Dialogue on Friday with Dr. Teodosio Imaña Castro*", La Paz, 31 May 1996. **CM, Vol. 3, Annex 71**.

[115] BCM, para. 25.

[116] BCM, para. 42.

2. The true facts with respect to the 1906 and 1908 concessions and the later (1928) channelization in Bolivia for sanitary reasons

2.58 Bolivia makes no mention of the 1906 Chilean concession of the Silala waters, obtained by the British private company FCAB from the Chilean authorities.[117] This 1906 Chilean concession matters because it shows that in 1906, prior to the construction of any waterworks in either Chile or Bolivia, the Silala River was flowing naturally across the border from Bolivia into Chile. Had it been otherwise, Chile would not have been in a position to grant a concession with respect to the waters.

2.59 Bolivia contends that, prior to the channelization, the waters of the Silala did not flow naturally across the border "in the rate and volume adequate for the Railway Company's intended purpose".[118] Bolivia relies on the language of the 1908 Bolivian deed of concession, stating that "[b]y building intake and channeling works, the previously mentioned springs could be used, even if at increased cost […]",[119] and that "the projected work shall make usable waters that are currently being lost benefitting no one."[120]

2.60 However, Bolivia's account of the construction of the waterworks and channels is chronologically inaccurate, ignores the evidence on record and is highly misleading.

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[117] Deed of Concession by the State of Chile of the Waters of the Siloli (N° 1.892) to The Antofagasta (Chili) and Bolivia Railway Company Limited, 31 July 1906 (henceforth "1906 Chilean concession"). **CM, Vol. 3, Annex 55**. See for its discussion, CM, paras. 2.21, 4.56-4.58; cf. BCM, para. 48.

[118] BCM, para. 65; see also, para. 63.

[119] BCM, paras. 63 and 65, quoting from Deed of Concession by the State of Bolivia of the Waters of the Siloli (N° 48) to The Antofagasta (Chili) and Bolivia Railway Company Limited, 28 October 1908. **CM, Vol. 3, Annex 41**.

[120] BCM, para. 67, quoting from Deed of Concession by the State of Bolivia of the Waters of the Siloli (N° 48) to The Antofagasta (Chili) and Bolivia Railway Company Limited, 28 October 1908. **CM, Vol. 3, Annex 41**.

2.61 As Chile explained in its Memorial, the first works were carried out in 1910, with an intake (Intake N° 1) being built in Bolivian territory just 600 metres from the international boundary.[121] There is no indication that any channels were built in the Bolivian wetlands or in the Silala ravine at that time and Bolivia has not shown otherwise.

2.62 The correct position is that the channelization was undertaken in 1928, almost eighteen years after FCAB started to take the Silala waters, for sanitary reasons.[122] The reason for constructing the channels is well documented in correspondence between the General Manager of FCAB in Antofagasta and the Board of Directors of FCAB in London, as follows:

> "For some time past a little difficulty has been encountered in keeping the water from this source up to that high standard of purity desired, and suspicions have been aroused by the fact that certain eggs of fly have been discovered, under microscopic examination, in the water in Antofagasta. These eggs hatch out into a specie of small green fly. The cause was finally traced to the head works in the Siloli valley where there is considerable vegetable growth through which the water has to flow before reaching the intake."[123]

2.63 The General Manager discussed two possible schemes to solve this problem:

> "The schemes for overcoming this difficulty have been prepared by the Waterworks Engineer, the first, that of cleaning up the course of the water through the valley by cutting an earth channel from the upper

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[121] CM, para. 4.60. See for FCAB's formal request to the Bolivian authorities to introduce the pipelines into Bolivia through Chilean territory, Request from FCAB to the Government of Bolivia, 3 August 1910, **CM, Vol. 3, Annex 65**; and for Bolivia's authorization thereof, Communication N° 71 from the Government of Bolivia to The Antofagasta (Chili) and Bolivia Railway Company Limited, 9 August 1910, **CM, Vol. 3, Annex 42**.

[122] CM, para. 4.61.

[123] Letter from the General Manager of FCAB in Chile to the Secretary of the Board of Directors of FCAB in London, 27 January 1928. **CM, Vol. 3, Annex 67.1**.

> springs to the existing intake works, and also a branch trench from the "Cajon" springs near the intake. The second scheme provides for the construction of a concrete channel in place of the earth channel."[124]

2.64 Given the well-documented historical record of the 1928 channelization, it is untenable for Bolivia to say that "Chile ignores the very purpose and justification for the construction of the channels".[125] To the contrary, the historical record does not support Bolivia's position that the channels were built to increase the water supply.[126]

2.65 Bolivia's current assertions that "prior to the installation of the artificial channels, Silala waters within Bolivia's *bofedales* region was relatively stagnant, with a considerably reduced cross-border water flow on the surface as compared to the present",[127] and that in its pre-channelized condition the Silala in Bolivia "did not flow naturally across the border in the manner, rate and volume that met the needs of the Railway Company",[128] are incorrect.

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[124] Ibid.

[125] BCM, para. 58.

[126] *A fortiori*, there is no evidence that the channelization in Orientales and Cajones "intentionally depleted those fragile wetlands" as claimed by Bolivia (BCM, para. 69). In fact, the FCAB opted for earth instead of concrete channels, due to the urgency of the matter and without giving any consideration to the increased efficiency that concrete channels may provide, see Letter from the General Manager of FCAB in Chile to the Secretary of the Board of Directors of FCAB in London, 27 January 1928: "The whole matter has been explained to Mr. Bolden during his visit with a recommendation that the work of renewing and improving the existing intake works and the cutting of the earth channel between the present springs and the intake of the Siloli pipe line should be carried out forthwith in view of the urgent necessity of same. It was explained that in the event of it being necessary subsequently to construct a concrete channel, the expenditure incurred in the cutting of the earth channel would then form a preliminary work for the concrete channel." **CM, Vol. 3, Annex 67.1**. As far as Chile is aware, no concrete channels were constructed afterwards and the 1928 earth channels are still more or less in place today.

[127] BCM, para. 62.

[128] BCM, para. 65.

2.66 The 1906 Chilean concession was requested to provide "abundant potable water of good quality to the city of Antofagasta",[129] and was considered significant enough to "solve […] the issue of potable water supply for the aforementioned city".[130] This demonstrates that there was a considerable flow entering from Bolivia into Chile prior to any waterworks or channelization.

2.67 It is also incorrect, as Bolivia now says, that a second pipeline (Pipeline N° 2) was constructed in 1942 to convey the waters "generated by the channelization" into Chilean territory.[131] As early as in 1916, a second pipeline had been planned, but FCAB had not been able to raise the necessary capital.[132] The capacity of the only pipeline installed at that time (Pipeline N° 1) was approximately 75 l/s,[133] and a second pipeline would have allowed the FCAB to capture double that amount.[134] Pipeline N° 2 was eventually constructed in 1942, fourteen years after the excavation of the channels in 1928, and bore no relation whatsoever to that earlier set of works.

2.68 Chile notes in passing that Bolivia asserts the use of explosives at the Silala headwaters to remove soil and rocks, again to increase the discharge of the springs.[135] Bolivia does not provide any evidence for this, other than a picture

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[129] 1906 Chilean Concession. CM, Vol. 3, p. 201.

[130] Ibid., p. 205.

[131] BCM, para. 52.

[132] Letter from the General Manager of FCAB in Chile to the Secretary of the Board of Directors of FCAB, 7 April 1916. **Chile's Reply ("CR"), Vol. 2, Annex 92**. See also Letter from the General Manager of FCAB in Chile to the Secretary of the Board of Directors of FCAB, 8 September 1916, explaining that the second pipeline was considered necessary to satisfy increasing water demands from American mining company "Chile Exploration Company" (Chilex). **CR, Vol. 2, Annex 93**.

[133] Robert H. Fox, The Waterworks Department of the Antofagasta (Chili) & Bolivia Railway Company, *South African Journal of Science*, 1922, p. 124. **CM, Vol. 3, Annex 75**. See also CM, para. 2.22.

[134] Letter from the General Manager of FCAB in Chile to the Secretary of the Board of Directors of FCAB, 7 April 1916. **CR, Vol. 2, Annex 92**.

[135] BCM, paras. 59 and 61.

of allegedly blasted rocks arranged along an unidentified section of the Silala River.[136] From the image presented, it is impossible to know whether, where, when, why and by whom these rocks were blasted. It proves nothing.[137]

3. Bolivia's failure to take account of the simple fact that the channels were built with Bolivian authorization

2.69 Even if Bolivia were right that the channels were constructed to increase spring discharge in the Silala wetlands (it is not), this would be an irrelevance. The channels were constructed by British private company FCAB (not Chile) pursuant to the 1908 Bolivian concession, and therefore with Bolivian authorization.[138]

2.70 The 1908 Bolivian concession is a sovereign act of the Bolivian State, regulated by Bolivian domestic law. Its conditions and enforcement cannot possibly lead to international responsibility on the part of Chile, as indeed both Parties have confirmed on various occasions in the past. For example, by Note of 3 September 1999, directed to Chile, Bolivia stated:

> "It is worth emphasizing that said concession was granted by the Prefecture of the Department of Potosí to a private Company and not to

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[136] BCM, p. 48, Fig. 19.

[137] Chile calls attention to Bolivia's reference to a case study on blasting as a method to increase yield from wells by a factor of 6 to 20, suggesting that such techniques may have been used at the Silala to enhance water flow from the springs. See BCM, para. 61, with reference to F.G. Driscoll, "Blasting – It turns Dry Holes into Wet Ones", *Johnson Drillers' Journal*, Nov/Dec, 1978, Johnson Division, UOP, Inc. St. Paul, MN, p. 3. The referenced article describes fracturing techniques at depth, bearing no relation whatsoever to the situation at the Silala, where springs discharge naturally from a shallow aquifer. Chile's experts consider that significant development of spring flow is not possible using these blasting methods. Peach, D.W. and Wheater, H.S., *Concerning the Geology, Hydrogeology and Hydrochemistry of the Silala River Basin* (henceforth "**Peach and Wheater (2019)**"), pp. 52 and 54.

[138] Deed of Concession by the State of Bolivia of the Waters of the Siloli (No. 48) to The Antofagasta (Chili) and Bolivia Railway Company Limited, 28 October 1908, p. 19. **CM, Vol. 3, Annex 41**.

> the Chilean State. Hence, all actions undertaken to date, as well as those that the cited Company carried out, were in the private sphere and with full acknowledgement of the Bolivian jurisdiction."[139]

2.71 Bolivia had the right to authorize the construction of the channels by the FCAB in Bolivian territory. But, if those channels had any impact on the cross-boundary surface flow of the Silala River (they have no significant impact), that could not somehow be attributed to, or lead to an obligation to pay compensation on the part of, Chile.

4. Notwithstanding the termination in 1997 of the 1908 concession, Bolivia has not removed the channels and restored the wetlands

2.72 Bolivia contends that the wetlands in Bolivia have been adversely affected by the construction of the waterworks in its territory.[140] To restore the wetlands, Bolivia says that it may have to modify the channels and drainage mechanisms.[141] To this end, it asks the Court to declare that it has sovereignty over these installations and the right to decide whether and how to maintain them (Counter-Claim a)).[142]

2.73 There is no need (and no basis) for any such declaration. Chile has no objection to Bolivia's sovereign decision to restore the wetlands in its territory, without prejudice to Bolivia's obligations towards Chile under customary international law and Chile's right to equitable and reasonable

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[139] Note N° GMI-656/99 from the Ministry of Foreign Affairs of Bolivia to the General Consulate of Chile in La Paz, 3 September 1999. **CM, Vol. 2, Annex 27**.

[140] BCM, paras. 73 and 176, quoting from Ramsar Convention Secretariat, *Report Ramsar Advisory Mission N° 84, Ramsar, Site Los Lipez, Bolivia*, 2018 (henceforth "Ramsar Report"). **BCM, Vol. 5, Annex 18**.

[141] BCM, para. 179.

[142] BCM, para. 181 a).

utilization of the waters of the Silala. There is no dispute between the Parties in this regard.

2.74 Moreover, Bolivia's interest in the restoration of the wetlands in its territory appears to be a matter of secondary importance to it. As follows from its second and third Counter-Claims, Bolivia would be willing to "deliver" to Chile the "artificially-flowing" waters of the Silala that are "engineered, enhanced, or produced in its territory", against payment of compensation by Chile to be agreed upon. Such "delivery" would, on Bolivia's case, apparently be premised on maintaining the channelization in the Bolivian wetlands (according to Bolivia, this produces the "artificial" flow for which payment is said to be due), rather than restoring the wetlands to their natural condition.[143]

2.75 Indeed, Chile notes that Bolivia could have removed the channels and restored the wetlands at any time over the last century, or at least following the termination of the 1908 Bolivia concession in May 1997.[144] This was not, however, the course of action taken by Bolivia:

(a) Instead, in April 2000, Bolivia granted a new concession to the waters of the Silala, this time to Bolivian company DUCTEC S.R.L., for the duration of forty years. This new concession authorized the commercialization and exportation of the waters for industrial use and human consumption.[145]

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[143] BCM, para. 181 b) and c).

[144] Administrative Resolution N° 71/97 by the Prefecture of the Department of Potosí, 14 May 1997. **CM, Vol. 3, Annex 46**.

[145] Concession Contract for the Use and Exploitation of the Springs of the Silala Between the Bolivian Superintendent of Basic Sanitation and DUCTEC S.R.L., 25 April 2000. **CM, Vol. 3, Annex 48**. The concession excluded the use of the waters of the Silala for potable water and sewerage services in Bolivia without an additional public utility concession, as well as for mining activities by third parties in Bolivian territory. Hence, the only potential end-users of the water rights granted to DUCTEC were in Chile. DUCTEC attempted to invoice FCAB and Corporación Nacional del Cobre de Chile (CODELCO) for their use of the water on Chilean territory, to no

(b) In the years following, Bolivia considered and partly developed several projects to make use of the waters of the Silala River, including a fish farm, a small dam and a mineral water bottling plant.[146] When requested by Chile to provide information on these projects in accordance with the international law applicable to international watercourses,[147] Bolivia affirmed its full sovereignty over the use and exploitation of these resources.[148]

2.76 Bolivia's newly stated intention to restore the wetlands appears to have coincided with Chile's submission of its Application on 6 June 2016. Shortly after, on 6 July 2016, Bolivia met with the Ramsar Secretariat in Geneva in relation to the Ramsar site Los Lípez of which the Silala forms part.[149] This meeting was followed by Bolivia's request, by letter of 27 July 2016, for a Ramsar Mission on site, expressing its "concern about the negative changes observed as to the ecological characteristics of the Los Lipes (sic) site, the Silala

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avail. See Invoice N° 003/00 from DUCTEC to CODELCO, 5 May 2000. **CM, Vol. 3, Annex 76**. See for Chile's formal objection to Bolivia's concession of the totality of the waters of the Silala to DUCTEC, Note N° 006738 from the Ministry of Foreign Affairs of Chile to the Ministry of Foreign Affairs of Bolivia, 27 April 2000. **CM, Vol. 2, Annex 31**. The DUCTEC concession was terminated on 30 May 2003, due to the illegitimacy of the Concession contract, see Bolivian Administrative Resolution Nº 75/2003 by the Superintendency of Basic Sanitation, 30 May 2003. **CM, Vol. 3, Annex 50**.

[146] CM, para. 3.26.

[147] Note N° 199/39 from the General Consulate of Chile in La Paz to the Ministry of Foreign Affairs of Bolivia, 7 May 2012. **CM, Vol. 2, Annex 34**. Note N° 389/149 from the General Consulate of Chile in La Paz to the Ministry of Foreign Affairs of Bolivia, 9 October 2012. **CM, Vol. 2, Annex 35**.

[148] See, among others, Note N° VRE-DGRB-UAM-020663/2012 from the Ministry of Foreign Affairs of Bolivia to the General Consulate of Chile in La Paz, 25 October 2012. **CM, Vol. 2, Annex 36**.

[149] Note N° VRE-Cs-58/2016 from the Ministry of Foreign Affairs of Bolivia to the Senior Advisor for the Americas of the Ramsar Convention Secretariat, 27 July 2016. **CR, Vol. 2, Annex 97**.

wetland and related areas, caused by the artificial channelization of its springs for the purpose of exploiting those waters […]".[150]

2.77 In any event, Bolivia has not explained to the Court why it has not restored the wetlands, and Chile wishes to emphasise that it has not been responsible (and could not have been responsible) for delay with respect to a restoration on Bolivian territory. Chile also considers that the full restoration of the wetlands would have minimal impact on the cross-border flow into Chile, and encourages Bolivia to undertake such measures as are necessary and appropriate to the wetland restoration (whilst complying with its obligations to Chile, including by way of notification and consultation).

C. Conclusion: The distinction between "natural" and "artificially-enhanced" flow with the legal consequences alleged by Bolivia is untenable under international law and Bolivia's second and third Counter-Claims must be dismissed

2.78 Bolivia's Counter-Claims b) and c) are premised on a distinction made by Bolivia between "natural flow" and "artificially-enhanced flow" that has no support in international law and indeed goes counter to the accepted principle of equitable and reasonable utilization of international watercourses. Bolivia also ignores key elements of the history of the Silala River and its uses and passes over the basic fact that the channelization of the Silala was built in Bolivia, with Bolivian authorization, and could have been removed by Bolivia long ago to restore the wetlands in its territory. Bolivia's second and third Counter-Claims have no justification and must be dismissed.

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[150] Ibid. Chile notes that in 2015, Bolivia reported "no negative change" in any of its Ramsar sites to the Ramsar Secretariat, see National Report on the Implementation of the Ramsar Convention on Wetlands submitted by the Plurinational State of Bolivia to the 12th Meeting of the Conference of the Contracting Parties, 2 January 2015, response to question 2.6.2. **CR, Vol. 2, Annex 95**.

CHAPTER 3

BOLIVIA'S CONTENTIONS ON THE ALLEGED IMPACT OF THE CHANNELIZATION IN BOLIVIA ARE UNTENABLE AS A MATTER OF FACT

3.1 Bolivia's second and third Counter-Claims are based on a series of contentions as to the impacts of the 1928 channelization in Bolivia. Those contentions are based on the estimates of Bolivia's experts, DHI, arrived at through a modelling exercise that DHI has carried out for the purposes of the current case. In this Chapter, Chile considers these factual contentions, but recalls its position that Bolivia's second and third Counter-Claims can and should be dismissed solely on legal grounds.

3.2 As is discussed in section A below, the Parties are largely in agreement on the nature and functioning of the Silala River as an international watercourse.

3.3 As explained in section B, the alleged impact of the channelization in Bolivia on the surface flow of the Silala (estimated by Bolivia at 30-40% "artificially-enhanced flow") is grossly overstated, if indeed such impact exists at all.

3.4 Chile has requested from Bolivia certain data and information that Chile's expert Prof. Wheater considers necessary to fully understand and critically assess the DHI model and its results.[151] Bolivia has not provided this information in time to be considered by Chile's experts in the present

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[151] Notes from the Agent of the Republic of Chile to the Agent of the Plurinational State of Bolivia of 5 November 2018 (**CR, Vol. 2, Annex 99.1**), 30 November 2018 (**CR, Vol. 2, Annex 99.3**) and 21 December 2018 (**CR, Vol. 2, Annex 99.5**).

submission.[152] Chile affirms its right to refer to the requested data and information once these have been reviewed and analyzed by Chile's experts.

3.5 Nevertheless, the information on the record is sufficient to make the following key points, that will be developed in this Chapter:

(a) Independently of any modelling efforts, all water in the Silala River basin will flow from Bolivia into Chile, whether as surface water or groundwater;

(b) The inflow in each scenario modelled by DHI is different, causing the outflow in each scenario to be different as well, proving nothing about the impact of channelization;

(c) DHI's modelling results are entirely dependent on magnifying the impact of the channels by modelling just 1% of the relevant area (the Near Field);

(d) Bolivia relies on a 2018 Report of the Ramsar Convention Secretariat[153] and its contentions that the wetlands in Bolivia are severely deteriorated, however this is contradicted by Bolivia's own 2017 Castel study[154] and a 2016 Ministerial report.[155]

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[152] Notes from the Agent of the Plurinational State of Bolivia to the Agent of the Republic of Chile of 22 November 2018 (**CR, Vol. 2, Annex 99.2**), 11 December 2018 (**CR, Vol. 2, Annex 99.4**), 11 January 2019 (**CR, Vol. 2, Annex 99.6**) and 7 February 2019 (**CR, Vol. 2, Annex 99.7**).

[153] Ramsar Report. **BCM, Vol. 5, Annex 18**.

[154] Ana Paola Castel, *Multi-Temporal Analysis through Satellite Images of the High Andean Wetlands (bofedales) of the Silala Springs, Potosí – Bolivia,* September 2017 (henceforth "Castel"). **CR, Vol. 2, Annex 98**.

[155] Ministry of the Environment and Water of Bolivia, *Characterization of Water Resources in the Southwest of the Department of Potosí – Municipality of San Pablo de Lipez "Wetlands of Silala Valley and Adjacent Sectors"* (Volume II), July 2016. **CR, Vol. 2, Annex 96**.

3.6 In short, there is nothing close to a sound factual and scientific basis for Bolivia's second and third Counter-Claims, which must therefore be rejected.

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

1. Chile and Bolivia agree that the Silala River is a perennial flow that rises at two sets of springs in Bolivia and flows along the natural topographic gradient from Bolivia into Chile

3.7 There is agreement between the Parties that the Silala River is a complex groundwater-surface water system that originates in two sets of springs in Bolivia and crosses the international border from Bolivia into Chile, due to the natural topographical gradient.[156] The gradient is estimated by Bolivia at approximately 3.7%.[157] The Parties also agree that the channelization in Bolivian territory did not alter or divert the natural direction of the flow of the water from Bolivia towards Chile.[158] Thus the direction of the flow of Silala River waters has been the same for thousands of years.

3.8 The Parties agree that surface water runoff contributes a very minor proportion of the average daily flow of the Silala River, which is groundwater dominated.[159] They also agree that the Silala River interacts with groundwater throughout its course and that the direction of the subsurface water (as of the

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[156] BCM, paras. 41-44.

[157] BCM, para. 44.

[158] DHI Report. BCM, Vol. 2, p. 267: "14. The canals have changed the *amount* of discharge from the Silala springs but *not the direction* of natural outflow from the Silala wetlands. Also, in a situation without the canals, the discharge direction is towards Chile." (Emphasis in the original).

[159] BCM, para. 47.

surface water) is westward towards and into Chile.[160] Bolivia's expert DHI estimates that the groundwater flow is at least of the same order of magnitude as the surface flow.[161]

2. *Chile and Bolivia agree that the 1928 channelization in Bolivia has only a minor effect on the direct loss of water to evaporation of no more than 2% of the current cross-border flow*

3.9 In addition, Chile and Bolivia agree that the channelization undertaken in 1928 may have resulted in reduced direct loss of water to evaporation, due to a possible reduction of the extent of surface water in the Bolivian wetlands. In Chile's Memorial, Chile's experts estimated the reduced evaporation at 1.3 l/s or 0.7% of the cross-border flow, but given the uncertainty in this calculation, they also included a more conservative estimate of 3.4 l/s or 2% of the cross border flow.[162] DHI's estimate is slightly lower than that, at 2 to 3 l/s of the combined cross-border groundwater and surface flows.[163] Both sides agree that this reduction of evaporation is a small component of the total water balance of the Silala River system and it of course does not account for the 30-40% "artificially-enhanced" flows claimed by Bolivia.

3.10 The conclusions as to evaporation have been reinforced by recent studies by Chile, in which estimates of evaporation from Bolivia's wetlands (with channelization) are very similar to evaporation from a similar wetland in the

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[160] BCM, para. 47. See also DHI Report, BCM, Vol. 5, p. 84: "groundwater level gradients and hydrogeological properties clearly indicate groundwater flow from Bolivia to Chile […]".

[161] DHI Report. BCM, Vol. 5, p. 84.

[162] CM, Vol. 1, p. 133.

[163] DHI Report. BCM, Vol. 2, p. 267.

Silala River basin in Chile (which has no channelization).[164] This suggests that the effects of channelization on the water balance, if any, are very limited.

3. *Chile and Bolivia agree on the complexity of the groundwater flow systems of the Silala, having different origins and recharge areas*

3.11 Chile's and Bolivia's experts agree that the springs in the Orientales and Cajones wetlands in Bolivia have different isotopic and chemical compositions, implying different origins and different recharge areas.[165] On the basis of data provided by Bolivia, the springs at the Orientales (Southern) wetland have chemical similarities to the deeper groundwater analysed in Chile and are likely a mix of locally recharged groundwater and groundwater from a regional aquifer. The spring waters at the Cajones (Northern) wetland have a chemical composition similar to that of springs found on the northern side of the Silala River ravine in Chile and, like them, have a locally recharged origin.[166] Hence, both Chile's and Bolivia's experts confirm the complex nature of the Silala River and groundwater flow systems.

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[164] In fact, estimated evaporation from the Bolivian wetlands with channelization is 10% greater than from the Chilean wetland without channelization, but this is within the margin of error for the method used. **Wheater and Peach (2019)**, p. 41.

[165] DHI Report. BCM, Vol. 4, p. 103.

[166] **Peach and Wheater (2019)**, p. 46. While it is likely that the springs have different ages, the dates provided by Bolivia's expert are incorrect, see **Peach and Wheater (2019)**, pp. 45-46.

4. While Chile and Bolivia maintain different interpretations of the geology and hydrogeology of the Silala River basin, this does not affect their common understanding of the nature of the Silala River as an international watercourse

3.12 Despite these important convergences between Chile's and Bolivia's experts, they maintain different interpretations of the geology and hydrogeology of the Silala River basin.

3.13 Bolivia's proposed succession and dates of (permeable) ignimbrite and lava deposits in the Silala River valley cannot be reconciled with Chile's recent geological mapping, radiometric dating results, drilling evidence and pumping test results.[167] This means that the aquifer system in the ignimbrites identified in Chile has not been recognized by Bolivia.[168] On the other hand, Bolivia infers a massive geological fault system that would run from the Orientales wetland to the Cajones wetland in Bolivia, bending around and following the line of the Silala River into Chile, that Chile's experts consider highly implausible. This inferred fault is not evidenced by any displacement of rocks on either side of the river valley, as would necessarily occur in a major fault zone.[169]

3.14 These differences in interpretation do not affect Chile's and Bolivia's common understanding of the Silala River as an international watercourse. However, they do affect the reliability of the DHI Near Field model, which is the only source of support for Bolivia's claims for the large effects of channelization, as discussed in more detail in section B below.

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[167] **Peach and Wheater (2019)**, p. 52.

[168] **Peach and Wheater (2019)**, p. 7.

[169] **Peach and Wheater (2019)**, pp. 22-23, 30-31 and 34.

B. Bolivia's estimation of the impact of the 1928 channelization in Bolivia on the cross-boundary surface flows (30-40% "artificial flow") is untenable and based on a fundamentally flawed numerical model

1. The three scenarios ("Baseline", "No Canal" and "Restored Wetlands") used by Bolivia to calculate the 30-40% "artificial flow" are inconsistent with the law of conservation of mass and cannot lead to a reliable calculation

3.15 The assessment of Bolivia's experts, DHI, of the impact of channelization is based entirely on a model that they have developed. This is an integrated (surface water and groundwater) numerical model of the Silala, within an area called the Silala Near Field. The Silala Near Field, however, covers an area of just 2.56 km^2 from the international border to just upstream of the Cajones and Orientales wetlands. This corresponds to just 1.1% of the total Silala groundwater catchment of 234.2 km^2,[170] also referred to as the Silala Far Field, as can be seen on Figure 1. The use of such a small area, as further identified below, leads to wholly unreliable results so far as concerns the DHI modelling exercise.

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[170] DHI Report. BCM, Vol. 2, p. 289.

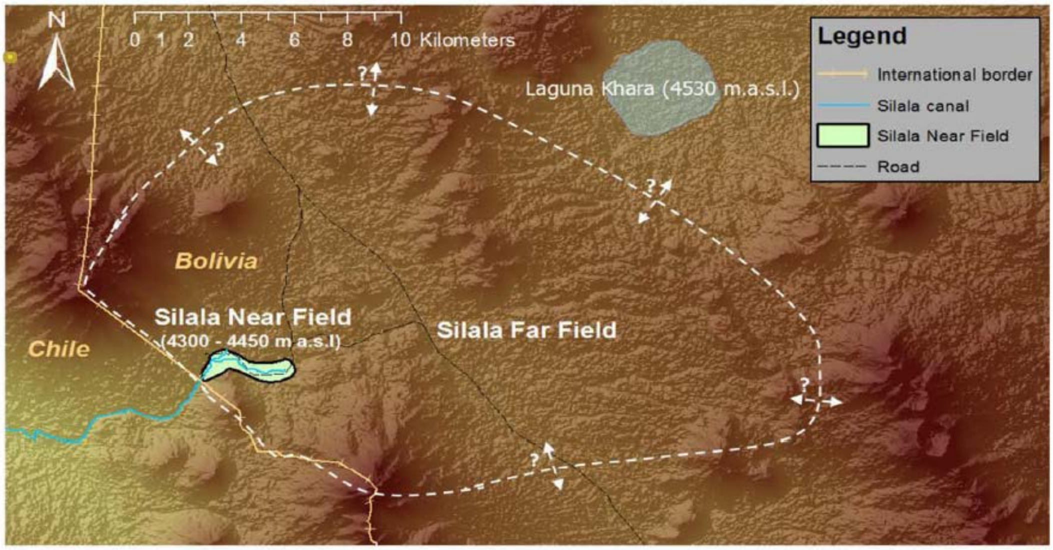

Figure 1. Approximate extents of the Silala Near Field (reproduced from DHI Report. BCM, Vol. 2, p. 271, Figure 3).

3.16 The Near Field model has been run by DHI for different scenarios, with and without channelization, and with and without a layer of restored peat. This is said to allow for assessment of the effects of the channel and drainage network in Bolivia on the surface and groundwater flows.[171]

(a) The Baseline Scenario of the DHI Near Field model represents the current situation, with the existing channels in Bolivia in place.

(b) The No Canal Scenario represents a situation in which these channels are removed and the surface water flow is largely controlled by the surface topographical slope.

(c) Finally, the Restored Wetlands Scenario considers how the fully restored wetlands might be expected to function in a distant future

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[171] DHI Report. BCM, Vol. 5, p. 66.

by considering the possibility of long-term peat accumulation in the wetlands.[172]

3.17 The Scenario results are shown in Table 1 of Annex H to the DHI Final Report[173]:

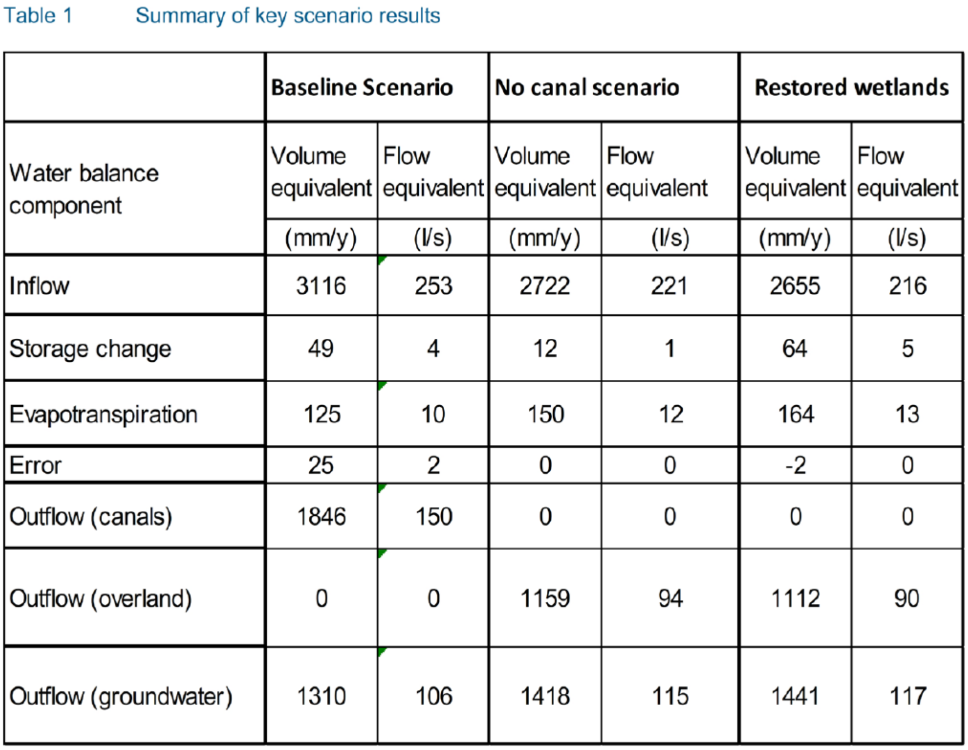

Table 1 Summary of key scenario results

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

Table 1. DHI's results of its modelling of different scenarios (reproduced from DHI Report. BCM, Vol. 5, p. 67, Table 1).

3.18 As Chile's experts point out, the Near Field model is severely flawed, in several important respects. In particular, the exaggerated effect of the channelization is largely driven by incorrectly defined boundary conditions of the

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[172] DHI Report. BCM, Vol. 5, p. 66.

[173] DHI Report. BCM, Vol. 5, p. 67.

model. Also, the model is based on an incorrect understanding of the geology and hydrogeology.

3.19 Before discussing these aspects of the Near Field model, the following observations can immediately be made, based on a simple review of DHI's Table 1, which show several issues of concern with the modelling:

(a) While Table 1 provides the model results of surface water and groundwater outflows on which Bolivia's arguments are based, it also presents information on the water balance of the Silala Near Field model.[174] The law of conservation of mass requires that the water balance must be closed for the system to be modelled, meaning that the inflow to the Near Field catchment and model must equal the total outflow, plus any increase in storage. In this case, the model has been run as a steady-state simulation,[175] for which inflows and outflows are constant (time-invariant) and must therefore be equal; there should be no change in storage.[176] However, Table 1 defines a change in storage for each scenario. This is a first indication that the model is not reliable.

(b) In the present case, the inflow to the model is the recharge from precipitation within the larger groundwater catchment area that feeds the springs in Bolivian territory. The outflow is the sum of surface and groundwater cross-boundary flows plus direct loss by evapotranspiration. As can be seen in Table 1, in the Baseline Scenario, the inflow is 253 l/s whereas the total outflow, including

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[174] The water balance over a given time period can be expressed as the equation ($P - E = R + \Delta S$), in which P stands for precipitation, E for evapotranspiration, R for discharge and S for change in storage, see CM, Vol. 1, p. 160.

[175] DHI Report. BCM, Vol. 5, p. 13.

[176] **Wheater and Peach (2019)**, p. 30.

evapotranspiration, is 266 l/s. Even allowing for the small change in storage, this is clearly wrong. Similarly, in the Restored Wetlands Scenario, the inflow is 216 l/s and the total outflow is 220 l/s, which is also incorrect. Only in the No Canal Scenario are inflow and total outflow equal (221 l/s). This is a further indication that the scenarios resulting from the DHI Near Field model are not in accordance with the law of conservation of mass and therefore render the model unreliable.

(c) The catchment area and recharge from precipitation remain the same in each of the three scenarios, and therefore the inflow in each scenario should also remain constant. However, as already noted above, the inflow to the model is different for each scenario considered.

In the Baseline Scenario the inflow is 253 l/s; in the No Canal Scenario the inflow is 221 l/s; and in the Restored Wetlands Scenario the inflow is 216 l/s.

This means that the difference in the inflows between the Baseline Scenario and the Restored Wetlands Scenario (i.e. 253 l/s less 216 l/s), equals 37 l/s. And if the inflows are corrected so that they equal the outflows, as required by conservation of mass,[177] the required inflow to the Baseline scenario is 266 l/s and to the Restored Wetlands Scenario is 220 l/s, i.e. a difference of 46 l/s.

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[177] Neglecting the change in storage in each Scenario, which is small and moreover not allowed in a steady-state simulation.

This closely approximates the net difference in outflows between those same two scenarios, of 49 l/s (i.e. a loss of 60 l/s in surface flows, less a gain of 11 l/s in groundwater flows into Chile).[178]

The noted difference in outflow is therefore primarily driven by the difference in inflow, without any apparent change in the catchment area or recharge to justify such variation.

(d) This difference in inflows raises the question, where would the "extra" recharge water in the Baseline Scenario go to once the channels have been removed? The topography and the geology determine that the recharge must flow to Chile, if not as surface water, then as groundwater.[179]

3.20 These initial observations all point to fundamental difficulties with the Silala Near Field model, in particular, the fact that the recharge from the Silala groundwater catchment changes for the different scenarios, while the recharge area and its precipitation remain the same. As Chile's experts explain, these changes in inflow are caused in very large part by the way the numerical model is set up, not by the channelization. Thus, the 30-40% "artificially-enhanced flow" alleged by Bolivia is also a result of the modelling exercise, not of the channels in Bolivia.

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[178] **Wheater and Peach (2019)**, p. 17.

[179] **Wheater and Peach (2019)**, pp. 3, 4 and 8.

2. Bolivia's estimation is based on a fundamentally flawed numerical model, resulting in a gross overestimate of the impact of the wetland channelization on surface flow rates, by a factor of about 20

3.21 A crucial step in any modelling exercise is the definition of the area that will be modelled and the conditions at its boundaries (the boundary conditions). One of the outstanding characteristics of the Near Field model is that it covers a very small area, equivalent to only 1.1% of the entire Silala hydrological catchment. The Silala Near Field boundary is drawn around the two wetlands in Bolivia and the Silala ravine in Bolivia, before crossing into Chile, as can be seen on Figure 1, but excludes 98.9% of the groundwater catchment area.

3.22 DHI uses a "fixed head" boundary condition at the outer model (upslope) boundaries in Bolivia. A "fixed head" boundary specifies that the water table will remain constant, but that means that flows across the boundary can change. This type of boundary condition is often used where a modelled area is next to a large lake or hydraulically connected to the sea, and in consequence, the model can draw for its inflows upon an infinite amount of water. However, as is obvious, there is no infinite amount of water available in the highlands of the Atacama Desert – in reality, the inflows are constrained by the available recharge from precipitation.

3.23 The effect of a “fixed head” boundary, as DHI itself explains, is that “flow into the model area may change if the groundwater table changes, e.g. due to changes in the surface water system”.[180] This is so because of Darcy’s law, one of the basic laws of groundwater flow, which states that “groundwater flow rate is proportional to the gradient of groundwater potential energy, or head”.[181]

3.24 The effect of Darcy’s law can be directly observed in the scenarios of the Near Field model. According to DHI, the channels in the Cajones wetland are generally less than 50 cm deep and the water tables in both wetlands are between 15 and 45 cm below surface.[182] By removing the channels in the No Canal Scenario, the groundwater table is elevated accordingly, by a maximum of 50 cm. As a result, the hydraulic gradient between the “fixed head” at the Near Field boundary and the groundwater table in the wetlands of the No Canal Scenario is reduced, causing less water to enter into the model area. This explains why the outflow decreases in the No Canal and Restored Wetlands Scenarios, and also why the inflow across the “fixed head” boundary is reduced.

3.25 This effect on the inflow is much exaggerated by DHI’s choice of a “fixed head” boundary for a very small-scale model, i.e. the Near Field model. It can readily be appreciated that the effect on the hydraulic gradient of a 50 cm difference in groundwater table height, although relatively small, is proportionally much more significant when the “fixed head” is set at a distance of 360 m, as in the Near Field model,[183] than when the “fixed head” is set at a distance of 10.500 m, which is the correct boundary of the Far Field, i.e. the

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[180] DHI Report. BCM, Vol. 5, p. 18.

[181] **Wheater and Peach (2019)**, p. 18.

[182] DHI Report. BCM, Vol. 3, pp. 12-13, Figures 6 and 7. See **Wheater and Peach (2019)**, p. 18.

[183] These are typical distances for the Near Field model, identified by Chile’s experts. See **Wheater and Peach (2019)**, Fig. 3 a).

Silala groundwater catchment boundary.[184] Chile's experts show, using DHI's simulated groundwater heads, that the change in average hydraulic gradient differs by a factor of 29, solely due to the geometry.[185]

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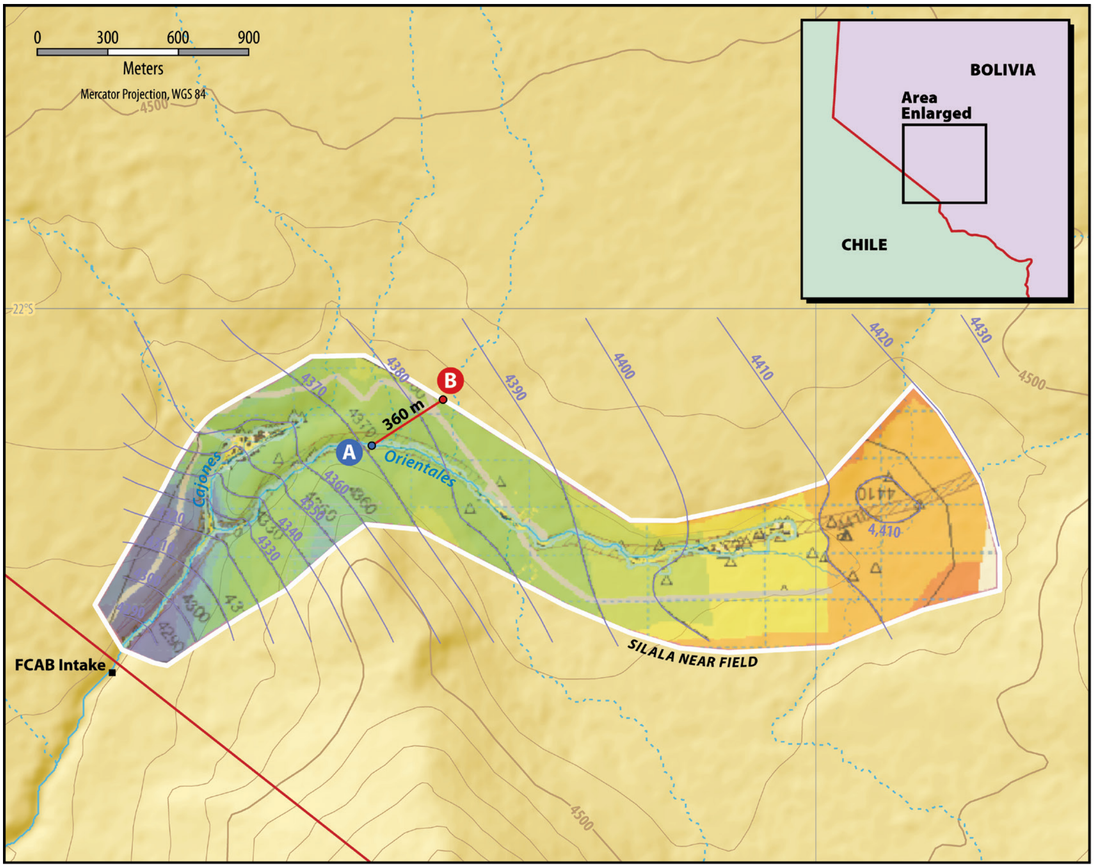
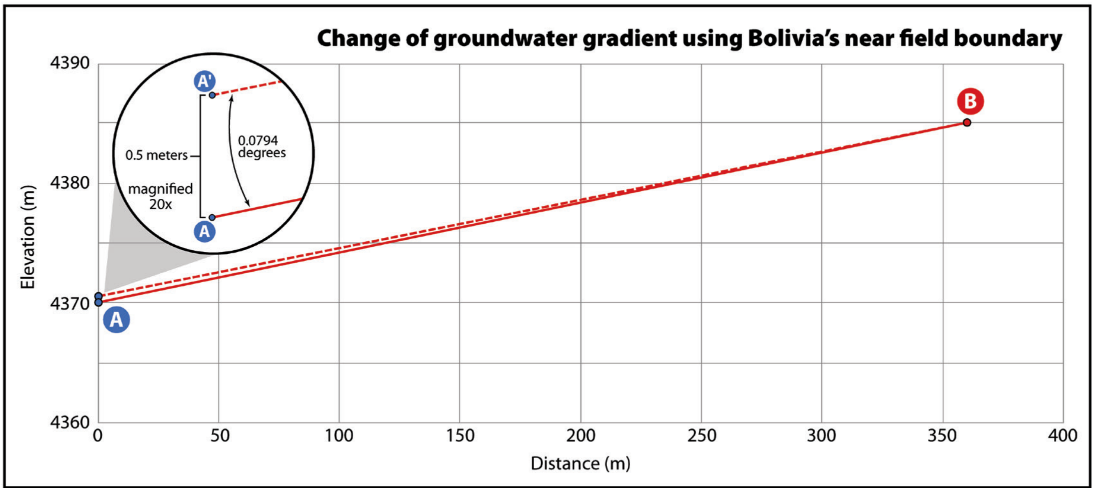
[184] **Wheater and Peach (2019)**, pp. 19-22.

[185] **Wheater and Peach (2019)**, p. 25.


0
300
600
900
Meters
Mercator Projection, WGS 84
4500
22°S
BOLIVIA
Area Enlarged
CHILE
4420
4430
4500
4400
4410
4390
4380
4370
B
360 m
A
Orientales
Cajones
4360
4350
4340
4330
4300
4290
4,410
SILALA NEAR FIELD
FCAB Intake
4500


Change of groundwater gradient using Bolivia's near field boundary
4390
4380
4370
4360
Elevation (m)
A'
0.5 meters
magnified 20x
0.0794 degrees
A
B
0
50
100
150
200
250
300
350
400
Distance (m)

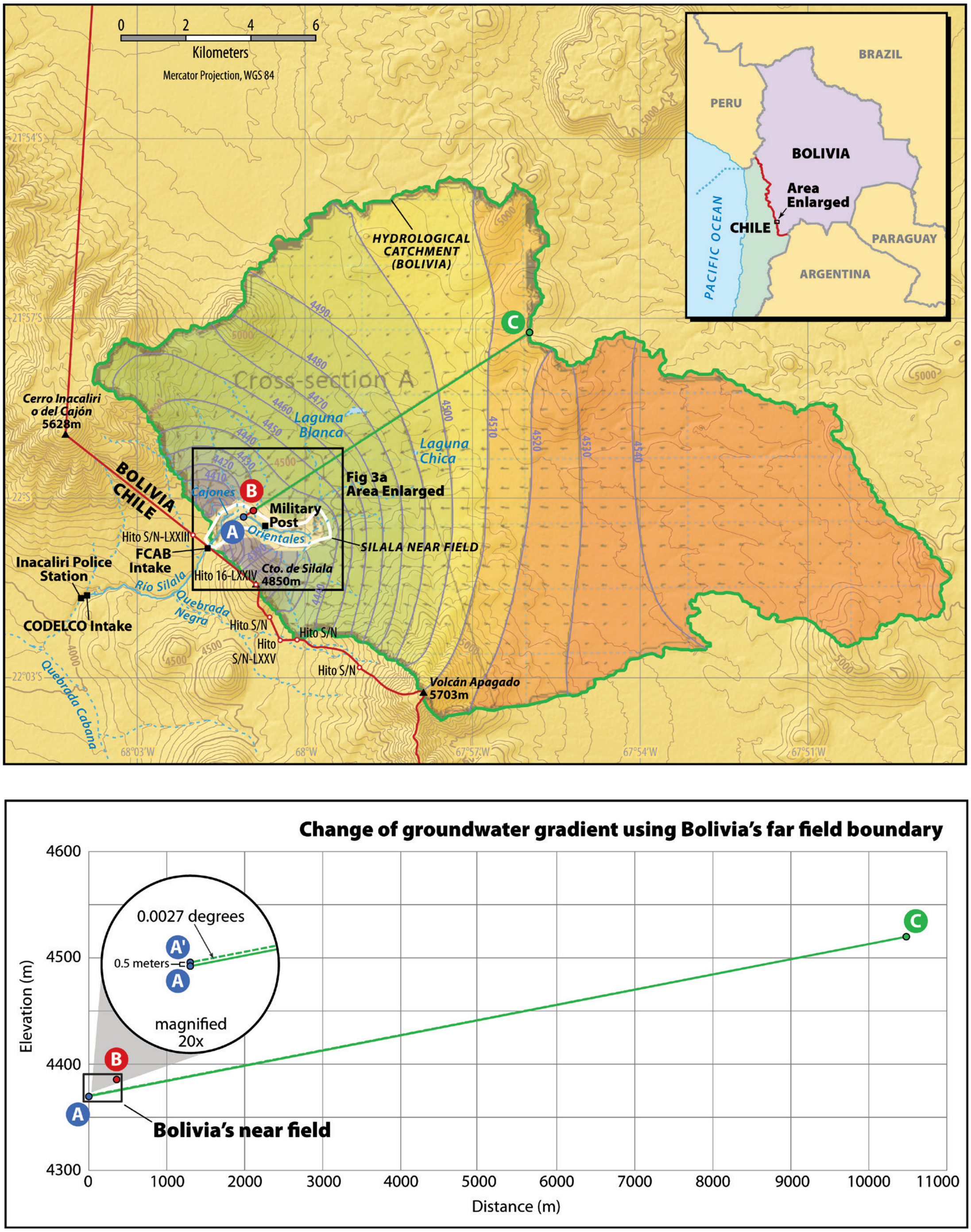


Figure 2. (a) A typical groundwater head gradient from the near field model boundary to the wetland; (b) A typical groundwater head gradient from the far field model boundary to the wetland (Wheater and Peach (2019), p. 23, Figures 3 (a) and (b)).

3.26 An elementary calculation, which considers DHI's estimated recharge as well as the topographic difference in height between the Near Field boundary and the Far Field boundary and other parameters, still results in an exaggeration of the effect of the removal of the channels on the water table inflow, by a factor of 12.[186]

3.27 The choice of a Near Field "fixed head" boundary has a similar exaggerating effect on the factor of "hydraulic resistance", introduced by DHI in the Restored Wetlands Scenario. In this scenario, DHI assumes that a peat layer of up to 60 cm will develop, over long time scales of centuries or more, where the channels used to be.[187] Because peat has relatively low permeability, DHI argues that this would create a zone of higher hydraulic resistance to groundwater emerging in the wetlands ("buffer zone").[188] In reality, should this peat layer indeed be a controlling factor,[189] the resistance to flow would cause the groundwater elevations to rise upslope. However, in the model, the "fixed head" condition at the model upslope boundary prevents this rise. Thus, the flow across the boundary into the model area decreases, to compensate for this effect.[190] Chile's experts use a simple calculation to demonstrate that the "buffer zone" has a disproportionate effect on the inflow in the Near Field area, as compared to the Far Field area. In their example, the effect is exaggerated by a factor of 23.[191]

3.28 Similarly, Chile's experts demonstrate that the combined effect of a 50 cm water table rise in the wetlands and the incorporation of a "buffer zone" of

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[186] **Wheater and Peach (2019)**, p. 25.

[187] DHI Report. BCM, Vol. 5, p. 70.

[188] Ibid. Chile's experts have labelled this "buffer zone", see **Wheater and Peach (2019)**, p. 27.

[189] Chile's experts note that DHI's representation of the hydrogeological situation is simplified and potentially misleading, see **Wheater and Peach (2019)**, p. 27.

[190] **Wheater and Peach (2019)**, p. 27.

[191] **Wheater and Peach (2019)**, p. 27.

1 m adjacent to the channels, together with the "fixed head" upslope boundary condition of the Near Field model, is a decreased inflow in the Near Field model area by 24%.[192] By contrast, those same boundary conditions in a Far Field model comprising the entire Silala catchment (which is the correct boundary), have a combined effect of reducing the inflow by only 1.2%.[193] This means that the effect of removing the channels and restoring the wetlands on the inflow (and hence, on the outflow) is exaggerated by a factor of 20.[194] This analysis, based on simple text book calculations, shows that Bolivia's exaggeration is directly attributable to the configuration of the Near Field model, with its "fixed head" upslope boundary condition at close distance to the wetlands. This forces the hydraulic gradient to decrease and less water to flow into the model area, exactly as predicted by Darcy's law.

3. The DHI Near Field model is built on an incorrect interpretation of the geology and hydrogeology

3.29 Chile's and Bolivia's experts have fundamentally different interpretations of the geology and hydrogeology of the Silala River basin. The geological sequences and dates proposed by Bolivia are not supported by recent geological mapping and radiometric dating, drilling evidence and pumping results as presented by Chile.[195] There is also no evidence for the high permeability fault along the course of the Silala River, introduced by DHI as an important feature in its Near Field model.[196] On the other hand, the faulting that has been identified by

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[192] **Wheater and Peach (2019)**, p. 28.

[193] **Wheater and Peach (2019)**, p. 28.

[194] **Wheater and Peach (2019)**, p. 28.

[195] **Peach and Wheater (2019)**, pp. 17-21 and 52.

[196] **Peach and Wheater (2019)**, pp. 29-30.

Chile's experts at the downstream end of the Silala catchment is not considered in the DHI model.[197]

3.30 A numerical model that is built on incorrect geology will not correctly represent the distribution of areas of high and low permeability in the basin. It assumes groundwater flow paths and distribution of high and low hydraulic conductivity that are not supported by evidence and may very well be different. This means that its predictions have no scientific basis and are highly likely to be incorrect.[198]

3.31 In addition, despite acknowledging the differences in origin and recharge area between the two sets of springs in Bolivia and the existence of separate aquifer systems,[199] DHI does not consider these features in the Near Field model.[200] The groundwaters emerging in the springs are very likely to have different residence times, due to their different groundwater flow paths coming from different recharge areas. This is likely to affect their response to the different scenarios run by the Near Field model, i.e. with or without channelization and with or without the hypothetical added layer of peat.[201] Ignoring this important feature and the complexity of the Silala groundwater system makes it unlikely that the Near Field model could successfully predict the behavior of the springs.[202]

3.32 According to Chile's experts, the lack of recognition of key characteristics of the hydrogeology of the Silala River, in particular the ages and

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[197] **Peach and Wheater (2019)**, pp. 32, 35 and 52.

[198] **Peach and Wheater (2019)**, p. 35.

[199] DHI Report. BCM, Vol. 4, p. 103.

[200] **Peach and Wheater (2019)**, p. 47.

[201] **Peach and Wheater (2019)**, p. 47.

[202] **Peach and Wheater (2019)**, p. 47.

sequences of permeable ignimbrites and the existence of separate aquifer and recharge systems, are serious flaws of the DHI Near Field model and make it highly improbable that DHI's scenario predictions could be correct.[203]

4. *Any reduction of the cross-boundary surface flow would anyway be compensated by an increase of cross-boundary groundwater flow*

3.33 DHI recognizes that reduction of surface flows in the No Canal and Restored Wetlands Scenarios will be compensated by increased groundwater flows.[204] They also acknowledge that the flow direction of the groundwater, as of the surface water, is from Bolivia towards Chile.[205] This means that all the water in the Silala catchment, less direct loss to evaporation, will ultimately reach Chile, whether as surface or groundwater flow.[206]

3.34 The combined outflows in the No Canal and Restored Wetlands Scenarios are 209 l/s and 207 l/s respectively, amounting to a total reduction of cross-boundary (surface and groundwater) flows as compared to the Baseline Scenario (256 l/s), of 18-19%. Taking into account that a simple analysis shows that the DHI Near Field modelling exaggerates the effect on outflows by a factor of 20, this indicates that the total reduction of cross-boundary (surface and groundwater) flows by removing the channels is likely to be a few percent at most, and therefore, negligible.

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[203] **Peach and Wheater (2019)**, p. 49 and **Wheater and Peach (2019)**, pp. 29-30.

[204] DHI Report. BCM, Vol. 2, p. 266: "11. Without the canals, more water crosses the border as groundwater."

[205] Ibid.: "5. The observed groundwater levels in the many boreholes established in the Silala 'Near Field' and above show a clear flow direction of the groundwater from East to West."

[206] **Wheater and Peach (2019)**, pp. 3, 4 and 8.

5. The conclusions of the Ramsar Report on wetland degradation at the Silala are unwarranted and are contradicted by recent evidence provided by DHI and other expert reports

3.35 In addition to the DHI expert report, Bolivia has presented a report of the Ramsar Advisory Mission N° 84 on the Los Lípez Ramsar Site (Ramsar Report).[207] The purpose of this report is to evidence significant degradation of the Silala wetlands in Bolivia.

3.36 The Ramsar Mission was requested by Bolivia in July 2016,[208] shortly after Chile had lodged its current Application, on 6 June 2016. The Ramsar Report is based on information provided by Bolivia and one site visit to the Los Lípez Ramsar Site, in November 2016.[209] It contains several statements that appear uncritically to reflect Bolivia's position on the Silala and that are not supported by the relevant evidence, including the DHI expert report and other recent studies undertaken by Bolivia.

3.37 The Ramsar Mission classifies the Silala groundwater system as a "non-renewable aquifer on the geological scale."[210] Conclusion 9 of the Ramsar Report states: "Studies with stable isotopes have shown that the waters that emerge in the Silala springs are fossil waters dating back to more than

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[207] Ramsar Report. **BCM, Vol. 5, Annex 18**. The Silala wetlands are located at the north-western boundary of the Los Lípez Ramsar Site in Bolivia. Chile notes that the Ramsar Report includes a discussion of several lagoons within the Los Lípez Ramsar site, some quite far removed from the Silala and none of which bear relation to the Silala wetlands.

[208] Note N° VRE-Cs-58/2016 from the Ministry of Foreign Affairs of Bolivia to the Senior Advisor for the Americas of the Ramsar Convention Secretariat, 27 July 2016. **CR, Vol. 2, Annex 97**.

[209] Ramsar Report. BCM, Vol. 5, p. 101.

[210] Ramsar Report. BCM, Vol. 5, p. 149.

10,000 years. In other words, these are waters that are not renewed by natural recharges of meteoric waters in the local aquifer."[211]

3.38 These statements are contradicted by DHI, who unequivocally confirm that the waters of the Silala are largely from recharge:

> "The hydrological catchment, Catchment B, can sustain a flow of 151-374 l/s from recharged water which is in the same order of magnitude as the observed surface water (160-210 l/s) and estimated cross border groundwater flow in the order of (100-230 l/s) (Annex F and Annex H).
> Overall, the analysis indicates that a large proportion of the water feeding the wetland is from recharge from rainfall and snow melt in the hydrological catchment."[212]

3.39 The Ramsar Mission also uncritically reproduces Bolivia's position that the channelization affected the extension of the wetlands, as follows:

> "The wetlands found in the Silala area have been highly affected by the construction of the water-catchment canals started in 1908. At present, there are only vestiges of the original wetlands that used to cover an area of about 141,200 m^2, or 14.1 hectares. The current surface area of the wetlands covers only about 6,000 m^2, or 0.6 ha, which are surrounded by the water catchment works and artificial canals (SERGEOMIN, 2003)."[213]

3.40 The SERGEOMIN (2003) report, the only and direct source for this statement, does not make any reference to historical studies or scientific investigations to confirm its estimation at 14.1 ha of the area originally covered by the wetlands. Nor does it provide any evidence for the alleged reduction of

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[211] Ramsar Report. BCM, Vol. 5, p. 167.

[212] DHI Report. BCM, Vol. 2, p. 290.

[213] Ramsar Report. BCM, Vol. 5, p. 163. Chile notes that the year 1908 coincides with the Bolivian concession, but not with the year the channelization was undertaken, which was in 1928. The reproduced text of the Ramsar Report is taken from Bolivian Geology and Mining Survey (SERGEOMIN), *Study on Hydrographic Basins, Silala Springs Basin, Basin 20*, June 2003 (henceforth "SERGEOMIN 2003"), pp. 59-60. **CR, Vol. 2, Annex 94**.

this surface area to a mere 0.6 ha in 2003. Indeed, elsewhere in the same SERGEOMIN (2003) report, the total surface of the wetlands in 2003 is estimated much higher, at 108.600 m^2 or 10.8 ha.[214] The very low estimate of the Silala wetland extension relied on by the Ramsar Mission is also contradicted by Bolivia's own more recent studies, including a 2016 study of the Bolivian Ministry of Environment and Water, which estimates the total extension of the wetlands at the Silala at 10.89 ha in June 1986, and at 9.81 ha in June 2010.[215]

3.41 A more complete study of the wetlands extension was commissioned by Bolivia in 2017 (the Castel study). It consists of a multi-temporal analysis using satellite imaging in order to assess changes at the Orientales and Cajones wetlands, between 1975 and 2017.[216] The Castel study estimates the current wetlands as fluctuating between 8.01 and 6.21 ha during the wet season, and between 6.75 and 2.16 ha during the dry season (1975-2000); and between 5.88 and 3.58 hectares during the wet season, and between 3.65 and 1.92 ha during the dry season (2002-2017).[217] Its estimates again do not come close to the 0.6 ha relied on by the Ramsar Mission from the SERGEOMIN (2003) report. Castel refrains from giving any estimates of the wetland extension prior to the channelization, for reason that no satellite images are available from the early twentieth century that could support such estimation.[218]

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[214] SERGEOMIN (2003), pp. 26 and 65. **CR, Vol. 2, Annex 94**.

[215] Ministry of the Environment and Water of Bolivia, *Characterization of Water Resources in the Southwest of the Department of Potosí – Municipality of San Pablo de Lipez "Wetlands of Silala Valley and Adjacent Sectors"* (Volume II), July 2016, p. 40. **CR, Vol. 2, Annex 96**. The Ramsar Report cites the 2016 study, noting a reduction by 1.08 ha in the wetlands surface area between 1986 and 2010, apparently without noticing that the estimates of the Ministry do not coincide with the very low estimate relied upon by the Ramsar Mission from the SERGEOMIN 2003 report. See Ramsar Report, BCM, Vol. 5, p. 163.

[216] Castel, p. 4. **CR, Vol. 2, Annex 98**.

[217] Castel, p. 38. **CR, Vol. 2, Annex 98**.

[218] Castel, p. 38: "[T]he Silala Spring high altitude wetlands have remained in this state of intervention since the beginning of the XX century, therefore they could not be analyzed through

3.42 The Castel study also provides no evidence for the "progressive degradation" of the wetlands which the Ramsar Mission claimed to have observed during its November 2016 site visit.[219] The Castel study affirms that for the entire period studied (1975-2017):

> "No significant long-term changes were noted during both periods studied in the surface of the high altitude wetlands. Both the Landsat images and the high resolution images show that although there is significant seasonal variability, there is no trend towards a decrease in the total surface area of the high altitude wetlands."[220]

3.43 Castel's study reinforces the results presented in Chile's Memorial that show strong seasonal and inter-annual variability of the wetlands, rather than long term change.[221] Recent results from Chile's science team show that the current extents of the Cajones and Orientales wetlands wholly fill the available valley floor and seasonally expand up the adjacent hillslopes, in the same way as a wholly undisturbed wetland in Chile.[222] So claims by the Ramsar Mission on wetland degradation appear wholly unfounded and counterfactual.

3.44 But even if it were the case that the Orientales and Cajones wetlands suffered from the 1928 channelization, this is not attributable to Chile. Bolivia authorized the FCAB works in its territory and could have restored the wetlands many years ago.

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satellite imaging over a period of time in a natural state, without intervention." **CR, Vol. 2, Annex 98**.

[219] Ramsar Report. BCM, Vol. 5, p. 163. Chile notes that the November 2016 site visit occurred at the end of the dry season.

[220] Castel, p. 38. See also pp. 15, 21, 25, 28 and 30. **CR, Vol. 2, Annex 98**.

[221] Alcayaga, H., *Characterization of the Drainage Patterns and River Network of the Silala River and Preliminary Assessment of Vegetation Dynamics Using Remote Sensing*, 2017, p. 31, Fig. 16. **CM, Vol. 4, Annex I**.

[222] **Wheater and Peach (2019)**, p. 44.

C. Conclusion: The impact of the 1928 channelization due to reduced loss to evapotranspiration, is limited to no more than 2% of the current cross-boundary surface flow; any additional impact argued by Bolivia is grossly exaggerated

3.45 As explained, the relevant remaining disagreement between the Parties concerns the quantitative effect of the 1928 channelization in Bolivia on the cross-boundary surface flow which, according to Bolivia's expert DHI, would be 30-40% less without the channelization.[223] According to Chile's experts, the effect of the channelization is minimal, while the very large estimate by DHI is implausible and defies common sense.[224] This disagreement is significant for Bolivia's case, because its position concerning "artificially-enhanced flows" is dependent upon its view that the science indicates that the channelization results in additional flows that enhance the natural flow by a factor of 30-40%.

3.46 Chile's experts have demonstrated that the DHI Near Field modelling has important flaws that have led to the exaggerated and incorrect results relied on by Bolivia as a base for its second and third Counter-Claims. DHI's estimates are based on a numerical model of only a small part of the Silala River basin, called the Near Field model, built on an incorrect understanding of the geology and hydrogeology of the Silala River system and using incorrectly defined boundary conditions. DHI's projections of long-term peat growth are also highly speculative.

3.47 Both Parties' experts agree that the 1928 channelization may have had a minor impact on the cross-border surface flow due to reduced evapotranspiration in the Bolivian wetlands, estimated by both at no more than

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[223] DHI Report. BCM, Vol. 2, p. 266.

[224] **Wheater and Peach (2019)**, p. 2.

2% of the current cross-boundary flow. Indeed, Chile's recent estimates of evaporation from satellite data show no detectable effect of channelization.[225]

3.48 It follows that there is no factual or scientific foundation for Bolivia's claim that the channels in Bolivia have resulted in a 30-40% "artificially-enhanced flow". Moreover, whatever the impact of the channelization – it is marginal – the distinction between natural and "artificial" flow is untenable in international law as was demonstrated in Chapter 2.

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[225] **Wheater and Peach (2019)**, p. 45.

SUBMISSIONS

With respect to the counter-claims presented by the Plurinational State of Bolivia, Chile requests the Court to adjudge and declare that:

(a) The Court lacks jurisdiction over Bolivia’s Counter-Claim a), alternatively, Bolivia’s Counter-Claim a) is moot, or is otherwise rejected;

(b) Bolivia’s Counter-Claims b) and c) are rejected.

Ximena Fuentes T.
Agent of the Republic of Chile
15 February 2019

Expert Report

Wheater, H.S. and Peach, D.W., *Impacts of Channelization of the Silala River in Bolivia on the Hydrology of the Silala River Basin*

IMPACTS OF CHANNELIZATION OF THE SILALA RIVER IN BOLIVIA ON THE HYDROLOGY OF THE SILALA RIVER BASIN

Drs. Howard Wheater and Denis Peach

January 2019

ABOUT THE AUTHORS

Dr. Howard Wheater

Dr. Howard Wheater is the Canada Excellence Research Chair Laureate in Water Security at the University of Saskatchewan, where he was founding Director of the Global Institute for Water Security, and Distinguished Research Fellow and Emeritus Professor of Hydrology at Imperial College London. A leading expert in hydrological science and modelling, he has published more than 200 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 was instructed by Hungary and Argentina at the International Court of Justice, and recently sat on the Court of Arbitration concerning the Indus Waters Treaty. He was, until 2014, vice-chair of the World Climate Research Programme's Global Energy and Water Cycle Exchange (GEWEX) project and leads 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. His role as Chair of the Council of Canadian Academies Expert Panel on Sustainable Management of Water in the Agricultural Landscapes of Canada saw release of a report in February 2013 entitled Water and Agriculture in Canada: Towards Sustainable Management of

Water Resources. 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 44 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 has given the Ineson Distinguished lecture at the GSL. 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.

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LIST OF ACRONYMS AND ABBREVIATIONS

BCM	–	Counter-Memorial of the Plurinational State of Bolivia
CM	–	Memorial of the Republic of Chile
DHI	–	Danish Hydraulic Institute
$ET_{a,NDVI}$	–	Actual evaporation rate estimated using NDVI data
ha	–	hectares
km^2	–	square kilometres
l/s	–	litres per second
m	–	metres
m/day	–	metres per day
m/s	–	metres per second
NDVI	–	Normalized Difference Vegetation Index

1 INTRODUCTION

1.1 Experts' Terms of Reference

In the context of the dispute between the Republic of Chile and the Plurinational State of Bolivia concerning the status and use of the waters of the Silala, to be heard before the International Court of Justice, the Republic of Chile has requested our independent expert opinion, as follows:

> "Questions for Dr. Howard Wheater, as a hydrological engineer:
>
> (i) What are the major points of scientific agreement between the Experts of Bolivia and those of Chile concerning the hydrology of the Silala River?
>
> (ii) What are the major points of scientific disagreement between the Experts of Bolivia and those of Chile concerning the hydrology of the Silala River?
>
> (iii) What new evidence has been produced, since Chile submitted its Memorial in July 2017, concerning the effect of the channelization of the flow on Bolivian territory on the watercourse of the Silala River that flows from Bolivia into Chile?
>
> Questions for Dr. Denis Peach, as a hydrogeologist:
>
> (i) What new evidence has been produced, since Chile submitted its Memorial in July 2017, concerning the understanding of the geology and hydrogeology of the Silala River?
>
> (ii) Does the hydrogeological conceptual understanding and parameterisation of the numerical models of Bolivia's Expert, the Danish Hydraulic Institute (DHI), provide an adequate basis to quantify the effects of channelization on the surface water and groundwater flows from Bolivia to Chile?
>
> (iii) Could the flow from groundwater-fed springs in the Cajones and Orientales springs have been significantly enhanced by the use of explosives?"

In this joint report we address the three questions to Wheater. A separate report (Peach and Wheater, 2019) addresses the questions to Peach.

1.2 Background to the report

This report follows two expert reports, Wheater and Peach (2017) and Peach and Wheater (2017), which were requested by the Republic of Chile as a contribution to its Memorial to the International Court of Justice. At the time, the core of the dispute between Chile and Bolivia was whether or not the Silala River is an international watercourse.

Following submission of Bolivia's Counter-Memorial (BCM), and in particular the report of Bolivia's consultants, the Danish Hydraulic Institute (DHI), on 3 September 2018, we now understand that there is agreement between the parties on the central point that the Silala River naturally flows from Bolivia to Chile and is an international watercourse. As we show below, there is also general agreement between Bolivia's experts and ourselves about the nature and functioning of the natural hydrological system.

The core of the dispute between Chile and Bolivia is now the quantitative effect of the channelization of the Silala, on Bolivian territory, on the cross-boundary flow. DHI estimates that the natural flows without drainage and channelization would be 30-40% less than the current situation (BCM, Vol. 2, p. 266). We disagree. In our opinion the very large estimates made by DHI are implausible, and indeed defy common sense.

1.3 Structure of the report

In section 2, we summarize our conclusions. We set out the points of agreement between the parties' experts in section 3, and then in section 4 explain the points of significant disagreement and the causes thereof. In section 5 we introduce new information from an undisturbed wetland in the Silala basin in Chile that is comparable to the Cajones and Orientales wetlands in Bolivia, and hence comment on the hydrological functioning of Bolivia's Cajones and Orientales wetlands. Section 6 presents our conclusions.

While this co-authored report represents our joint opinion, Wheater is the lead author of the report.

2 SUMMARY

We are pleased to note important areas of agreement between Bolivia's experts, the Danish Hydraulic Institute (DHI), and ourselves.

We agree in general terms about the hydrology of the Silala River and its catchment area. A central point is that the Silala River, which rises in two sets of springs in Bolivia that support the Cajones and Orientales wetlands, flows naturally from Bolivia to Chile and is an international watercourse. The river is primarily fed by groundwater, and interacts with groundwater along its course. The groundwater is recharged from an extended groundwater catchment, termed by DHI the hydrological catchment. In addition to the surface water flow in the river from Chile, there is an extensive groundwater system also flowing from Bolivia to Chile, recharged from the groundwater catchment area, and possibly further afield. The recharge from the groundwater catchment area, apart from the water lost in evaporation in the wetlands of the basin, will flow from Bolivia to Chile, either as surface water or as groundwater.

We also agree with DHI that the channelization that occurred in Bolivia in the 1920s, through excavation of channels in the Bolivian wetlands and lining the main river channel downstream of the wetlands, will have affected the river flows. We agree that the channels in the wetlands may have reduced evaporation losses, and we agree that this effect will be small, no more than 2% of the current flow to the border (in our current view, based on new Chilean data, probably much less). We further agree that there may have been some changes to river-groundwater interactions downstream of the wetlands due to the main river channelization, but these affects also will be small.

There is however one major point of disagreement. DHI suggest that groundwater inflows to the Cajones and Orientales springs may have been affected by the channelization due to a change in the gradient of groundwater flow, and by the removal of peat overlying the springs. They claim these latter effects are large, so that the total impacts of the channelization account for 30-40% change in surface water flows. We agree that these effects may occur, but find DHI's large estimates to be implausible. These estimates are wholly based on hydrological modelling of a small area around the springs (the Near Field), which we find to be fundamentally flawed.

Errors in the modelling include the fact that the underlying geology is mis-represented, and the boundary conditions for the model are inappropriate. In particular, water table conditions at the model upslope boundary are held constant. One effect of this is that the inflows to the model change significantly for the different scenarios investigated by DHI, whereas in reality, the recharge arises from the precipitation over the groundwater catchment, and is unaffected by the channelization. And because the inflows to the model change, the model outputs change too. The combined surface water and groundwater flows in DHI's model change by 18-19% for the different scenarios. In reality of course, this recharge can only flow to Chile – either as surface water or as groundwater.

We demonstrate below, using simple calculations, that this erroneous boundary assumption can exaggerate the effects of water table rise and peat cover by a factor of 20, and appear to explain DHI's exaggerated estimates. In our opinion, the effects of water table rise and peat cover will be minor, a few percentage at most of the cross-border flow. And any reduction in surface water flow would be accompanied by a corresponding increase in groundwater flow, both flowing down the topographic and hydraulic gradient to Chile.

We address in summary, the three questions posed to us by Chile. Further detail is provided in the full report that follows:

(i) What are the major points of scientific agreement between the Experts of Bolivia and those of Chile concerning the hydrology of the Silala River?

We and Bolivia's experts agree that:

1. The Silala River flows naturally from Bolivia to Chile. The river rises in two sets of springs in Bolivia, which maintain the Cajones and Orientales wetlands.
2. The river is primarily fed by groundwater and interacts with groundwater along its course to the border and beyond.
3. In addition, there are substantial groundwater flows from Bolivia to Chile, likely of an equivalent magnitude to the surface water flows.
4. Construction of drainage channels and river channelization in the 1920s will have had some effect on the flow. An increase in flow due to these works is expected.
5. The impact of drainage on evaporation from the wetlands is small.

(ii) What are the major points of scientific disagreement between the Experts of Bolivia and those of Chile concerning the hydrology of the Silala River?

We and Bolivia's experts disagree about the magnitude of the impact of the drainage works. In our opinion, Bolivian estimates of a 30-40% effect on flows are implausible. These estimates have been produced by a Near Field model of surface water-groundwater interactions. We have shown that the model is based on incorrect geology, that simple calculations show that incorrect assumptions of the model's boundary conditions lead to an overestimate of the impacts, by a factor of approximately 20, and that the change in inputs to the model is unrealistic.

(iii) What new evidence has been produced, since Chile submitted its Memorial in July 2017, concerning the effect of the channelization of the flow on Bolivian territory on the watercourse of the Silala River that flows from Bolivia into Chile?

New studies based on detailed monitoring of an undisturbed Chilean wetland within the Silala basin, coupled with high resolution remote sensing data, show that Bolivian and Chilean wetlands continue to fully occupy the valley floor, and seasonally extend up the base of adjacent hillslopes. The condition 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 the Cajones and Orientales wetlands, some 10% greater than that of the undisturbed Quebrada Negra wetland. At least from the satellite data, it appears that there has been no significant change in evaporation associated with the channelization of the Bolivian wetlands, and hence no effect of evaporation change on river flows.

In summary, we remain confident that the effects of the drainage works on evaporation are quite limited, as stated in Chile's Memorial (CM), at most equivalent to a flow of 2-3 l/s on average, i.e. some 2% of the natural flow, but in the light of our recent results, probably less. Other effects will be similarly small. Bolivia's estimates of 30-40% changes in river flow are due to errors in DHI's modelling and are implausible. We also reiterate that there is no doubt that the

Silala River is an international watercourse, and we are pleased to note the agreement of Bolivia’s experts on this point.

3 POINTS OF SCIENTIFIC AGREEMENT BETWEEN THE PARTIES’ EXPERTS CONCERNING THE HYDROLOGY OF THE SILALA RIVER

3.1 Agreement that the Silala River is an international watercourse

Our evidence in Chile’s Memorial and the supporting scientific annexes showed that:

The Silala River rises at two sets of springs (Cajones and Orientales) in Bolivia and flows along the natural topographic gradient from Bolivia to Chile, crossing the border in a ravine. The geomorphological history shows that the river has flowed from Bolivia to Chile in its current ravine for at least 8000 years.

The characteristics of measured river flow at the border show that the dominant source of the river water is groundwater. In addition to the Cajones and Orientales springs, we have found other spring flows contributing additional surface water flows to the river and significant groundwater flows at depth, downstream of the border. There are also areas where the river flow loses water to the underlying groundwater system.

This was summarized by Wheater and Peach (CM, Vol. 1, p. 177). We stated that:

- ‘[T]he topography of the Silala River catchment area is such that natural drainage from […] Bolivia flows across the international border between Bolivia and Chile.’
- ‘[W]hile the source areas for the perennial flow at the border lie in two major sets of groundwater springs in Bolivia (the water sources for the

Orientales and Cajones wetlands), the river interacts with groundwater throughout its subsequent course.'

- 'This [the Silala River] is […] "a system of surface waters and groundwaters constituting by virtue of their physical relationship a unitary whole and normally flowing into a common terminus."'

We are pleased to note that Bolivia's consultants DHI agree with the above statements. 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). They argue that the channelization works carried out in Bolivia in 1928 have influenced the magnitude of flow at the border, but note that 'The canals have changed the amount of discharge from the Silala springs but not the direction of natural outflow from the Silala wetlands', 'in a situation without the canals, the discharge direction is towards Chile' and 'In a situation without the canals, it is not possible that all surface water discharged from the wetlands infiltrate from the confluence point to the border' (BCM, Vol. 2, pp. 266-267). Further, 'groundwater level gradients and hydrogeological properties clearly indicate groundwater flow from Bolivia to Chile' and '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).

Thus, in addition to the agreement between the parties that the Silala River naturally flows from Bolivia to Chile, there is agreement between Bolivia's experts and ourselves about the existence of substantial groundwater flows from Bolivia to Chile. It is clear that, whether as surface water, or as groundwater, the water from the Silala River catchment area flows from Bolivia to Chile. There is also general agreement concerning the nature and functioning of the natural hydrological system, as we show below.

3.2 Agreement concerning the likely Groundwater Catchment area

In Chile's Memorial the topographic catchment of the Silala River was defined (CM, Vol. 1, p. 140, Figure 2), i.e. the area that drains surface or near-surface flows naturally to the border, but the possibility of groundwater inflows from areas beyond that, within Bolivia, was noted (CM, Vol. 4, p. 273, Figure 7-1). Our current best estimate of the larger area contributing groundwater recharge to the Silala River, based on topographic and geological analysis, is shown in Figure 1, below.

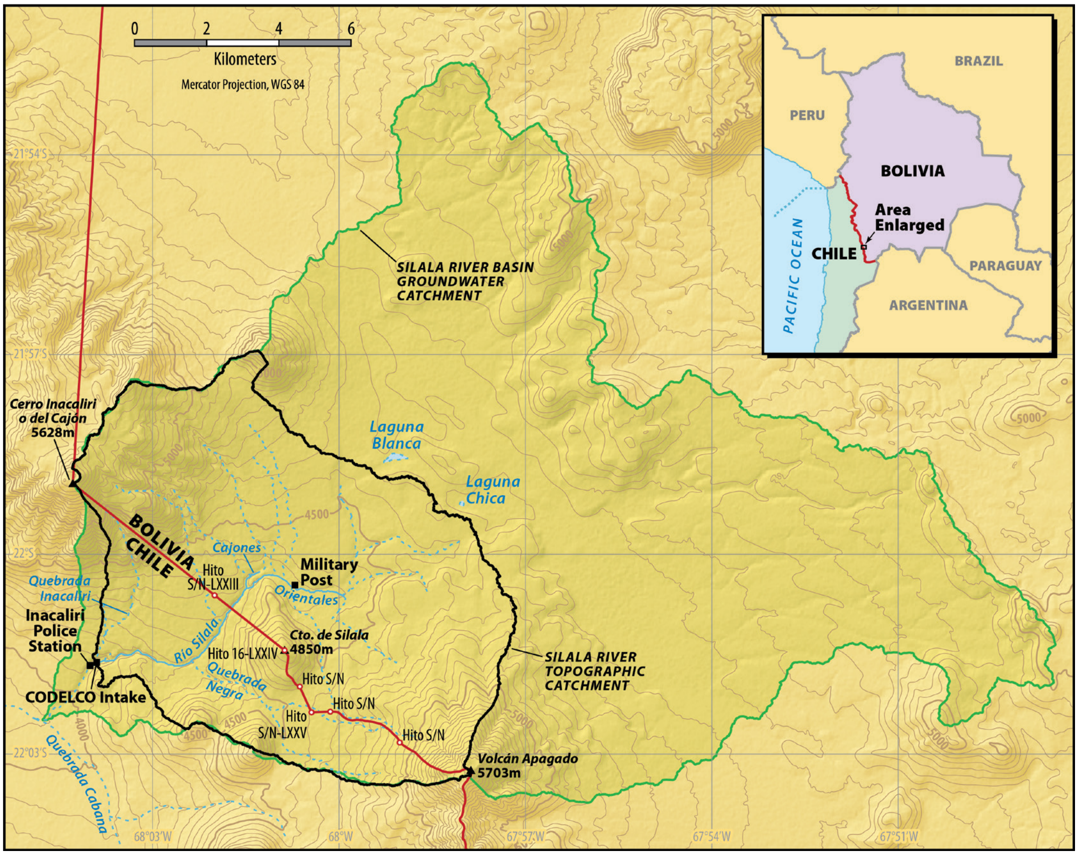

Figure 1. Silala River topographic catchment (outlined in black) and groundwater catchment (outlined in green).

This area is very similar to that identified by DHI as the ‘hydrological catchment’ (BCM, Vol. 2, p. 275, Figure 5) of the Silala River (with minor differences due to the use of a different Digital Elevation Model), although both we and DHI (BCM, Vol. 4, p. 103) acknowledge that it is possible that there may be additional groundwater contributions from further, more distant, sources.

3.3 Agreement concerning the potential for the effects of channelization in Bolivia to affect surface water flows at the border

The original concessions for use of the waters of the Silala date from 1906 (from the Government of Chile) and 1908 (from the Government of Bolivia), and at that time small structures were put in place in the river near the border to allow diversion of the waters into collector channels and pipes for transmission to downstream users. Some 20 years later, in 1928, modifications were made to the upstream channel in Bolivia. As we noted in our previous report, ‘[e]arth channels of the order of 0.6 x 0.6 m cross-section were constructed and subsequently lined with stone. They thus act as drains and are able to receive water from the wetland soils (and to release water back to riparian soils).’ (CM, Vol. 1, p. 134).

We are grateful to Bolivia for providing further details of the geometry of the drains and recent photographs (BCM, Vol. 1, pp. 41-42, Figures 15 and 16), including the areas where they have been blocked in recent years to divert in-channel flow to adjacent wetlands (BCM, Vol. 2, p. 370, Figure 4). Bolivia also provides data on the effect of the drains on groundwater elevations in the wetland source areas (BCM, Vol. 3, pp. 12-13, Figures 6 and 7). These show that the current water table depths in the drained wetlands range from 0.15 to 0.4 m below surface in the Cajones wetlands (Bolivia’s ‘Northern’ wetland) and from 0.15 to 0.45 m in the Orientales wetland (Bolivia’s ‘Southern’ wetland). In other words, instead of having standing water on the surface, water levels have reduced, but by less than 50 cm.[1]

Both we and Bolivia's experts agree that there will be some effect of these drainage works and the channelization of the river on the flows at the border. However, while both sides agree on the various effects that are possible, and agree about the magnitude of some of these, there is strong disagreement about the magnitude and significance of others. DHI suggests that in total these effects could give rise to a potential 30-40% change in flows, arguing that channelization increased river flows, and that long term restoration of the wetland peat soils could lead to further reductions in flow (BCM, Vol. 2, p. 266). In our view these estimates are wildly exaggerated and implausible, for reasons that we explain below.

Concerning changes in evaporation from the wetlands, we noted, for example, '[w]hile active, the channel works are likely to have reduced the extent of surface water in the wetlands and hence reduced the direct loss of water to evaporation […]. Any resulting reduction in evaporation would potentially provide additional water for surface discharge, including cross-border flows.' (CM, Vol. 1, p. 134). Bolivia agrees, and the various estimates presented by both sides are discussed in 2.4 below. There is general agreement that while changes to evaporation are expected, they will have minor effects on river flows.

We agree too that the channelization may have affected the interaction of surface water and groundwater downstream of the wetlands, in Bolivia, although in our opinion these effects will be small. For example, DHI states that infiltration from the river will have been reduced in reaches where the groundwater tables are lower than terrain level (BCM, Vol. 2, p. 276), thereby increasing the surface flows downstream. This is certainly possible, although as can be seen from

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[1] Assuming that the spatially-variable standing water had a depth of less than 5 cm.

Bolivia’s profiles of water table elevation (BCM, Vol. 2, pp. 285-287, Figures 11-13), groundwater levels are predominantly higher than channel bed levels along the main channel and much of the Cajones (northern) and Orientales (southern) tributaries, so that groundwater would be likely to be contributing flow to the stream under those conditions. Chile’s observations downstream of the border gave infiltration losses from a losing reach of 3.3 l/s over an approximately 2 km reach (CM, Vol. 5, p. 489), whereas we estimate that the length of potentially losing reaches in Bolivia is 1.4 km, which suggests that any surface water losses to groundwater in Bolivia are likely to be quite limited. It is also important to note that, as stated by Bolivia, this is a coupled surface water-groundwater system. DHI states (BCM, Vol. 2, p. 266) that ‘[t]he observed groundwater levels in the many boreholes established in the Silala “Near Field” and above show a clear flow direction of the groundwater from East to West. Together with evidence from boreholes of a pervious and water holding aquifer this proves the presence of cross border groundwater flow into Chile.’ Both the Bolivian interpretation of the hydrogeology and our own agree that water lost from the river to groundwater will still flow to Chile, albeit as groundwater rather than surface water flow.

There is therefore general agreement between Bolivia’s experts and ourselves that the 1928 drainage works will have affected surface flows across the border due to reduced direct loss of water by evaporation and possibly by infiltration, but that the effects of these on surface and groundwater flow from Bolivia to Chile are minor.

Bolivia also proposes that major changes have occurred to the groundwater discharges that feed the Bolivian wetlands, due to changing groundwater levels associated with the construction of channels in the wetlands, and to the effects of the wetland peat soils and their possible future long term evolution, creating hydraulic resistance to groundwater discharge to the wetlands (BCM, Vol. 5, p. 83). We agree that such effects could occur, but in our opinion these will also be very minor. Bolivia’s estimates are infeasible and appear to arise, in the major part, due to errors in their model simulations, as we show below.

3.4 Agreement concerning the effects of drainage on wetland evaporation

We and Bolivia’s experts agree that the effect of the drainage works in the immediate area of the Cajones and Orientales springs in Bolivia is to lower the water table in the area of the springs.

The effect of the drainage works will be to reduce the areas where surface water would have occurred, and from which the rates of evaporation are relatively high. However, the water tables are still very close to the surface (15-45 cm from the Bolivian data), so that water remains readily available for the wetland vegetation to evaporate. Overall, some reduction in evaporation is expected, making more water available for discharge in the river. DHI (BCM, Vol. 2, p. 303) estimates this effect to be equivalent to 2 to 3 l/s of river flow. When we prepared our contribution to Chile’s Memorial, our best estimate (CM, Vol. 1, p. 161) was that the annual average would change by 1.3 l/s (0.7% of the flow); however, recognizing the large uncertainty in these estimates, we quoted an upper bound estimate of 3.4 l/s, or 2% of the flow (CM, Vol. 5, p. 448). We return to this issue in section 5 below, in the light of recent work by Chile’s scientists, in which remote sensing data have been used to estimate evaporation from an undisturbed wetland (the Quebrada Negra) within the Silala basin in Chile, as well as from the Cajones and Orientales wetlands in Bolivia (Muñoz and Suárez, 2019). However, it remains the case that we and Bolivia’s experts are in broad agreement concerning the impacts of drainage on evaporation from the wetlands and that these impacts are no more than 2% of the current cross boundary surface water flow. The water evaporated is a small component of the water balance.

4 POINTS OF SIGNIFICANT SCIENTIFIC DISAGREEMENT BETWEEN THE PARTIES' EXPERTS CONCERNING THE HYDROLOGY OF THE SILALA RIVER

4.1 Effects of wetland drainage on groundwater discharges to the wetlands

As noted above, one effect of the channelization of the Cajones and Orientales wetlands is to reduce groundwater water table elevations, and we noted the agreement between the parties' experts concerning the effects on evaporation. A further potential effect of the channelization is to influence the groundwater flows that feed the wetland springs. DHI states that '[t]his has increased the hydraulic gradients, reduced hydraulic resistance through the springs and increased their discharge' (BCM, Vol. 5, p. 83). We agree that these are plausible effects. However, DHI argues that these effects are so large that natural flows without drainage and channelization would be 30-40% less than the current situation (BCM, Vol. 2, p. 266). On this point we strongly disagree. The effects proposed by DHI on groundwater discharges to the wetlands will be small; in our opinion the very large estimates made by DHI are implausible. We note that the DHI results are based entirely on their Near Field modelling. While we have yet to be provided with details of the model configuration, boundary conditions or parameters, nevertheless from the available summary information we believe that there are important flaws in the modelling, and that these have led to these exaggerated effects, as we show below.

We also note that the 30-40% changes in surface flow referred to by Bolivia do not include the compensating increases in groundwater flow to Chile. As can be seen from Table 1 of Annex H to the DHI Report (BCM, Vol. 5, p. 67), reproduced below, in the baseline case, the combined river and groundwater flows total 256 l/s, and in the 'no canal' and 'restored wetlands' cases, the combined outflows are 209 and 207 l/s respectively – i.e. an 18% and 19% reduction in total flow to Chile. Bolivia's exaggerated claim of a 30-40% change in surface flows is therefore misleading; they are claiming a change in water flowing from Bolivia to Chile of less than 20%. However, as discussed in more detail below, this is an error; whether as surface water, or as groundwater, the water from the Silala River catchment area flows from Bolivia to Chile.

4.1.1 Water balance considerations

A basic reason for not accepting DHI's estimates of major changes to groundwater discharge to the wetland springs comes from simple consideration of the water balance of the Groundwater Catchment (their Hydrological Catchment). Provided the groundwater catchment remains the same, the recharge to the aquifer(s) must either emerge from springs, and flow to the Silala River, or flow as groundwater down the hydraulic gradient toward the lower end of the catchment, in the process crossing the international border into Chile.

Recharge to the Silala groundwater catchment, which supplies the Bolivian springs and the groundwater flow to Chile, is independent of the groundwater flow regime and, unless the recharge area changes, the sum of these flows should remain the same. Fundamentally, the water recharging the aquifers which supply the Bolivian springs and seepages in both Cajones and Orientales wetlands must be accounted for in either flow that emerges from the springs and wetlands to form the Silala River or as groundwater flow, in this case into Chile, as agreed by Bolivia's experts. Any works on channels or in wetland restoration may affect local evaporation, and the balance between surface flow and groundwater flow, but will not affect recharge. Recharge to the aquifer system must therefore be matched by balancing outflows, which might include evaporation, surface flows or groundwater flows.

These groundwater flows, as agreed by Bolivia's experts (DHI, 2018a), flow to Chile in the south west in a regional aquifer composed of Ignimbrite deposits which pass underground from Bolivian territory to Chile. The aquifer occupies the Silala groundwater catchment and extends into Chile. Should hydraulic resistance at the Bolivian wetland springs increase to reduce surface flow, as proposed by DHI (2018b), the groundwater would still flow down gradient into Chile, as explained in Peach and Wheater (2019).

Groundwater recharge to supply the Cajones and Orientales springs is calculated by DHI as the difference between precipitation and evaporation (estimated by DHI to be 24 mm/year (BCM, Vol. 3, p. 478)) over their Hydrological Catchment area of 234 km^2 (BCM, Vol. 2, p. 274). As discussed above, this recharge rate is unaffected by drainage of the wetlands, nor in DHI's calculations is there any mention of the recharge area changing. However, the results from DHI's near field model clearly show that the inflow to the model, which arises from this recharge, changes for the different scenarios considered. In Table 1 below (reproduced from BCM, Vol. 5, p. 67, Table 1), the 'inflow' varies from 3116 to 2655 mm/year (253 to 216 l/s flow equivalent), depending on scenario. These significant inflow changes make no physical sense, and are unexplained by DHI. They are the primary reason for DHI's estimates of the changes in surface water and groundwater outflows to Chile.

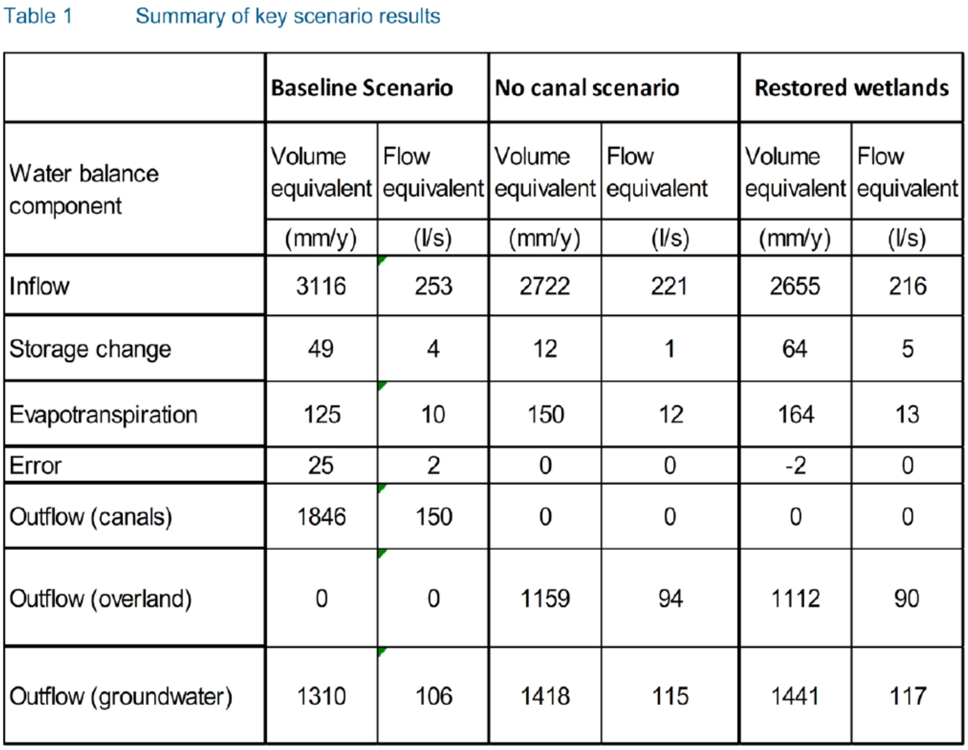

Table 1 Summary of key scenario results

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

Table 1. DHI's results of its modelling of different scenarios (reproduced from BCM, Vol. 5, p. 67, Table 1).

The question then arises, if in the no-channelization and restored wetlands scenarios surface water and groundwater outflows to Chile are indeed 18-19% lower than in the baseline scenario with channels, given the strong topographic and hydraulic gradients directing groundwater to the springs, and precipitation/recharge remaining the same, where will the 'extra' recharge water go to if not to Chile?[2]

There is no obvious pathway for recharge to be diverted around the Near Field model domain (see Peach and Wheater, 2019), so this change in recharge input

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[2] It is estimated by Bolivia that impacts of drainage on wetland evaporation account for 2-3 l/s (BCM, Vol. 5, p. 67, Table 1), so evaporation effects cannot account for a change in outflows that is estimated by DHI (for the Restored Wetlands in comparison with the Baseline Scenario) to be a 49 l/s net difference (i.e. a loss of 60 l/s in surface flows, less a gain of 11 l/s in groundwater flows into Chile).

must be regarded as unrealistic. Although Bolivia has not provided full details of the model configuration or boundary conditions, we believe that this is most likely a direct result of the boundary assumptions in DHI's modelling, which we discuss in sections 4.1.2 and 4.1.3 below in more detail.

4.1.2 Increased hydraulic gradients

Turning to the effects of the channelization in reducing water levels in the wetlands, we recall DHI's statement (BCM, Vol. 5, p. 83) that the drainage has increased the hydraulic gradients. It should be noted that one of the most basic laws of groundwater flow is Darcy's law (Darcy, 1856), which states that groundwater flow rate is proportional to the gradient of groundwater potential energy, or head.[3] So a change in gradient can indeed be expected to generate a change in groundwater flow rate.

However, we recall that DHI (BCM, Vol. 2, p. 280, Figure 6) shows that the collector drains in the Cajones (Northern) wetland are generally less than 50 cm deep, and that the measured water tables in both wetlands are between 15 and 45 cm below surface. This is a very small change in water table elevation.

We note that DHI has defined a groundwater recharge area in Bolivia that extends up to some 20 km from the springs and to topographic elevations of approximately 5686 m.a.s.l., compared to the spring elevations of 4370 m.a.s.l., i.e. a 1316 m topographic difference. We have no information on groundwater levels in this distant recharge area, but we use DHI's results (BCM, Vol. 3, p. 488, Figure 11) (adapted below as Figure 2) to explain our concerns.

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[3] For 1 dimensional flow in the s direction, Darcy's law states that (see, e.g., Verruijt, 1970):

$q = -KA\ dh/ds$,

where groundwater flow rate is q (m^3/d), K is the hydraulic conductivity of the aquifer (m/d), A is the cross-sectional area of flow (m^2), and h is the potential energy, or head (m).

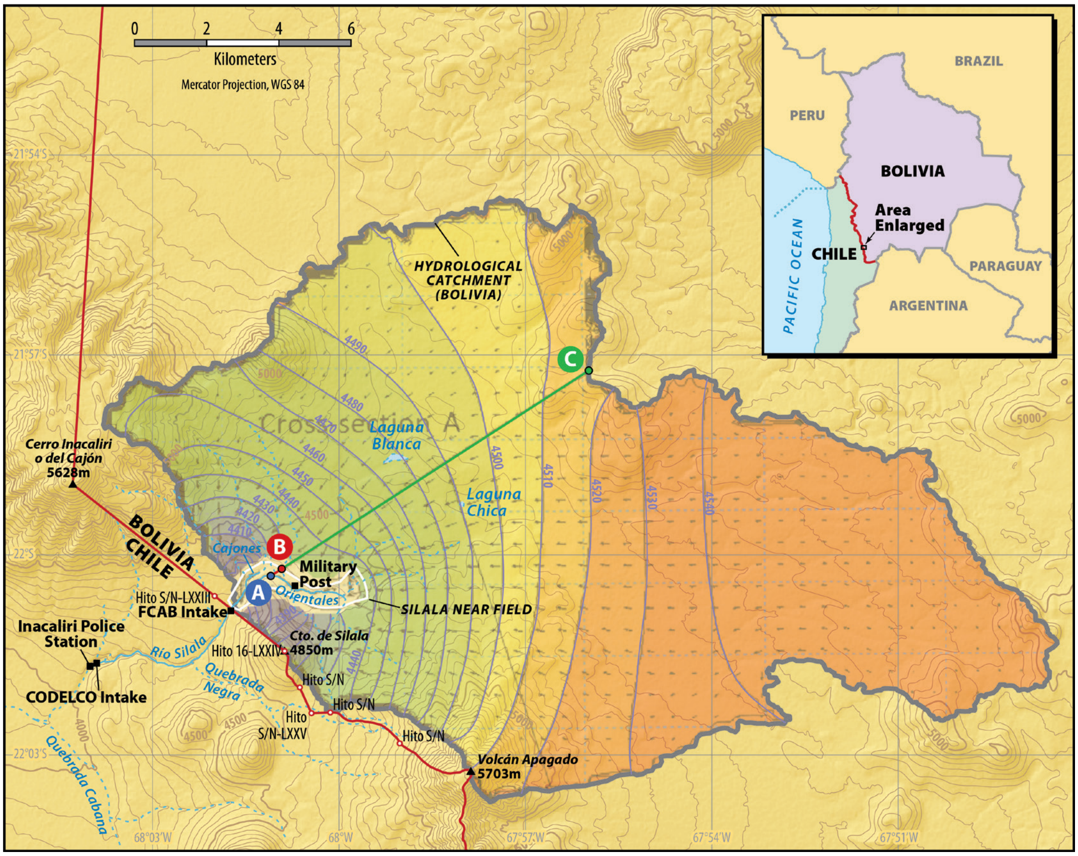

Figure 2. Simulated groundwater potential (head) in the Ignimbrite aquifer, adapted from a DHI's figure (BCM, Vol. 3, p. 488).

It can be seen from their simulated groundwater elevations and their cross section, shown here as BC, that groundwater flows from a groundwater elevation (head) of approximately 4520 m.a.s.l. to the Cajones and Orientales springs at approximately 4370 m.a.s.l. (i.e. a vertical difference of 150 m), over a horizontal distance of approximately 10500 m. It is therefore difficult to conceive how a lowering of water table elevation by less than 50 cm (i.e. less than 0.3% of the groundwater elevation difference of 150 m) can significantly affect groundwater discharge.

DHI produced these estimates using a very small-scale model (their Silala 'Near Field' model) of the immediate vicinity of the springs (BCM, Vol. 5, p. 16,

Figure 2). The area represented is 2.56 km^2, approximately 1% of their Hydrological Catchment area of 234 km^2.[4] DHI emphasize that their results are subject to high levels of uncertainty, hence ‘quantitative uncertainty analysis is not feasible’ and further note that ‘model uncertainty should not be ignored in the interpretation of results’ (BCM, Vol. 2, p. 303). However, there has been no attempt made to consider model uncertainty. Further, there are several basic problems with the model, which lead us to conclude that the model set-up, and in particular the boundary conditions, explains the erroneous results.

When setting up a groundwater model, a key issue is the selection of the conditions at the model boundaries (known as the boundary conditions). For catchment simulation, it would be common to take the whole basin as the modelled domain, typically with no-flow boundaries, so that recharge is included in the simulation. However, as DHI use a small Near Field domain, an alternative approach is needed to represent the boundary conditions. This could be a specified inflow at the boundary, a specified head, or some combination of the two. As noted in a standard text book on groundwater modelling by Rushton and Redshaw (1979, p. 132), ‘when specifying a groundwater flow problem it is common practice to take a line along which the groundwater potential is constant, and to enforce this as a boundary condition. *This is a valid condition if the groundwater potential remains at this constant value because the aquifer is in hydraulic continuity with the sea or a large lake. However a fixed potential implies that there is an infinite source of water on which the aquifer can draw*.’[5]

DHI have used a ‘fixed head’ boundary condition to represent groundwater flow into the model from the groundwater recharge area (their hydrological catchment) (BCM, Vol. 5, p. 18). This means that they have fixed the water table elevation

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[4] This is a reasonable approach in principle, but only if the flows at the boundaries of the model can be correctly represented. Conventionally such a small area model would be nested within a larger scale model to overcome this difficulty.

[5] Emphasis added.

(and hence the groundwater 'head' or potential energy) at the boundary of their model, which is very close to the springs. They then vary the water table in the wetland, to allow for the effect of drainage, but the upslope boundary water table remains unchanged, whereas in reality it would also respond to the change in wetland water table (a water table rise/fall in the wetlands would be accompanied by a water table rise/fall at the near field boundary). This violates Rushton's basic criterion that a fixed potential is a valid boundary condition *if the groundwater potential remains at a constant value*. Rushton also notes that a fixed potential implies that there is an infinite source of water on which the aquifer can draw. In this case, the fact that while the boundary head is fixed, the inflow to the model is unconstrained, has allowed the inflow to the model to change, in response to the changing head gradient due to the change in wetland water level. In reality, of course, the boundary inflow is equal to the amount estimated from the recharge calculation. DHI's choice of a fixed head boundary condition has given rise to the change in 'Inflow' noted above. The incorrect boundary condition thus gives rise to the incorrect changes in inflows in DHI's Table 1.

This boundary condition is unrealistic, and this has important consequences because, as noted above, a) the water table gradient change determines the groundwater flow,[6] b) the gradient change is exaggerated using this assumed fixed water table so close to the wetland, and c) the fixed head boundary condition imposes no constraints on the rate of flow across the boundary, so the inflow changes to accommodate the errors associated with the exaggerated gradient change.

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[6] Darcy's law (Darcy, 1856) states that groundwater discharge is proportional to the gradient of groundwater potential energy, or head.

A simple topographic cross-section illustrates the fact that this boundary condition grossly exaggerates the effect of the drains on the gradient of the groundwater flow. We use as an example, based on DHI's simulated heads, a hypothetical flow path AB, from the springs to the Near Field model boundary (Figure 3a), a distance of around 360 m, to show that a change of 0.5 m in water table elevation at the springs changes the average gradient of groundwater head by 0.0794 degrees.

However, if we refer back to the far field flow path of Figure 2, and consider a fixed head to be specified at the far field boundary, where it is more likely to be constant, rather than at the near field boundary, the change in average gradient is 0.0027 degrees (Figure 3b).

The average gradient differs by a factor of 29. It is obvious from Darcy's law that this will have important consequences in calculating flows, and it can therefore readily be appreciated, from even this simple geometric comparison, that the assumption of the fixed head at the near field boundary has important consequences for DHI's calculation of the effect of the drains on the spring flows, which we discuss below.

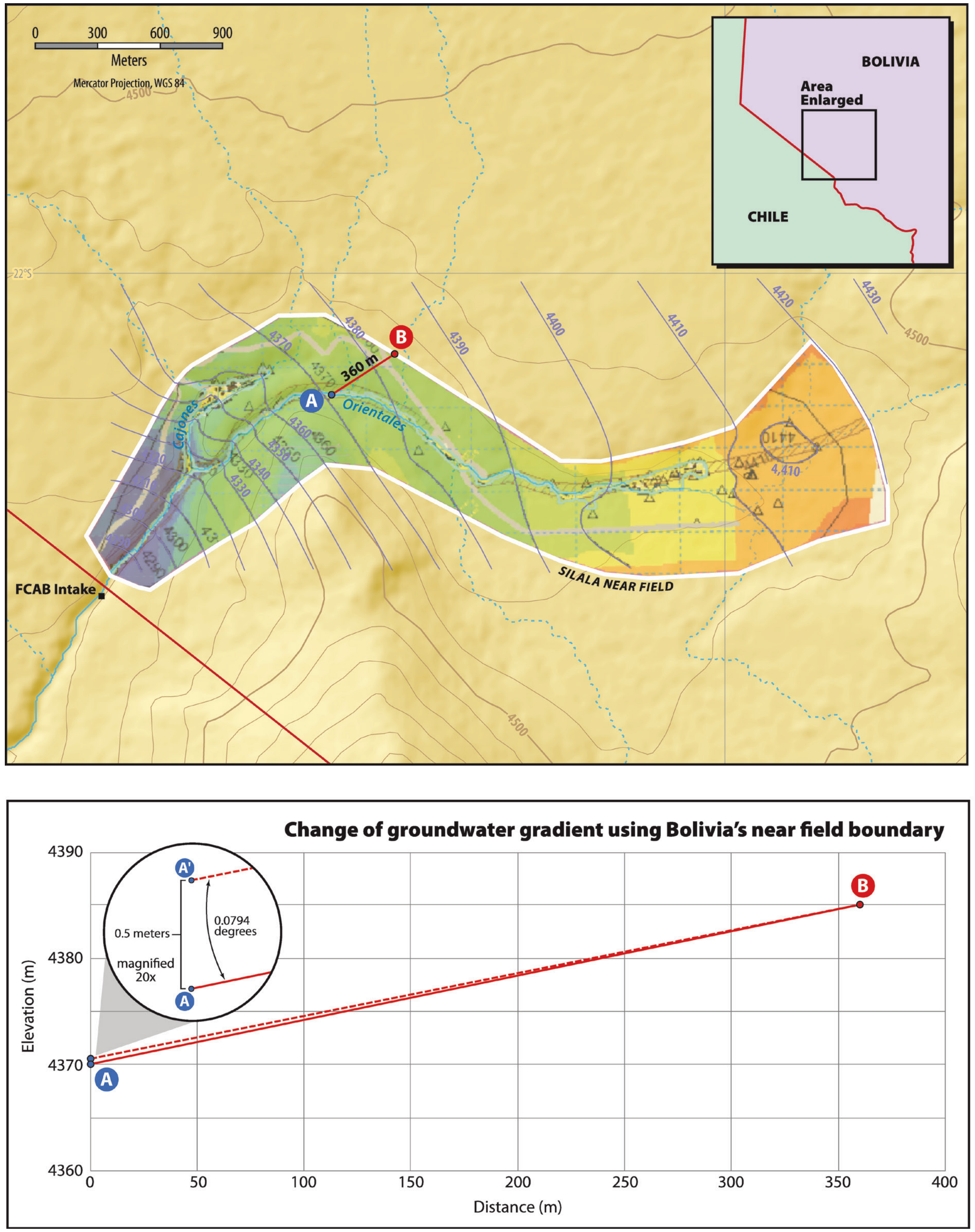

Figure 3a. A typical groundwater head gradient from the near field model boundary to the wetland.

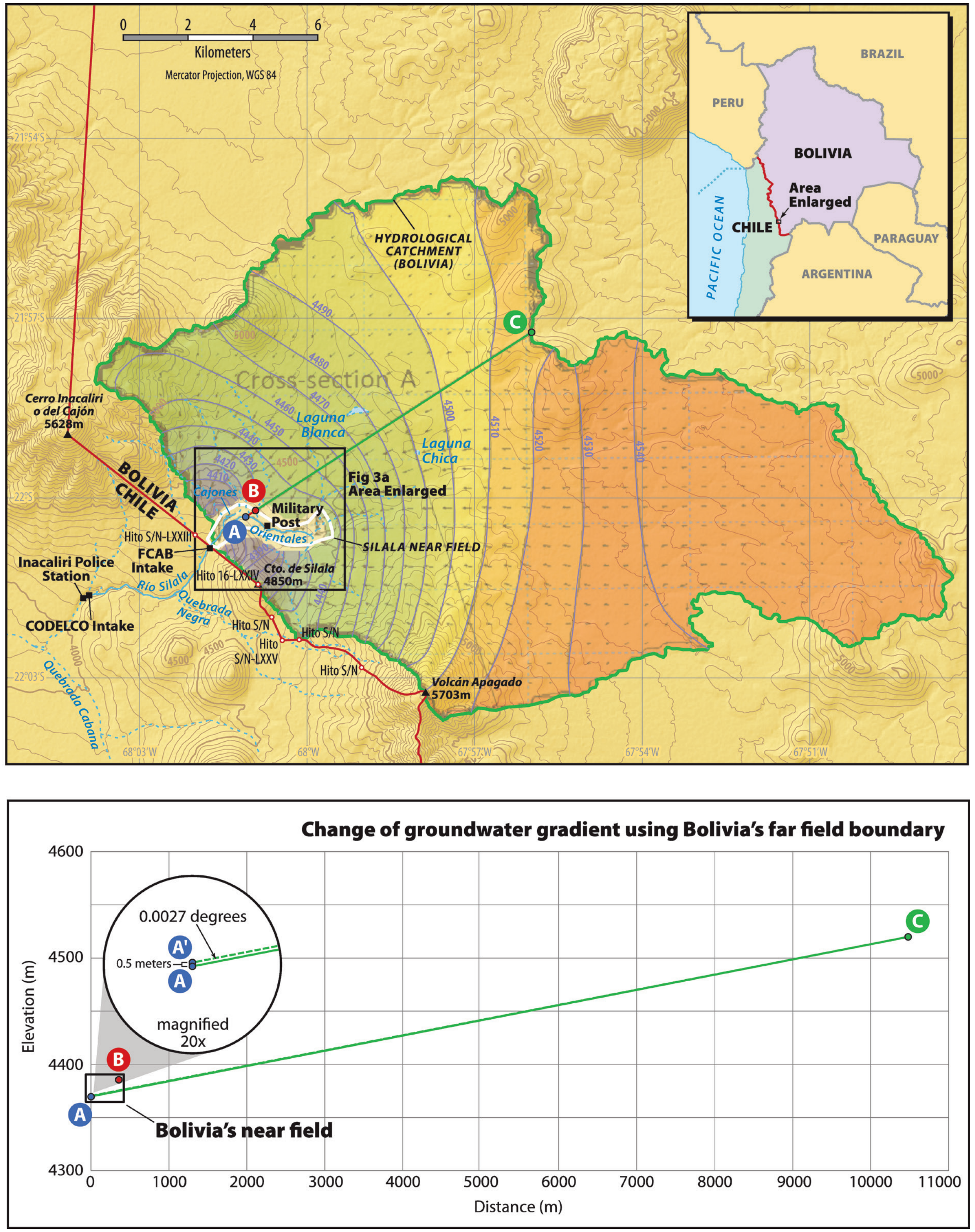

Figure 3b. A typical groundwater head gradient from the far field model boundary to the wetland.

A text book calculation, based on an analytical solution to the equations of groundwater flow, can be used as an example to indicate the potential effect of the erroneous boundary condition on the groundwater discharge in a little more detail (see Appendix 1 of this report for details and, for example, Verruijt (1970), p. 53). This is a two-dimensional calculation, based on uniform properties, and is not therefore attempting to represent the detail of the DHI simulation, which is not known to us, but merely to demonstrate the magnitude of the effect of their boundary condition assumptions. We consider first the effect of a change in water table elevation in the wetland, due to channelization. Later we consider a change in resistance to flow.

Figure 4 shows an idealized two-dimensional hillslope segment[7] of length 360 m based for illustration on the Near Field model section of Figure 2, draining from a constant head boundary (at 4385 m.a.s.l.) to discharge to a wetland (at 4370 m.a.s.l.). The difference in head is 15 m. For the purposes of demonstration, we assume that the aquifer is uniform, with a typical hydraulic conductivity (4.3 m/day, or $5x10^{-5}$ m/s, see BCM, Vol. 5, p. 21, Table 3, Upper Silala Ignimbrite), recharge rate (24 mm/year, BCM, Vol. 3, p. 478) and an aquifer depth of 400 m (BCM, Vol. 5, p. 17), as used by DHI. If the water table is increased by 0.5 m to represent the effect of infilling the channels with aquifer material, the groundwater discharge decreases by 3.3%. Alternatively, if we take a fixed head boundary condition at the far field boundary, as in Figure 2, section AC, 10500 m away (Figure 5), and increase the water table at the springs by the same 0.5 m, the effect is 0.28% decrease in discharge. Both effects are small, but DHI's incorrect choice of boundary condition exaggerates the effect of hydraulic gradients on water table change due to channelization by a factor of 12 (note that this is less than the factor of 29 quoted above due to the additional detail included in these calculations; specifically the recharge applied along the section,

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[7] Note that scales are distorted to allow the problem to be visualized.

which results in a groundwater gradient that varies along its length, unlike in the simpler example above).

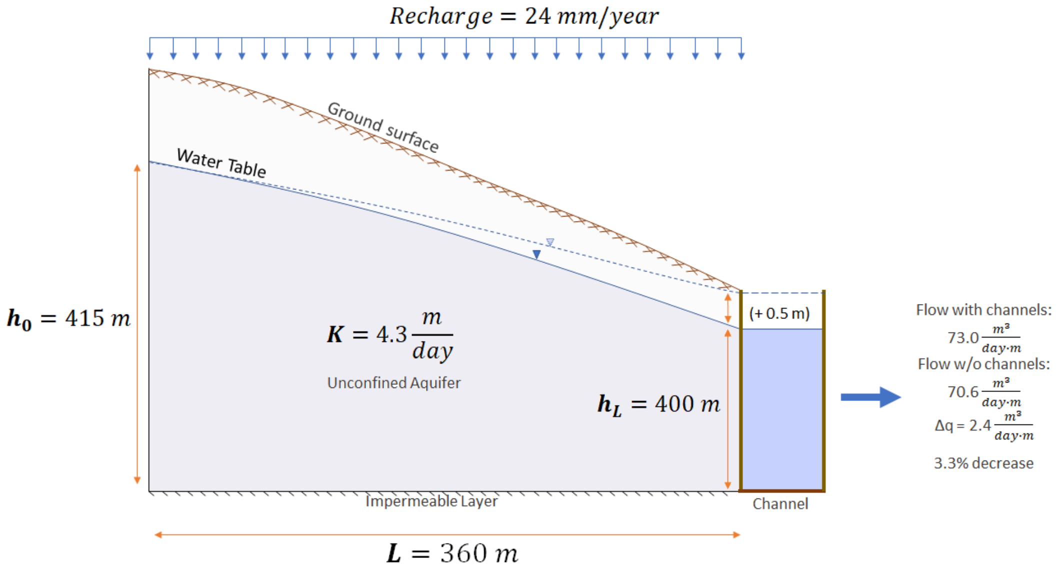

Figure 4. Effect of fixed groundwater head at near-field boundary on spring discharge.

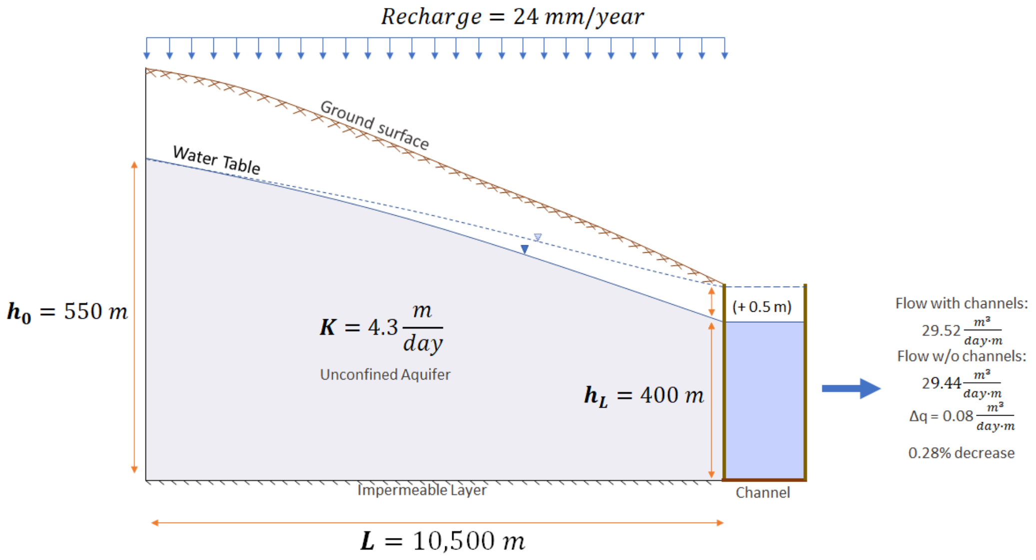

Figure 5. Effect of fixed groundwater head at a more realistic 10.5 km boundary on spring discharge.

4.1.3 Reduced hydraulic resistance

A second effect of the drainage and channelization works proposed by DHI (BCM, Vol. 5, p. 83) is that of reduced hydraulic resistance. DHI argues that construction of the drainage works has removed a layer of soil[8] (BCM, Vol. 2, p. 374), and that this has increased the groundwater discharge. They also argue that in a restored wetland, up to 60 cm thickness of peat will develop, accumulating at a rate of 0.1-1 cm/year, and that a thicker peat layer implies a higher resistance to groundwater emerging in the wetlands (BCM, Vol. 5, p. 70). There are several reasons why this is a misleading simplification of the hydrogeological situation, as discussed in section 5 below, see also Muñoz and Suárez (2019). However, once again an elementary calculation (Appendix 1, part 2) shows that the choice of the Near Field model boundary condition grossly exaggerates any such effect. Figure 6 shows a near field fixed head boundary, 360 m from the spring emergence, with the same elevation difference (15 m) as above. We introduce a 'buffer zone' at the base of the slope, representing conceptually the effect of a 1 m layer of peat on the groundwater flow path adjacent to the channel. We take peat permeability 2 orders of magnitude lower than the ignimbrite aquifer (0.043 m/day = 5 x 10^{-7} m/s, consistent with the lower limit of DHI's assumptions (BCM, Vol. 5, p. 26, Table 4)). The effect of the buffer zone is to reduce the groundwater inflow to the wetland by 22%. However, if a far field (10500 m) fixed head boundary is used (Figure 7), the effect of the same buffer configuration is a flow decrease of just 0.9%. The buffer zone has a disproportionate effect (by a factor of 23) on the flow field in the Near Field model, due to the choice of near field fixed head boundary.

If we now combine the effect of changing hydraulic gradient and reduced hydraulic resistance and superimpose the effect of a 0.5 m water table rise

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[8] DHI argues that 'By excavating the soil […] the hydraulic resistance to the groundwater discharge […] has been reduced.'

together with the peat layer (also shown in Figures 6 and 7), the flow decreases by 24% for the near field configuration, and 1.2% for the far field, i.e. the effect is magnified by a factor of 20.

While these calculations are highly simplified, they clearly demonstrate that the inappropriate choice of near field boundary condition has grossly exaggerated the effects of the drainage channels, by around 20 times, on both the reduced groundwater heads and any hypothetical reduced hydraulic resistance. The Far Field calculation of a 1% effect of these changes is indicative of the expected order of response, and when combined with possible changes in evaporation (and also considering the water balance issues discussed in Section 3.1.1), we remain of the view that the impact of the channelization on river flows is of the order of a few percent change in river flows.

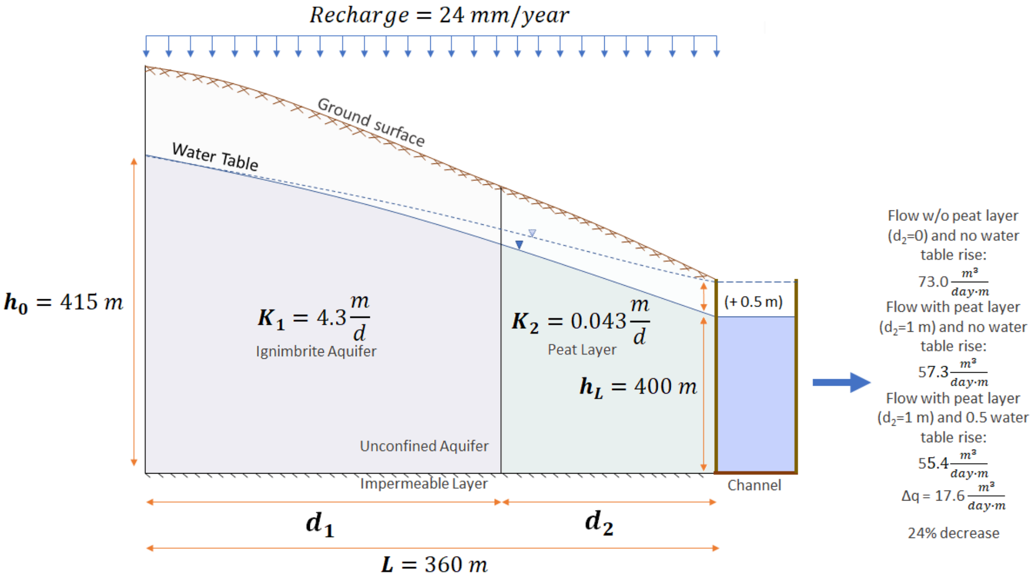

Figure 6. Effect of low conductivity zone on spring discharge – near field fixed head.

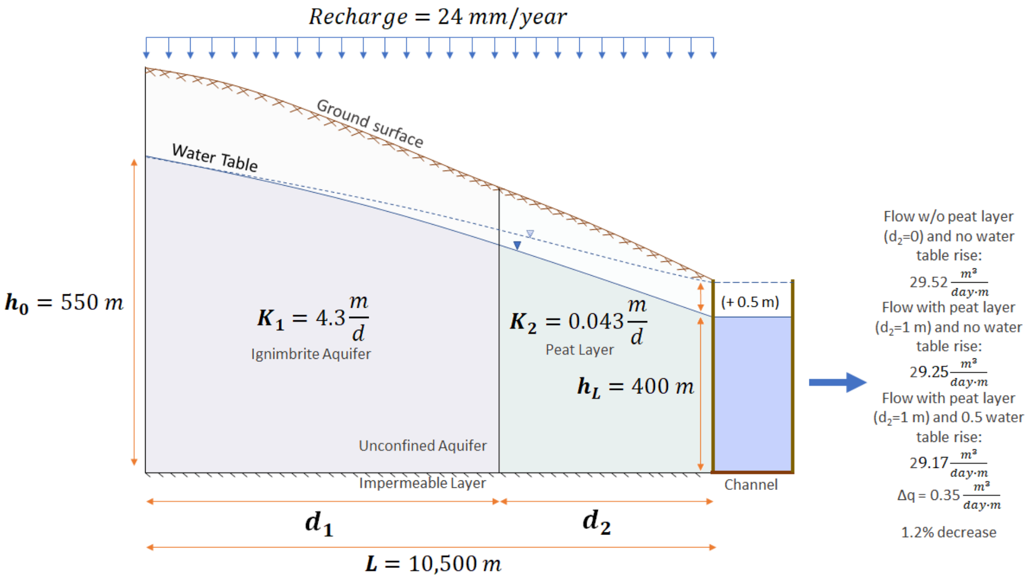

Figure 7. Effect of low conductivity zone on spring discharge – far field fixed head.

4.1.4 Other modelling issues

As noted above, Bolivia’s assertions concerning the impacts of channelization depend entirely on the use of a Near Field coupled surface-groundwater model to simulate the effects. We have shown above that a basic error in the choice of model boundary condition has led to the exaggeration of these effects, and that resulting change in recharge inputs to the model is incorrect. While we have focused above on incorrect specification of the near field model inflow boundary, a similar problem arises with other model boundaries. For example, the near field model outflow boundary is specified as a fixed hydraulic gradient, which makes no allowance for the fact that a changing groundwater flow gradient would be expected in response to the hypothesized flow changes. Also the groundwater table elevation contours shown in Figure 35 of Annex G to the DHI Report are inconsistent with the model’s assumed lateral boundary conditions (BCM, Vol. 5, p. 49). We believe these are no-flow boundaries, but if that is the case, the contours of groundwater head must be orthogonal to the model boundaries, and clearly that is not the case in this Figure.

Both we and Bolivia's experts understand that the hydrogeology of the Silala system is complex, and difficult to understand from the limited data available. Nevertheless, the detail of the local geology is particularly important in understanding the Near Field groundwater flows, and any response to channelization. The DHI groundwater representation is flawed in many important respects, and not representative of the true situation, as discussed in detail in Peach and Wheater (2019). One obvious indicator of this is that the groundwater modelling fails to recognize the fact that both the major ion and carbon isotope chemistry of the Cajones and Orientales spring waters are very different, and therefore the sources of the water are different. The DHI Hydrogeological Conceptual Model recognizes this (BCM, Vol. 2, p. 294), but the numerical modelling fails to take into account this basic feature of the data. This and other aspects of the geology are discussed in more detail by Peach and Wheater (2019).

It is also relevant to note at this point that there are other areas of concern with the model, although our analysis is hampered by the fact that (as yet) we have no detailed information on the configuration, parameters, forcing data or outputs of the various models used. Nevertheless several issues are immediately evident:

1. The near field model is stated to have been run as 'steady-state' (BCM, Vol. 5, p. 13, 'a stationary model approach has been adopted'). Since there is no variation with time, this means that the model inputs must equal the model outputs, with, by definition, no change in storage. This is not the case in the DHI results. For example in DHI's summary table of results (BCM, Vol. 5, p. 67, Table 1) annual storage changes (accumulating each year) are quantified for each of the 3 scenarios (baseline, no canal, restored wetlands). This is a basic model error.
2. The near field model results as presented in the same table do not add up. For example under the Baseline Scenario, the inflow to the model (from recharge) is 253 l/s flow equivalent, and the losses from the model total

266 l/s (loss to evaporation 10 l/s, surface water outflow 150 l/s and groundwater outflow 106 l/s). Even allowing for an ‘error’ term (2 l/s) and a change in storage (4 l/s, but note this term is not permissible in a steady state model), the numbers do not make sense. Also under the Restored wetlands Scenario, the inflow (216 l/s) and the total outflow/losses (220 l/s) are not the same.

4.2 Other areas of disagreement

There are many additional points of detail for which DHI’s analysis differs somewhat from ours, including for example precipitation over the Silala topographic basin and its larger groundwater catchment. However, in our view, these other differences are relatively minor in the overall context of this dispute, and in many respects to be expected, given the challenges of quantifying hydrological response with very limited data. However, the key point is that the DHI Near Field model is based on inaccurate geology (as discussed in detail by Peach and Wheater, 2019), has inappropriate boundary conditions, resulting in inconsistent water balances, and therefore does not explain correctly the effects of the channelization in Bolivia on the surface and groundwater flows to Chile.

5 NATURAL VARIABILITY AND FUNCTIONING OF THE BOLIVIAN WETLANDS AND TOPOGRAPHIC CONSTRAINTS

The BCM refers in many places to wetland degradation without providing any supporting data to show that significant degradation has occurred over time. To the contrary, Bolivia cites results from Castel (2017) that confirm Chile’s observations (CM, Vol. 4, p. 37, Figure 16) of the strong role of natural annual and seasonal variability in determining the area of active wetland vegetation, but show no long term trend over the recent decades for which data are available.

Despite that, DHI refers to the changes made by channelization in the Bolivian wetlands and asserts, for example, that ‘[t]his has reduced the size of wetlands’ (BCM, Vol. 2, p. 374). The Ramsar report (BCM, Annex 18) states that ‘[a]t present, there are only vestiges of the original wetlands that used to cover an area of about 141,200 m^2, or 14.1 hectares. The current surface area of the wetlands covers only about 6,000 m^2, or 0.6 ha. […]’ (BCM, Vol. 5, p. 163). This is clearly a wildly inaccurate statement, as can be seen from a) Bolivia’s own data of the wetland areas (Castel, 2107), and b) Chile’s remote sensing data, presented in the Memorial (CM, Vol. 4, p. 37, Figure 16), in Chile’s Reply (Muñoz and Suárez, 2019), and in summary data in this report, see Table 2 below. It is not our intention to state that the channelization is without any effect on the Bolivian wetlands, however it is important that any degradation be appropriately quantified so that its effects on the Silala River flow may be better understood.

To aid understanding of the functioning and dynamic behaviour of the Silala wetlands, Chile has recently established a detailed study of the Quebrada Negra wetland, located within the Silala River topographic basin in Chile (Muñoz and Suárez, 2019), as shown in Figure 8. This wetland is of comparable areal extent to the Cajones and Orientales wetlands in Bolivia (approximately 3 hectares) but is undisturbed by any human activity.

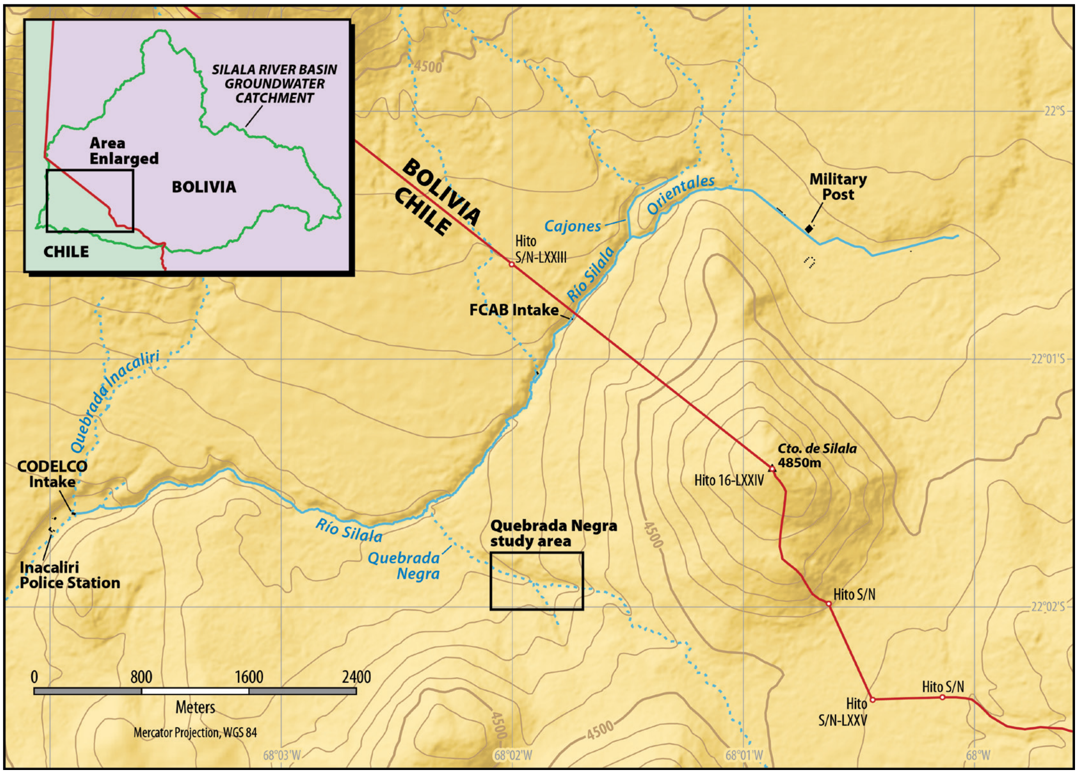

Figure 8. Location of the Quebrada Negra wetland within the Silala River topographic catchment in Chile (Muñoz and Suárez, 2019).

Selected photographs of the wetland are reproduced here, in Figures 9-11, after Muñoz and Suárez (2019). It can be seen that the wetland fills the valley bottom, which is characterized by natural channels that flow in response to spring emergence, interconnect to form a braided network, then lose their flow through re-infiltration. It can also be seen that vegetation extends up the base of adjacent slopes, focused on small tributary ravines, indicating spring emergence at the hillslope boundaries of the lowland wetland.

Figure 9. Photograph of the Quebrada Negra wetland, taken from the northern slope (Muñoz and Suárez, 2019).

Figure 10. Photograph taken at the Quebrada Negra wetland, looking upstream (Muñoz and Suárez, 2019).

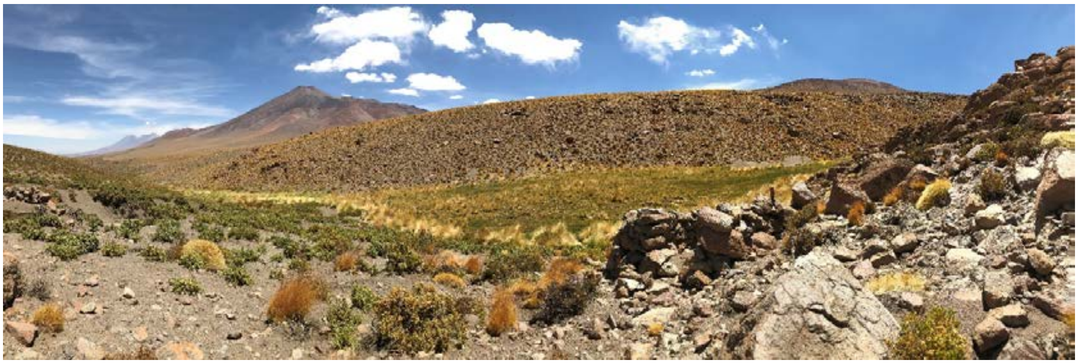

Figure 11. Photograph of the Quebrada Negra wetland, taken from the southern slope (Muñoz and Suárez, 2019).

The visual images from Bolivia in the Counter-Memorial show extensive areas of active vegetation in the Cajones and Orientales wetlands, despite the presence of the channelization (e.g. BCM, Vol. 2, p. 273, Figure 4; p. 333, frontispiece; p. 370, Figure 5; p. 372, Figure 8). See, for example, the frontispiece of Annex B to the DHI Report, reproduced as Figure 12, below:

Figure 12. Photograph of Bolivian wetland (BCM, Vol. 2, p. 333).

Chile’s Memorial used Landsat remote sensing imagery (from 1987 to 2016) to show that the active area of the Cajones and Orientales wetlands varied strongly, both seasonally and from year to year (CM, Vol. 4, p. 37, Figure 16), but with no overall trend. This point is also made by Bolivia. Castel (2017) uses Landsat imagery from 1975 to 2000 to come to the same conclusions, as noted above – high seasonal and inter-annual variability is seen in the wetland vegetated area, as mapped using the Normalized Difference Vegetation Index NDVI (which shows vegetation activity), but no evident trend.

In Chile’s recent work, Muñoz and Suárez (2019) use higher resolution satellite imagery (Sentinel-2, 10 m resolution) for the period July-November 2018 (Figure 13), which allows the extent of vegetation extent to be mapped onto the topography.

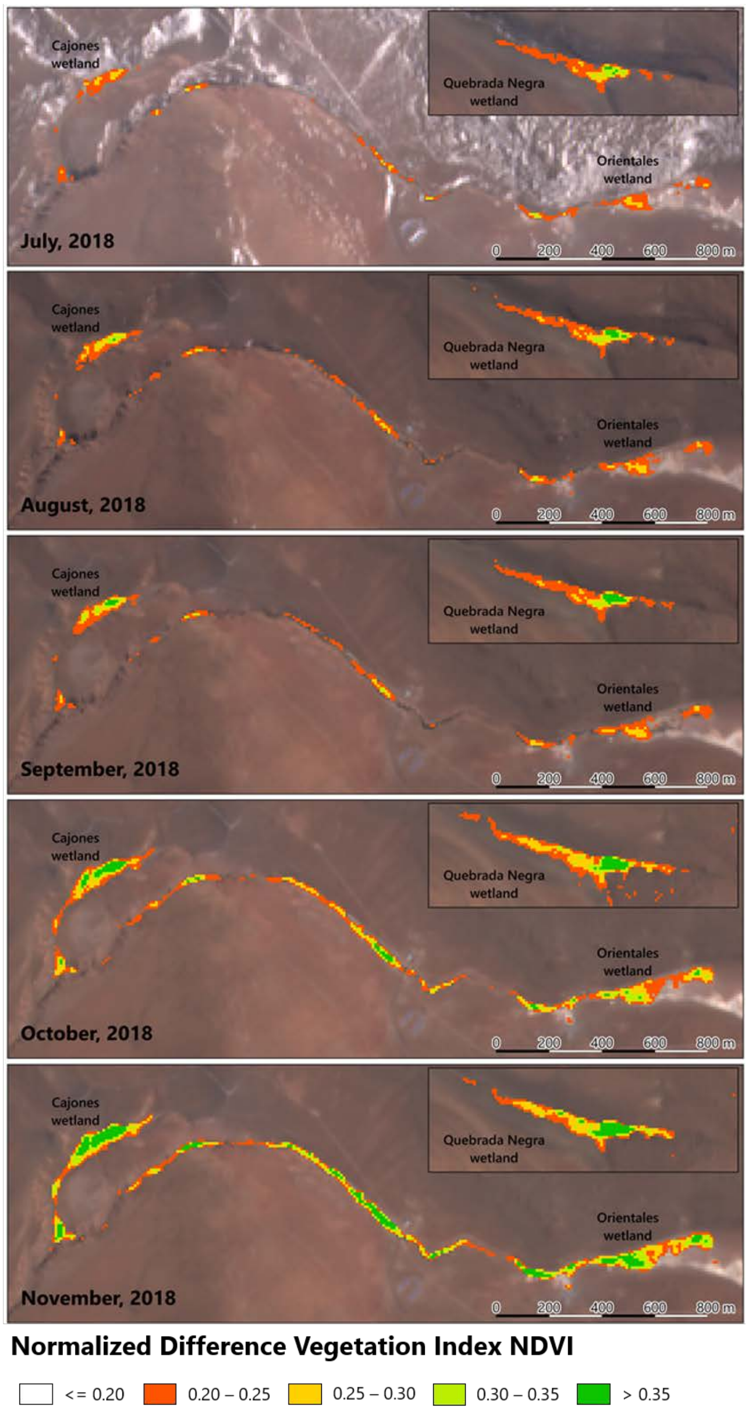

Figure 13. Quebrada Negra, Cajones and Orientales wetlands average NDVI distribution from July to November 2018 (Muñoz and Suárez, 2019).

The results are reproduced in Figures 14-16 below for the Bolivian Cajones and Orientales wetlands, and the Chilean Quebrada Negra. It can be seen that the active vegetation fully occupies the lowland areas of the respective valleys, and that seasonally, vegetation expands up the base of the adjacent slopes.

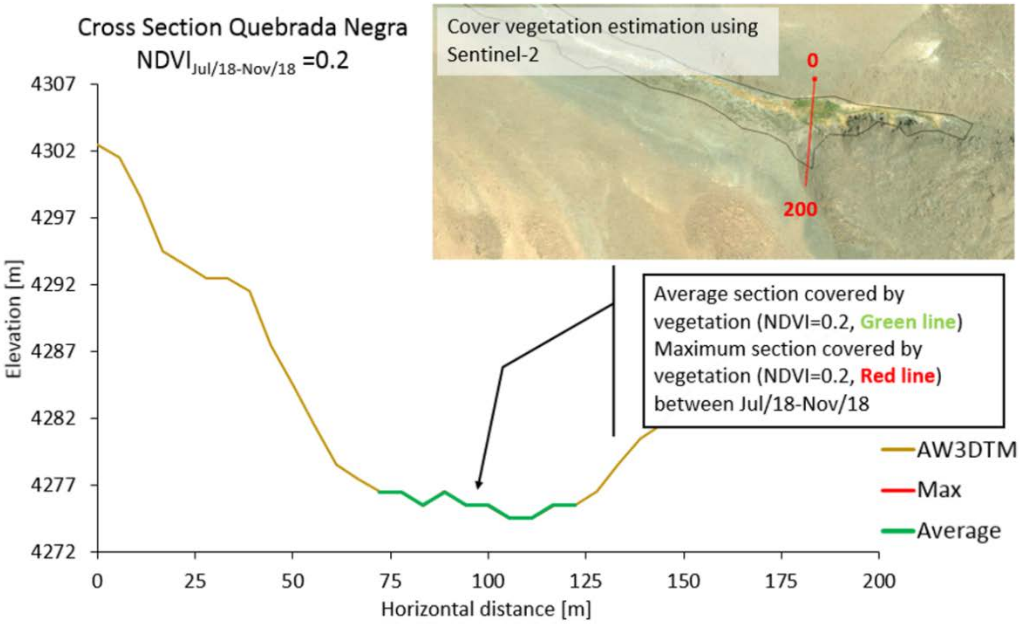

Figure 14. Cross section of vegetation cover (NDVI>0.2) and topography of the Quebrada Negra wetland. Average (Green Line) and Maximum (Red Line) cross section of vegetation cover have the same extension. For this reason, only average green cover (green line) is visible (Muñoz and Suárez, 2019).

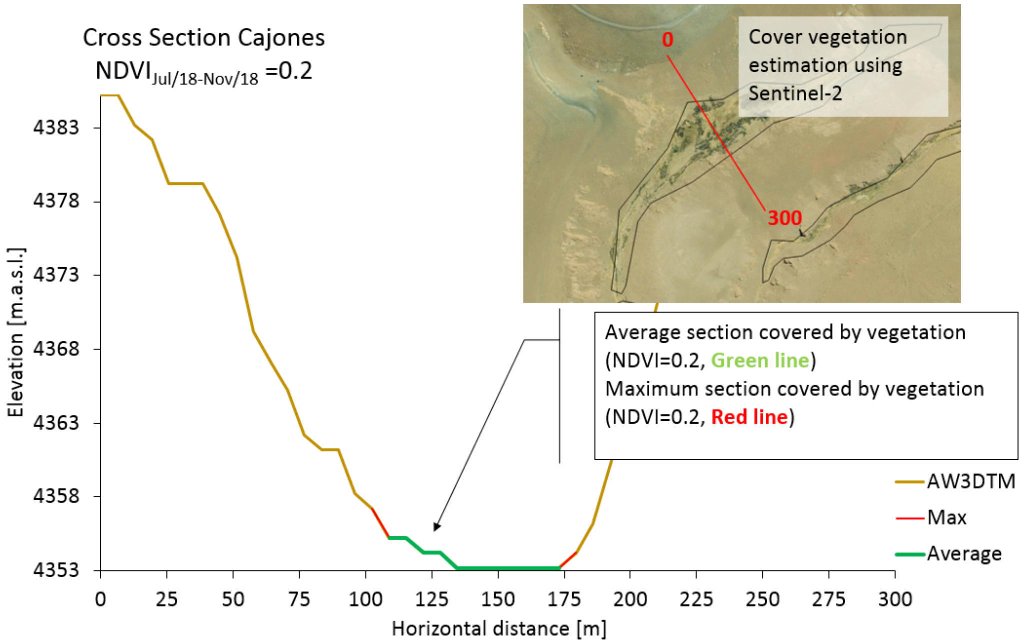

Figure 15. Cross section of vegetation cover (NDVI>0.2) and topography of the Cajones wetland (Muñoz and Suárez, 2019).

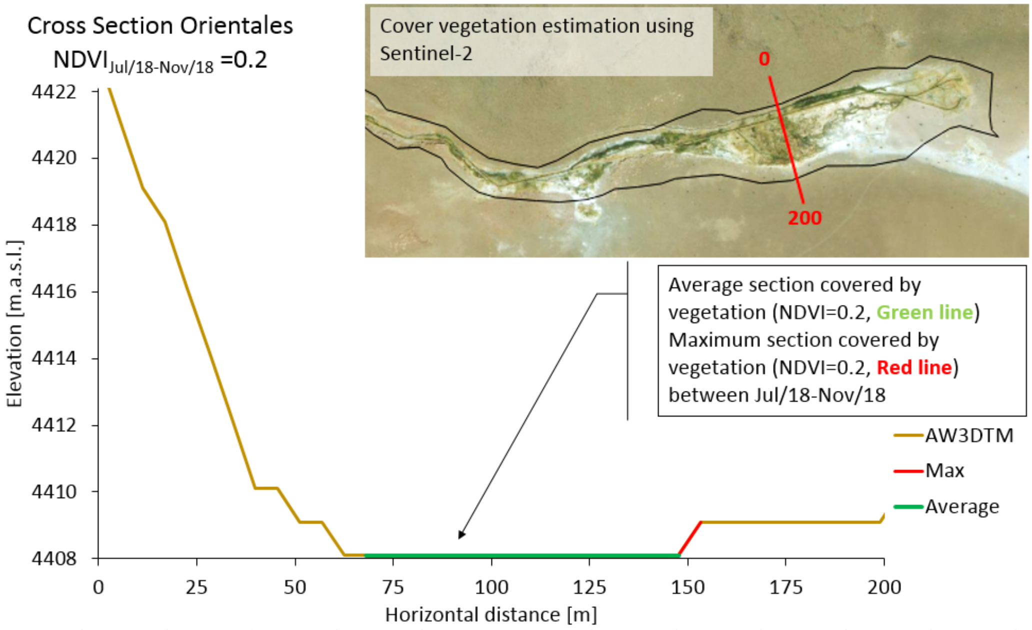

Figure 16. Cross section of vegetation cover (NDVI>0.2) and topography of the Orientales wetland (Muñoz and Suárez, 2019).

The conclusion is that the channelization activities in Bolivia's wetlands, which are focused entirely on the flat topography of the valley floors, have not significantly affected the area of active wetland in the valley floors.

We turn now to the effects of channelization on wetland evaporation. While we expect some impacts of the drainage works on wetland vegetation, as areas of surface water ponding will have been reduced, the fact that the water tables remain so close to the surface means that wetland vegetation has a plentiful water supply and can transpire freely.

The key indicator is obtained from the high resolution Sentinel-2 satellite NDVI data, for the period July-November 2018, summarized in Table 2 below (after Muñoz and Suárez, 2019). We recall that this period is the southern hemisphere Winter, emerging into Spring. Note that the combined area of the Cajones and Orientales wetlands is always much larger than the 0.6 hectares quoted as the 'current' area in the Ramsar report (BCM, Vol. 5, p. 163).

	Area covered by vegetation (ha)				
	July	**August**	**September**	**October**	**November**
Cajones wetland	0.81	1.12	1.31	2.2	2.41
Orientales wetland	2.23	2.7	2.86	6.09	7.5
Combined Cajones and Orientales wetlands	3.04	3.82	4.17	8.29	9.91
Quebrada Negra wetland	2.13	2.31	2.58	4.12	3.43

Table 2. Area covered by vegetation in the Quebrada Negra, Cajones and Orientales wetlands, from July to November, 2018 (Muñoz and Suárez, 2019).

A first order estimate of the annual actual evaporation rates can be derived from summer NDVI data, following the methodology of Groeneveld (2007), as explained in Muñoz and Suárez (2019). The results are shown in Table 3, below.

	Annual $ET_{a,NDVI,}$ (mm/year)	
	Mean	**S.D.**
Cajones wetland	705	17
Orientales wetland	702	23
Quebrada Negra wetland	631	21

Table 3. Annual $ET_{a,NDVI,}$ Mean and Standard Deviation (S.D.) in mm/year estimated for the Quebrada Negra, Cajones and Orientales wetlands (after Muñoz and Suárez, 2019).

The estimated annual evaporation rates from the Cajones and Orientales wetlands are very similar, and 10% higher than the evaporation rate from the Quebrada Negra wetland. Considering the respective wetland areas, the total annual evaporation is equivalent to a flow rate in the Silala River of 0.6 l/s for the Cajones wetland, 2.3 l/s for the Orientales and 0.7 l/s for the Quebrada Negra.

As noted above, we and Bolivia's experts are in broad agreement concerning the impacts of drainage on evaporation from the wetlands and that these impacts are no more than 2% of the current cross boundary flow. The water evaporated is a small component of the water balance. However, the conclusions from the recent work of Muñoz and Suárez (2019) are that any effects of canalization on wetland evaporation in the Orientales and Cajones wetlands are non-detectable from the satellite data, and in fact both Bolivian wetlands appear to evaporate at a greater rate than the 'undisturbed' Quebrada Negra wetland, although this is within the expected margin of error for this method.

Having established that the channelization of the wetlands in Bolivia does not seem to have affected the areal extent of the wetlands, or to have had a significant effect on evaporation rates, we turn again to the field studies reported by Muñoz and Suárez (2019) to provide further insights into wetland function. A very detailed groundwater monitoring programme (82 monitoring points, with groundwater head measured at two different depths at each location, see Figure 17) has been put in place.

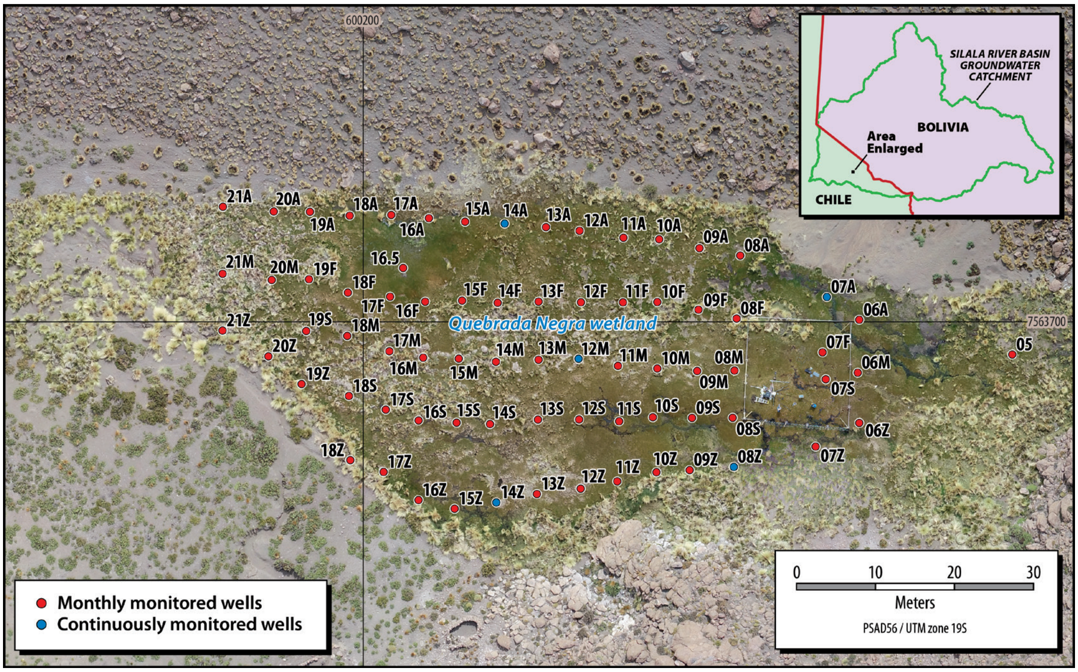

Figure 17. Layout of the monitoring wells in the Quebrada Negra wetland. Location with sensors for continuous groundwater level monitoring are depicted in blue (Muñoz and Suárez, 2019).

Results to date have shown that the areas of groundwater inflow to the wetlands are quite heterogeneous. In fact, over much of the valley floor, the hydraulic gradients show downwards flow (Figure 18) – and clearly in such areas, a drainage channel would not affect groundwater emergence. Areas of upwelling arise at the upper boundary of the wetland, along the base of the hillslopes that surround the wetland, and only in limited locations within the main wetland itself. This perhaps explains why the apparent effects of the drainage channels on the Bolivian wetlands, in terms of spatial extent, wetland function, and evaporation, have been more limited than might have been expected by Bolivia.

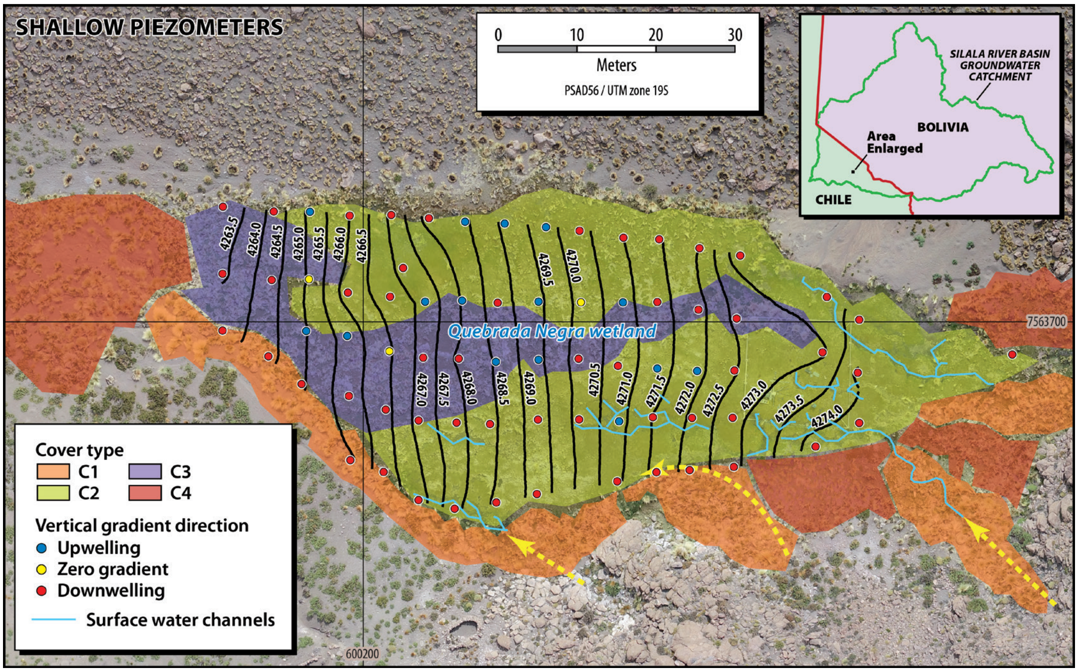

Figure 18. Contour lines of groundwater levels (m.a.s.l.), at shallow piezometers, measured during September 2018 at the main grassland of the Quebrada Negra wetland. Red circles represent points where positive gradient (downwelling) was observed, blue circles represent the points where negative gradient (upwelling) was observed and yellow circles represent points where zero-gradient was observed. Surface channels observed in the wetland are identified as light blue lines. Apparent surface water sources are marked with dashed yellow lines, and C1-C4 are vegetation cover types as defined by Muñoz and Suárez (2019).

6 CONCLUSIONS

(i) What are the major points of scientific agreement between the Experts of Bolivia and those of Chile concerning the hydrology of the Silala River?

We and Bolivia’s experts agree that:

1. The Silala River flows naturally from Bolivia to Chile. The river rises in two sets of springs in Bolivia, which maintain the Cajones and Orientales wetlands.
2. The river is primarily fed by groundwater and interacts with groundwater along its course to the border and beyond.

3. In addition, there are substantial groundwater flows from Bolivia to Chile, likely of an equivalent magnitude to the surface water flows.
4. Construction of drainage channels and river channelization in the 1920s will have had some effect on the flow. An increase in flow due to these works is expected.
5. The impact of drainage on evaporation from the wetlands is small.

(ii) What are the major points of scientific disagreement between the Experts of Bolivia and those of Chile concerning the hydrology of the Silala River?

We and Bolivia's experts disagree about the magnitude of the impact of the drainage works. In our opinion, Bolivian estimates of a 30-40% effect on flows are implausible. These estimates have been produced by a Near Field model of surface water-groundwater interactions. We have shown that the model is based on incorrect geology, that simple calculations show that incorrect assumptions of the model's boundary conditions lead to an overestimate of the impacts, by a factor of approximately 20, and that the change in inputs to the model is unrealistic.

(iii) What new evidence has been produced, since Chile submitted its Memorial in July 2017, concerning the effect of the channelization of the flow on Bolivian territory on the watercourse of the Silala River that flows from Bolivia into Chile?

New studies based on detailed monitoring of an undisturbed Chilean wetland within the Silala basin, coupled with high resolution remote sensing data, show that Bolivian and Chilean wetlands continue to fully occupy the valley floor, and seasonally extend up the base of adjacent hillslopes. The condition of the wetland vegetation, as indicated by remote sensing, is similar in all three wetlands, and associated estimates of actual evaporation suggest that the higher evaporation rates are observed from the Cajones and Orientales wetlands, some 10% greater than that of the undisturbed Quebrada Negra wetland. At least from the satellite data, it appears that there has been no significant change in evaporation associated with the channelization of the Bolivian wetlands, and hence no effect of evaporation change on river flows.

In summary, we remain confident that the effects of the drainage works on evaporation are quite limited, as stated in Chile's Memorial, at most equivalent to a flow of 2-3 l/s on average, i.e. some 2% of the natural flow, but in the light of our recent results, probably less. Other effects will be similarly small. Bolivia's estimates of 30-40% changes in river flow are due to errors in DHI's modelling and are implausible. We also reiterate that there is no doubt that the Silala River is an international watercourse, and we are pleased to note the agreement of Bolivia's experts on this point.

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APPENDIX 1

SIMPLIFIED CALCULATION OF HILLSLOPE GROUNDWATER FLOWS

A simplified analytical calculation of groundwater flow in an idealized hillslope is used to demonstrate that DHI's use of a fixed head boundary condition for the Near Field modelling of the Bolivian wetlands leads to exaggerated impacts on groundwater flows to the wetland, in response firstly to changes in wetland water table elevation and secondly to the presence of a peat layer of reduced hydraulic conductivity.

1. Groundwater response to change in wetland water table elevation

We adopt, for demonstration purposes, the groundwater head field proposed by DHI (BCM, Vol. 3, p. 488, Figure 11) (see Figure A1 below).

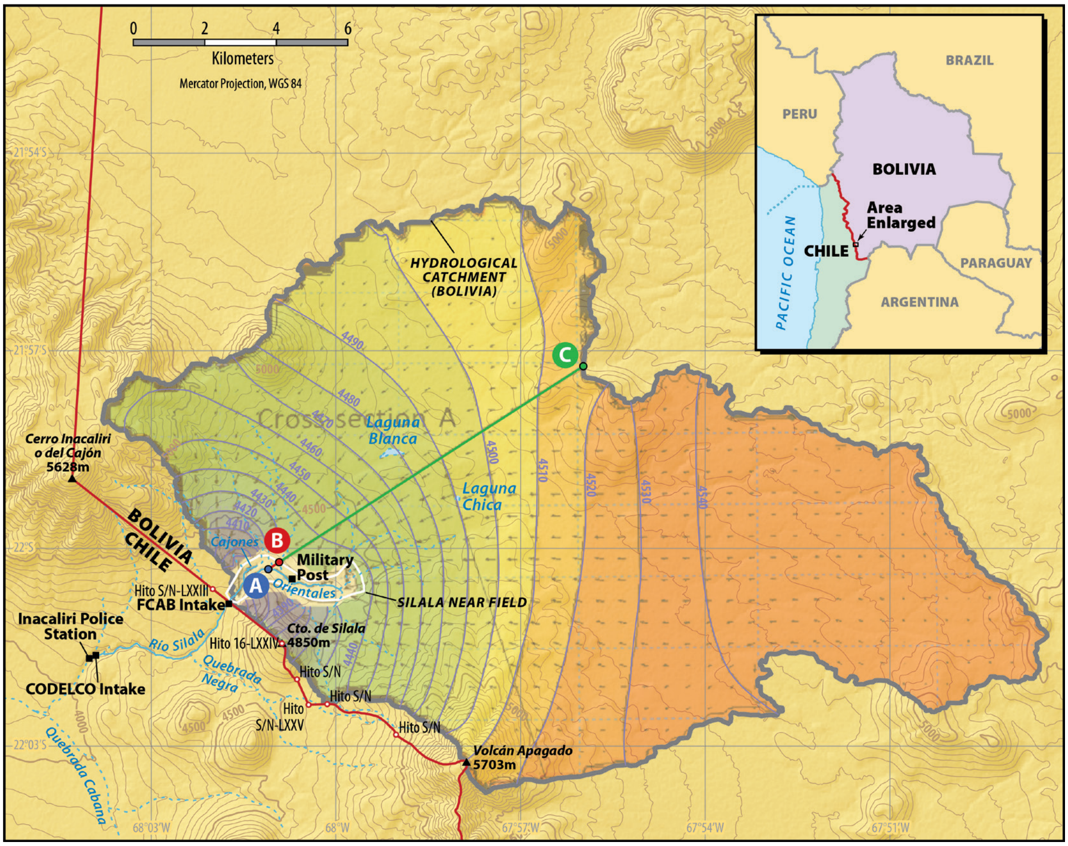

Figure A1. Simulated groundwater potential (head) in the Ignimbrite aquifer, adapted from DHI's Annex E, Figure 11 (BCM, Vol. 3, p. 488).

We consider an idealized hillslope, which represents groundwater flow in an aquifer discharging to a wetland, and consider flow paths of two different lengths, informed by cross-sections AB and AC on Figure A1. A fixed head boundary condition at the far field boundary C is compared with DHI's assumption of a fixed head at the Near Field boundary B to demonstrate the effect of the boundary condition assumption on the calculation. The water table elevation in the wetland is taken as the downstream boundary condition.

We consider a text book calculation (see Verruijt, 1970, p. 53), as shown in Figure A2 below, of one-dimensional steady groundwater flow, for a cross–section of unit thickness, under the assumption that flow is approximately horizontal (the well-known Dupuit-Forchheimer approximation (Dupuit, 1863; Forchheimer, 1886)), which means that the groundwater head can be taken as equal to the water table height.

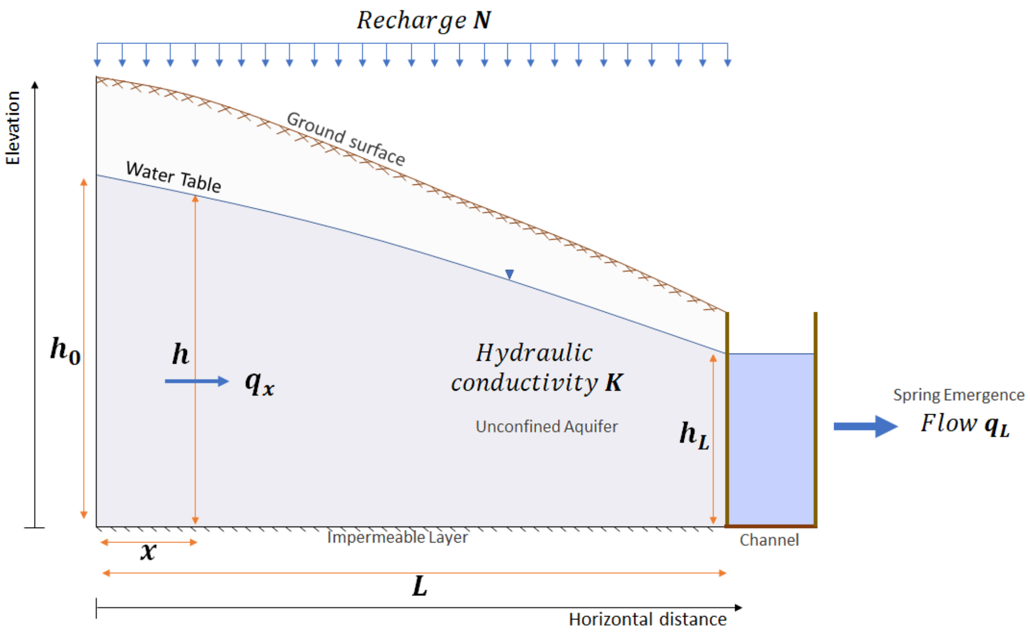

Figure A2. Schematic of groundwater hillslope flow, from fixed head upslope boundary to fixed head wetland water table elevation.

Darcy's Law relates the groundwater flow velocity through a cross-sectional area of aquifer to the gradient of groundwater potential, or head.

Hence from Darcy's law,

$$v_x = -K\frac{dh}{dx}$$

where v_x is the groundwater flow velocity (m/day), h is the 'head' or water table elevation (m), K the hydraulic conductivity (m/day) and x the horizontal length dimension (m).

If we introduce a recharge rate (i.e. precipitation-evaporation) N (m/day), then from conservation of mass,

$$N = v_x \frac{dh}{dx} + h \frac{dv_x}{dx}$$

And it can simply be shown that

$$\left(\frac{K}{2}\right) \frac{d^2(h^2)}{dx^2} + N = 0$$

For a hillslope of length L, with constant head boundaries h_0 and h_L, if q_L is the discharge per unit width (m^3/day/m), known as the specific discharge,

$$q_L = \frac{K\left(h_0^2 - h_L^2\right)}{2L} + \frac{NL}{2}$$

For the **Near Field** calculation, based on the DHI simulation in Figure A1 above and the flow path from B to A, the difference in heads is taken as the difference between elevation 4370 m.a.s.l. and 4385 m.a.s.l., i.e. 15 m, with a path length of 360 m. We take DHI's recharge rate of 24 mm/year (BCM, Vol. 3, p. 478), hydraulic conductivity K = 4.3 m/day (BCM, Vol. 5, p. 21, Table 3) and a 400 m deep aquifer below the wetland as proposed by DHI (BCM, Vol. 5, p. 17), and assume a 0.5 m rise in wetland water table if the channels are removed (Figure A3).

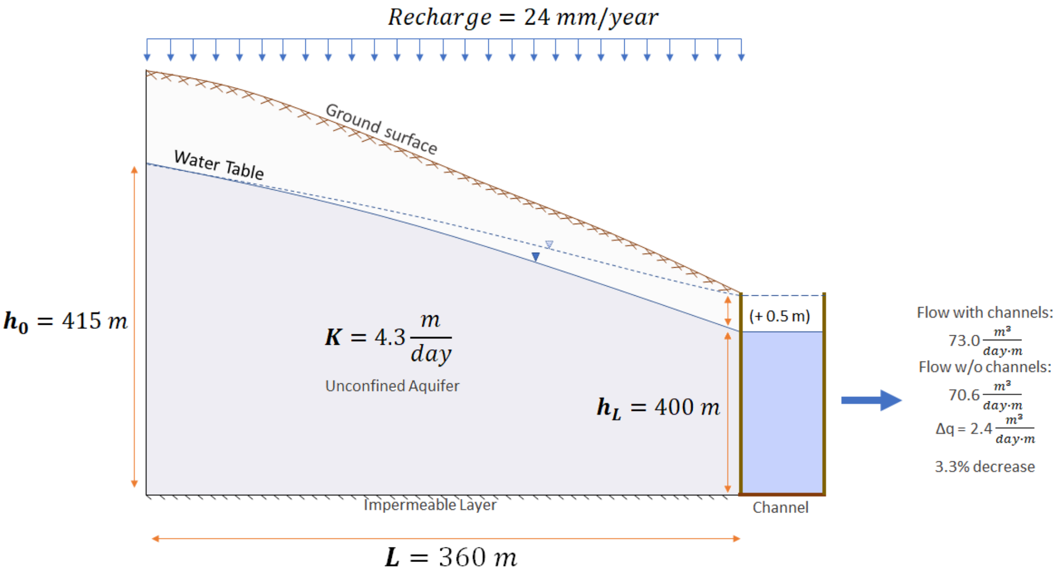

Figure A3. Schematic for Near Field flow path discharge calculation.

Similarly, for the **Far Field**, the difference in heads is taken, again from DHI (2018) and based on flow path CA, as the difference between elevation 4520 m.a.s.l. and 4370 m.a.s.l., i.e. 150 m, with a path length of 10500 m (Figure A4).

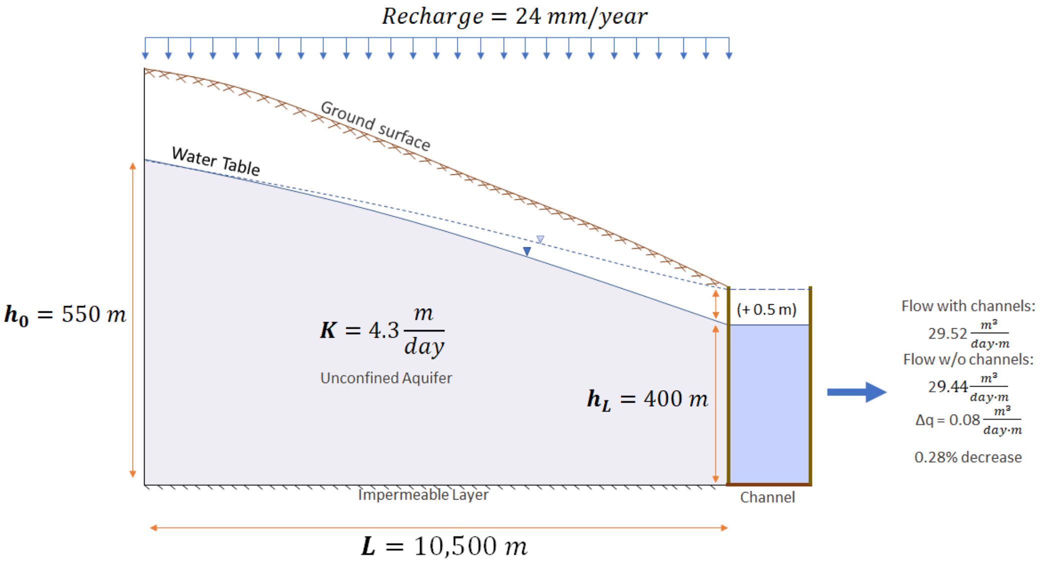

Figure A4. Schematic for Far Field flow path discharge calculation.

The results are summarized in Table A1 below, and show that the incorrect assumption of a fixed head at the near field boundary increases the effect of a water table rise by a factor of 12.

		Groundwater discharge $m^3/m/day$
NEAR FIELD	With channel in place	73.0
	With channel removed 0.5 m water table rise	70.6
	% decrease in flow	3.3%
FAR FIELD	With channel in place	29.5
	With channel removed 0.5 m water table rise	29.4
	% decrease in flow	0.28%
RATIO of % CHANGE		**11.8**

Table A1. Summary of results – channel removal/water table rise.

2. **Groundwater response to the presence of a peat layer of reduced hydraulic conductivity**.

DHI assumes that over a long period of time, in the absence of disturbance, an increased depth of peat will develop in Bolivia's wetlands (BCM, Vol. 5, p. 70). As the peat is expected to have relatively low hydraulic conductivity, DHI argue that this will reduce the groundwater discharge to the wetland. Here, we demonstrate that if such an effect were to occur, its estimated magnitude would be grossly exaggerated by the assumption of the fixed head boundary condition in DHI's Near Field model. We adopt the same approach as in example 1 above, i.e. we use a simplified representation of the groundwater flow, which can be solved analytically, to indicate the nature and potential magnitude of this erroneous assumption.

For this analysis, we assume that groundwater will flow downslope through a groundwater aquifer to the wetland area, and emerge though a peat layer that underlies the wetland, as shown schematically in Figure A5, below. As noted by DHI (BCM, Vol. 2, p. 279), the depths of peat range typically from 0.2 to 1.0 m in the wetlands, and the drainage channels are said to cut through most of the wetland soils. We therefore assume two cases; one with no peat cover, the other – a notional undisturbed condition - has 1 m depth of peat.

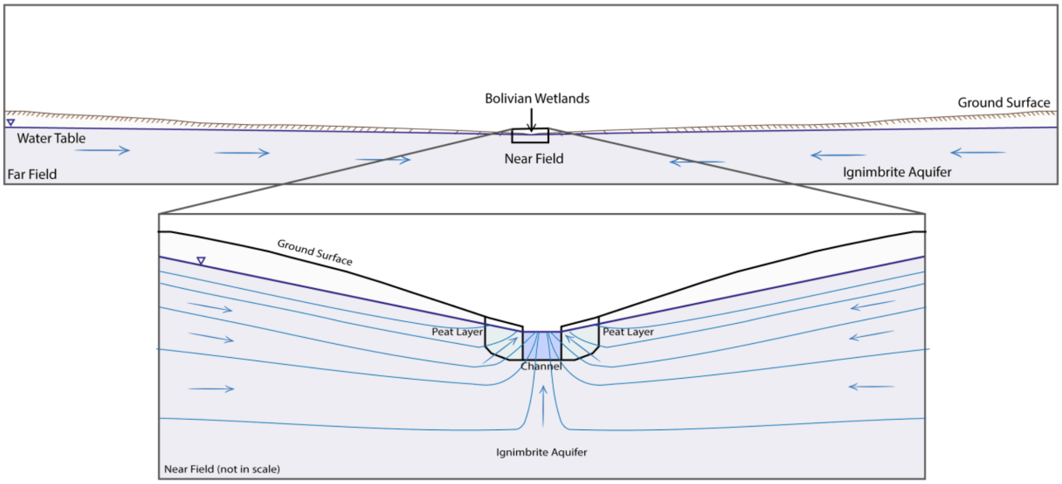

Figure A5. Schematic representation of hillslope and valley bottom flow paths, showing near field and far field domains.

We represent the effect of a layer of reduced permeability on the groundwater flow path by introducing a section of reduced permeability at the base of the hillslope, as shown in Figure A6, where $d_2 = 1$ m.

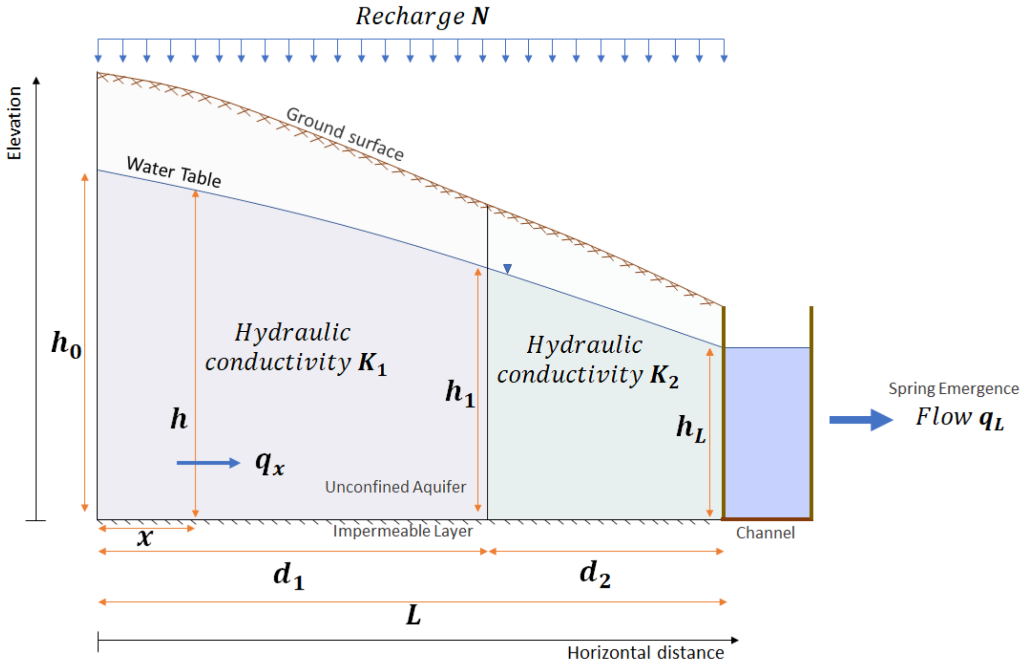

Figure A6. Schematic for flow path discharge calculation.

For uniform steady state groundwater flow, with recharge N, the relationship for specific groundwater discharge q_A in the A domain (left hand zone) is given by:

$$q_A(x_1) = Nx_1 - \frac{Nd_1}{2} + \frac{(h_0^2 - h_1^2)}{2d_1} K_1$$

In addition, the specific groundwater discharge q_B in the B domain (right hand zone) is given by:

$$q_B(x_1) = N(x_1 - d_1) - \frac{Nd_2}{2} + \frac{(h_1^2 - h_L^2)}{2d_2} K_2$$

By mass balance conservation: $q_A(d_1) = q_B(d_1)$. From this, the value of h_1, the hydraulic head value at $x_1 = d_1$ is:

$$h_1 = \sqrt{\frac{N(d_1 + d_2) + \frac{K_1 h_0^2}{d_1} + \frac{K_2 h_L^2}{d_2}}{2m}}$$

Where

$$m = \frac{K_1}{2d_1} + \frac{K_2}{2d_2}$$

Hence, the specific discharge rate q at $x_1 = d_1 + d_2$ is:

$$q = \frac{Nd_2}{2} + \frac{(h_1^2 - h_L^2)}{2d_2} K_2$$

The dimensions and principal parameters are as used in Figures A3 and A4 above. Here we reduce the permeability by two orders of magnitude for a peat layer of 1 m thickness, to a value of 0.043 m/day, typical of DHI's estimates for a peat soil. The Near Field simulation shows a 22% decrease in flow due to the 1 m peat layer, and a total decrease of 24% if the water table is increeased by 0.5 m. The Far Field simulation shows a 1% decrease due to the peat layer, and a 1.2% decrease if in addition the water table rises by 0.5 m.

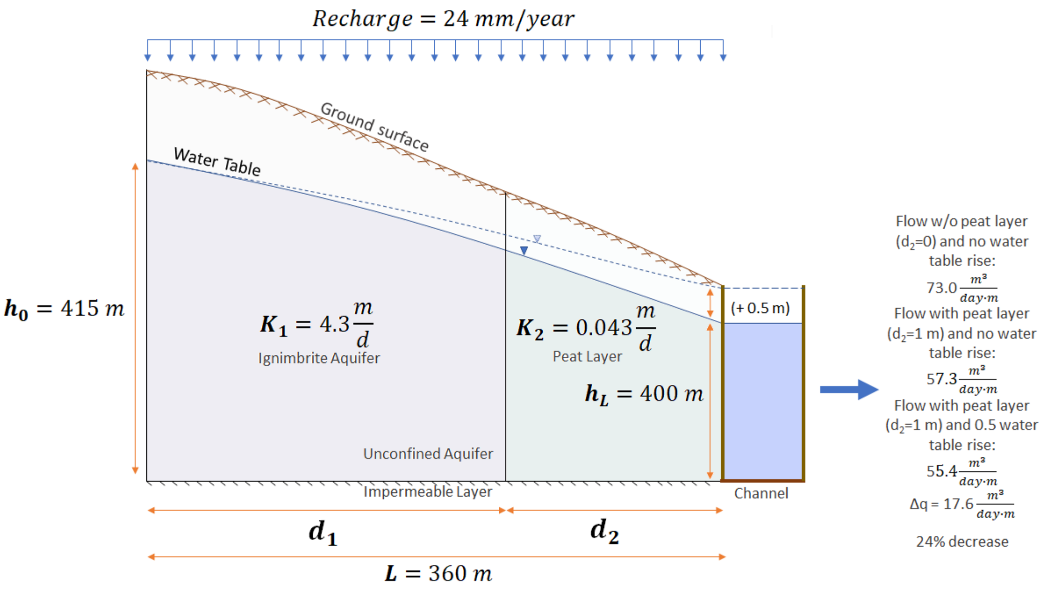

Figure A7. Schematic for Near Field flow path discharge calculation.

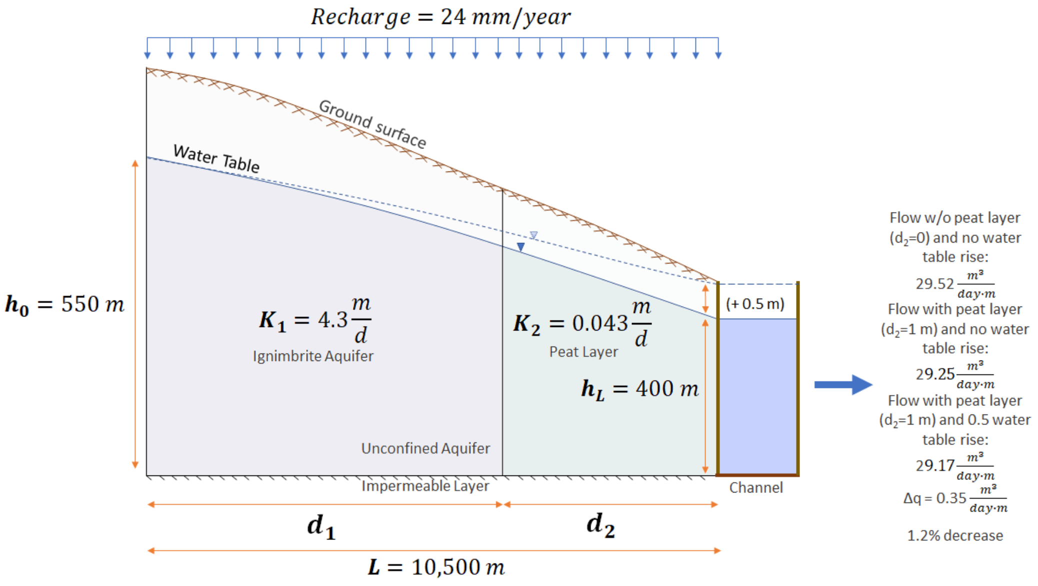

Figure A8. Schematic for Far Field flow path discharge calculation.

		Groundwater discharge m3/m/day
NEAR FIELD	With channel in place	73.0
	With 1m peat layer	57.3
	% decrease in flow	21.6%
FAR FIELD	With channel in place	29.5
	With 1 m peat layer	29.2
	% decrease in flow	0.9%
RATIO of % CHANGE		**23**

Table A2. Summary of results – impacts of peat layer of 1 m thickness.

		Groundwater discharge m3/m/day
NEAR FIELD	With channel in place	73.0
	With channel removed 0.5 m water table rise and 1 m peat layer	55.4
	% decrease in flow	24.1%
FAR FIELD	With channel in place	29.5
	With channel removed 0.5 m water table rise and 1 m peat layer	29.2
	% decrease in flow	1.2%
RATIO of % CHANGE		**20**

Table A3. Summary of results – impacts of peat layer and channel removal/water table rise.

3. Conclusions

While these calculations are simplified, they nevertheless show convincingly that an inappropriate choice of a fixed water table elevation at the Near Field boundary exaggerates the effects of water table rise and increased hydraulic resistance, by the order of a factor of 20.

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Expert Report

Peach, D.W. and Wheater, H.S., *Concerning the Geology, Hydrogeology and Hydrochemistry of the Silala River Basin*

CONCERNING THE GEOLOGY, HYDROGEOLOGY AND HYDROCHEMISTRY OF THE SILALA RIVER BASIN

Drs. Denis Peach and Howard Wheater

January 2019

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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 46 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, 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 has given the prestigious Ineson Distinguished lecture at the GSL. He has led geological and hydrogeological research programmes in the UK and has sat on several 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.

Dr. Howard Wheater

Dr. Howard Wheater is the Canada Excellence Research Chair Laureate in Water Security at the University of Saskatchewan and was founding Director of the Global Institute for Water Security. He also holds the posts of Distinguished Research Fellow and Emeritus Professor of Hydrology at Imperial College London. A leading expert in hydrological science and modelling, he has published more than 200 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 was instructed by Hungary and Argentina at the International Court of Justice, and recently sat on the Court of Arbitration concerning the Indus Waters Treaty. He was, until 2014, vice-chair of the World Climate Research Programme’s Global Energy and Water Cycle Exchange (GEWEX) project and leads 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. His role as Chair of the Council of Canadian Academies Expert Panel on Sustainable Management of Water in the Agricultural Landscapes of Canada saw release of a report in February 2013 entitled Water and Agriculture in Canada: Towards Sustainable Management of Water Resources. In 2018 he was the only non-US member of a US National Academies panel that reported on Future Water Priorities for the Nation.

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LIST OF ACRONYMS AND ABREVIATIONS

BCM - Bolivian Counter-Memorial
ca - About or approximately
CM - Chilean Memorial
cm - Centimetre
DHI - Danish Hydraulic Institute
GML - Global Meteoric Water Line
LML - Local Meteoric Water Line
l/s - Litres per second
Ma - Million years before present
SERGEOMIN (Bolivia) - Servicio Nacional de Geología y Minería de Bolivia (Bolivian National Geology and Mining Service)
SERNAGEOMIN (Chile) - Servicio Nacional de Geología y Minería de Chile (Chilean National Geology and Mining Service)
pMC - Percent modern carbon
µS/cm - Micro siemens per centimetre
^{13}C - Carbon-13
^{14}C - Carbon-14
^{2}H - Deuterium
$\delta^{2}H$ - Ratio of deuterium and hydrogen
^{18}o - Oxygen-18
$\delta^{18}O$ - Ratio of oxygen-18 (^{18}O) and oxygen-16 (^{16}O)

1 INTRODUCTION

1.1. Experts' Terms of Reference

In the context of the dispute between the Republic of Chile and the Plurinational State of Bolivia concerning the status and use of the waters of the Silala, to be heard before the International Court of Justice, the Republic of Chile has requested our independent expert opinion, as follows:

> "Questions for Dr. Howard Wheater, as a hydrological engineer
>
> (i) What are the major points of scientific agreement between the Experts of Bolivia and those of Chile concerning the hydrology of the Silala River?
>
> (ii) What are the major points of scientific disagreement between the Experts of Bolivia and those of Chile concerning the hydrology of the Silala River?
>
> (iii) What new evidence has been produced, since Chile submitted its Memorial in July 2017, concerning the effect of the channelization of the flow on Bolivian territory on the watercourse of the Silala River that flows from Bolivia into Chile?
>
> Questions for Dr. Denis Peach, as a hydrogeologist
>
> (i) What new evidence has been produced, since Chile submitted its Memorial in July 2017, concerning the understanding of the geology and hydrogeology of the Silala River?
>
> (ii) Does the hydrogeological conceptual understanding and parameterisation of the numerical models of Bolivia's expert, the Danish Hydraulic Institute (DHI), provide an adequate

basis to quantify the effects of channelization on the surface water and groundwater flows from Bolivia to Chile?

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

In this report we consider the three questions to Peach. The questions to Wheater are addressed in Wheater and Peach (2019). While this report represents our joint opinion, the lead author has been Dr. Denis Peach.

1.2. Background to the report

In 2016 we were requested by the Republic of Chile to write two expert reports on the Silala River, which were subsequently submitted to the International Court of Justice in July 2017 as part of Chile's Memorial (Wheater and Peach, 2017; Peach and Wheater, 2017). At that time, the core of the dispute between Chile and Bolivia was whether or not the Silala River is an international watercourse.

Following submission of the Bolivian Counter-Memorial (BCM) on 3 September 2018, we were requested to write expert reports to comment on the scientific underpinning for the counter claims made by the Plurinational State of Bolivia.

We now understand that there is agreement between the parties on the central point that the Silala River naturally flows from Bolivia to Chile. And as discussed in Wheater and Peach (2019), there is also general agreement between Bolivia's and Chile's experts about the nature and functioning of the natural hydrological system.

The core of the remaining dispute between Chile and Bolivia is the quantitative effect of the channelization of the Silala, in Bolivian territory, on the cross-boundary flow. The Bolivian expert consultant, Danish Hydraulic Institute (DHI), estimates that the natural flows without drainage and channelization would be 30-40% less than the current situation (BCM, Vol. 2, p. 266). We disagree with the DHI estimates of the effects of channelization. In our opinion the very large estimates made by DHI are implausible.

DHI's estimates are wholly based on the results of a DHI integrated groundwater and surface water model, which purports to represent the natural hydrological system that supplies spring flow to the headwaters of the Silala River. In this report we examine the conceptual basis for the construction of the DHI numerical model. We draw on further geological and hydrochemical investigations carried out during 2018, subsequent to the submission of Chile's Memorial (CM), to improve our knowledge and understanding of the geology and hydrogeological functioning of the Silala River and associated groundwater flows. We show below that the DHI modelling is based on a flawed interpretation of the geology, hydrogeological and hydrogeochemical functioning of the basin, and therefore has no validity as a basis for detailed modelling of the effects of channelization on surface water or groundwater flows.

1.3. Structure of the report

Section 1 describes the background to the report, its structure and the location of the Silala River, ravine and catchment area. Section 2 answers the question posed and briefly summarizes the major findings. Section 3 provides a description of the geology of the Silala River basin, its ravine and groundwater catchment area, and highlights the shortcomings of the DHI interpretations and evidence upon which they have based their numerical model. Section 4 describes the hydrochemistry of the surface and groundwaters of the Silala River basin and the origin of the groundwaters and surface water of the basin and the significance of the origins for groundwater modelling. Section 5 summarizes the hydrogeology of the Silala

River basin. Section 6 assesses the evidence for the enhancement of spring flows by explosive methods as stated in the BCM. Section 7 draws some conclusions and answers the questions for Dr. Denis Peach, as a hydrogeologist. Section 8 lists the references cited in this report.

1.4. Silala River basin – location and spatial extent

The Silala River originates in Bolivia and flows into the Antofagasta Region of Chile. It is one of the main tributaries of the San Pedro River. This, in turn, is a tributary of the Loa River, the longest river in Chile (440 km long) and the main watercourse in the Atacama Desert region, discharging into the Pacific Ocean. More detail about the location is provided in the Chilean Memorial (CM, Vol. 1, pp. 137-144).

Figure 1-1 shows the topographic catchment area of the Silala River and key features of the river network. In CM, we noted the possibility of groundwater recharge and inflows from areas beyond the topographic catchment, within Bolivia (CM, Vol. 4, p. 273, Figure 7-1; Arcadis, 2017). Figure 1-1 shows an estimate of this extended groundwater catchment, based on topographic and geological analysis. This area is very similar to that identified by DHI as the 'hydrological catchment' (BCM, Vol. 2, Figure 5, p. 275) of the Silala River (with minor differences due to the use of a different Digital Elevation Model), although we, and DHI (BCM, Vol. 4, p. 103), acknowledge that it is possible that there may be additional groundwater contributions from other, more distant, sources.

We note that the river originates in groundwater springs at the Cajones and Orientales wetlands in Bolivia, which are the main source of its perennial flow at the international border. The water supplying these springs is predominantly derived from precipitation on the extended groundwater catchment area in Bolivia, though the river also receives water from springs in Chile that are fed, at least in part, from the topographic catchment area. The Chilean and Bolivian experts agree that surface water runoff contributes a very minor proportion of the average daily flow of the Silala River. In this report we discuss the geology of the extended groundwater catchment, and hence the hydrogeological controls on surface water and groundwater flows from Bolivia to Chile, informed by recent analyses of water chemistry. In particular, we highlight important features of the geology and geochemistry that Bolivia's modelling fails to represent.

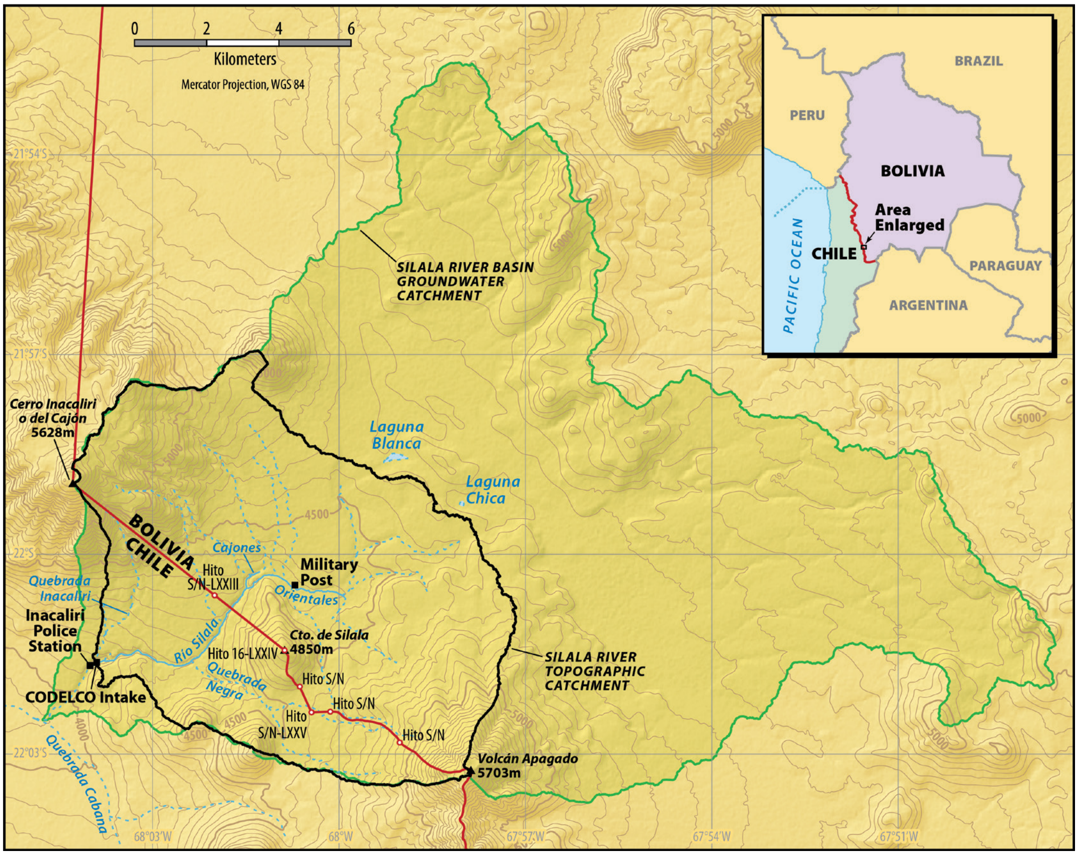


Figure 1-1. The Silala River (perennial drainage solid blue and ephemeral streams in dotted blue lines) and topographic catchment area (outlined in black), showing some of the main physiographic features in and around the catchment. The extended groundwater catchment area for the Silala River is shown in green and includes a large area in Bolivian territory.

2 SUMMARY OF FINDINGS

In this section we briefly answer the questions posed in our terms of reference and summarise our conclusions.

(i) What new evidence has been produced, since Chile submitted its Memorial in July 2017, concerning the understanding of the geology and hydrogeology of the Silala River?

New investigations in the Silala River topographic catchment have included field observation, re-logging of borehole drill cuttings, geological mapping and radiometric dating of the Chilean-named Silala Ignimbrite and Pliocene lavas. This new information has revealed a more detailed understanding of the stratigraphy in Chile and the extensive presence of a debris flow that lies at the base of the Chilean-named Silala Ignimbrite and the upper boundary of the Chilean-named Cabana Ignimbrite. It has also revealed a major fault in Chile, a few hundred metres below the junction of the Silala River and the Quebrada Negra tributary valley. The stratigraphy and this structure have not been considered in the Bolivian hydrogeological conceptual understanding, or incorporated into their numerical models. DHI introduce a new fault system running through the Bolivian wetlands and down the Silala River ravine into Chile (DHI, 2018), but no evidence to support this has been found in Chile.

New hydrogeochemical investigations have revealed the distinct character of the spring and groundwater of the Quebrada Negra. And in conjunction with the Chilean data, Bolivian chemical and isotopic analyses have revealed: a) the distinctly different recharge origins of the spring water of the Bolivian wetlands, Cajones (referred to in DHI, 2018 as the North Wetland or Bofedal) and Orientales (referred to in DHI, 2018 as the South Wetland or Bofedal), and b) the close similarities of the Chilean spring waters, recharged from perched aquifers, to the spring and groundwaters of the Cajones wetland in Bolivia. As with the geological structure and stratigraphy, above, this important difference in recharge to the two Bolivian springs is not incorporated in DHI's modelling.

(ii) Does the hydrogeological conceptual understanding and parameterisation of the numerical models of Bolivia's expert, the Danish Hydraulic Institute (DHI), provide an adequate basis to quantify the effects of channelization on the surface water and groundwater flows from Bolivia to Chile?

The DHI numerical models incorporate an incorrect stratigraphy and an implausible fault system and take no account of the down-gradient Chilean geological structure or the difference in origin of the Cajones and Orientales spring waters. In particular,

a. The ignimbrite aquifer system identified in Chile (the Chilean Silala and Cabana Ignimbrites), together with an interbedded fluvial debris flow has not been recognized by DHI in their report (DHI, 2018), nor incorporated into their models, neither has the vertical heterogeneity in permeability. This will undoubtedly mean that the groundwater flowpaths that they simulate as a result of their models' permeability distribution will be wrong.

b. The fault system that they propose will also affect the groundwater flowpaths and the ease with which groundwater can move in their invoked fault system region.

c. The different origins of the Cajones and Orientales spring waters are due to the two distinct aquifer systems identified by Chile (with considerable supporting evidence (sections 3, 4 and 5)), but these have not been included in the DHI models.

d. The faulting mapped at outcrop downgradient in Chile and the presence of Pliocene lavas (sections 3 and 5) between the two (Chilean) ignimbrites (in Chile) which cause a decline in the permeability of the Cabana and Silala Ignimbrites in Chile has similarly not been considered.

We conclude that the DHI models do not simulate the groundwater system properly and are unfit to quantify the effects of channelization in the Bolivian wetlands or accurately represent the current hydrological system.

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

The evidence for showing that the groundwater-fed springs of the Cajones and Orientales wetland has been enhanced by explosives is flimsy and the reference to development of deep borehole yields by explosive methods is inapplicable. The springs could not have been developed significantly to increase yields by the explosive methods suggested by Bolivia.

In summary, we have shown that the numerical modelling results that have been presented by Bolivia to demonstrate the alleged effects of channelization in the Bolivian wetlands are incorrect. Their models are based on a misrepresentation of the current hydrological system and the proposed scenarios. In short, with this conceptual basis, their models could only produce implausible predictions.

3 GEOLOGY OF THE SILALA RIVER, RAVINE AND GROUNDWATER CATCHMENT AREA

In this section, we discuss why Bolivia's geological interpretation of the Silala groundwater catchment is incorrect in several important respects. This interpretation provides the basis for their understanding of the hydrogeology of the catchment and hence for the construction of the numerical models developed by the Bolivian experts, DHI (DHI, 2018), to simulate groundwater and surface water flows within the Silala River basin. The geological interpretation presented by DHI is implausible, and inconsistent with Chile's data. Hence, we conclude that DHI's modelling is flawed and unsuitable as a basis for predicting the effects of channelization.

3.1. The geological context of the Silala River

The regional scale geology in an area of approximately 20 km radius around the Silala River is dominated by volcanic rocks. The outcrops of these rocks provide evidence of the volcanic processes occurring in the region over the last approximately 12 Ma (SERNAGEOMIN (Chile), 2017). Volcanism is often episodic and between these events there may be periods of erosion and deposition of sediments. Some of the oldest volcanic rocks that are exposed in this region include sequences of ignimbrite rocks. These are permeable and form the major aquifers in the region.

Covering the volcanic rocks are alluvial and colluvial sediments consisting of sands, gravels including boulders and silts. These form minor local perched aquifers in the Silala basin in Chile. Here they provide flows to many springs, particularly along the northern side of the Silala River ravine.

Ignimbrites are deposited from explosive volcanic eruptions that extrude a mix of volcanic gases, molten rock and ash in a highly fluid pyroclastic flow, flowing under gravity at speeds of at least 100 km/hour (Wilson and Houghton, 2000). Such flows are very destructive and tend to fill depressions and valleys in the existing topography. They often travel long distances, up to tens of kilometres. The other extrusive volcanic rocks that outcrop in the region, including the Silala catchment, are lavas, which consist of more or less fluid molten rock. These lavas erupted in a less explosive manner than the ignimbrites. They would have flowed down-gradient from a volcanic vent, often at very low velocities, and travelled much shorter distances. They can normally be seen around volcanoes, outcropping radially around the volcanic centre, and often appear like lobes. These can be seen on Figure 3-1 (e.g. PPlv – in purple and Msv – in pale brown) and Figure 3-2 (e.g.Pliv(a) – in purple and Msvd- in pale brown) and reflect the way the lava flows have moved down slope from the eruption vent. The younger lava flows, if andesitic or basaltic, are often permeable. Other rocks that outcrop high on the sides of the volcanoes include glacial till, composed of rock fragments in a matrix of clay. These were deposited by glaciers in the Pleistocene ice ages and normally have low permeabilities. Fluvial debris flows are common in volcanic regions and their sedimentary nature provides a high porosity in which to store groundwater and can provide high intergranular permeability. Because of their different permeabilities, a numerical model must be built on a correct interpretation of the geological sequences.

As part of the studies and investigations referred to in section 1.2, further field studies, geological mapping and rock dating have been carried out by the Chilean National Geology and Mining Service (SERNAGEOMIN), since the submission of Chile's Memorial in September 2017. These are reported in SERNAGEOMIN (Chile), 2019.

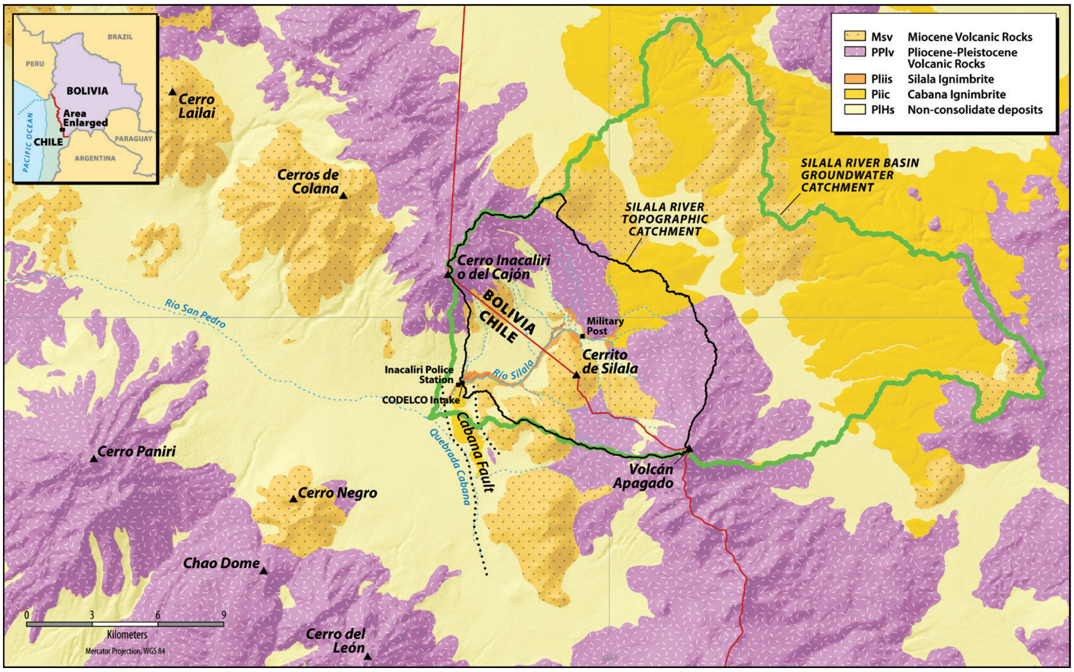


Figure 3-1. Synthesis of geology for the region in which the Silala River basin is located. Solid black line corresponds to the topographic catchment area of the Silala River (SERNAGEOMIN (Chile), 2019). The green line corresponds to the extended groundwater catchment, as shown in Figure 3-2 (SERNAGEOMIN (Chile), 2019, amended from SERNAGEOMIN (Chile), 2017).

The rocks that can be found outcropping in the Silala River catchment are shown on the detailed geological map reproduced in Figure 3-2 (SERNAGEOMIN (Chile), 2019). This map has been compiled from the recently updated studies of SERNAGEOMIN (Chile), 2019; and from the report by SERGEOMIN (Bolivia), 2017. On Figures 3-1 and 3-2 the yellow colours represent ignimbrites and the purple and light brown colours represent different ages of lavas.

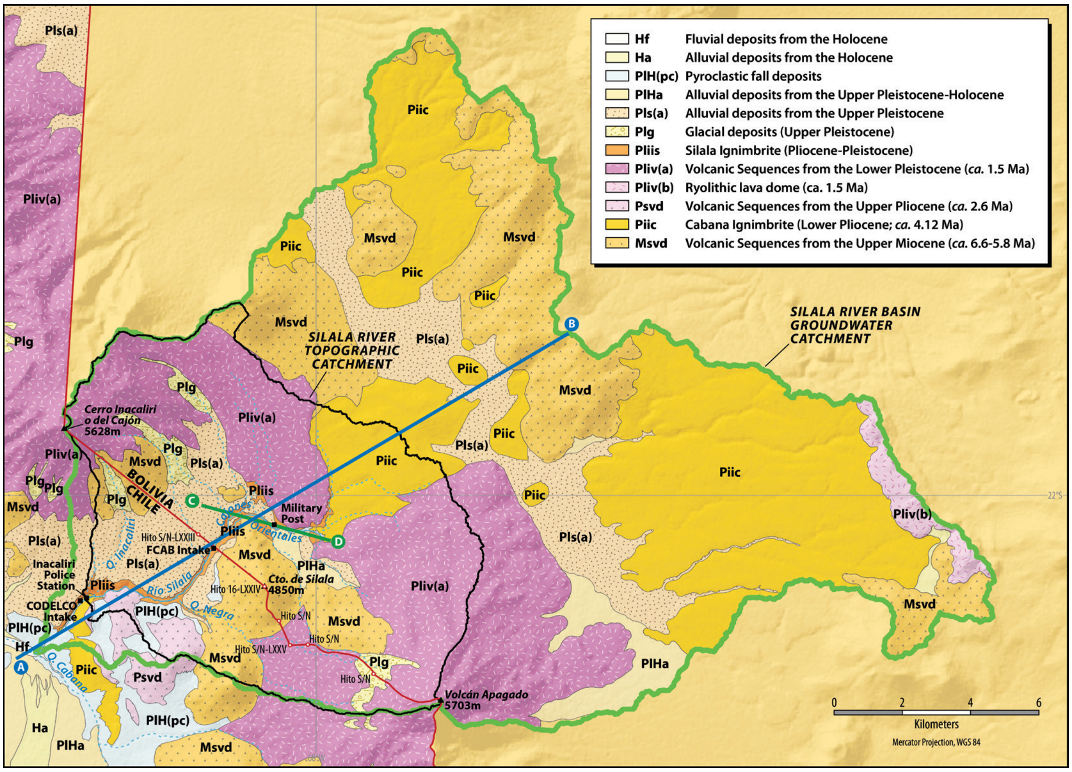


Figure 3-2. Map showing a compilation and interpretation of the geology of the Silala groundwater catchment (SERNAGEOMIN (Chile), 2019). This includes Bolivian territory and used Bolivian maps and data from SERGEOMIN (Bolivia), 2003 and 2017. The map shows the line, A-B, of the cross section on Figure 3-8 and the green line, C-D, of the cross-section, also on Figure 3-8.

The compilation shown in Figure 3-2 is in many respects similar to the maps in SERGEOMIN (Bolivia), 2017; but there are fundamental differences of interpretation that significantly affect the hydrogeology of the area and the construction of any numerical model. The first significant difference is in the sequence of geological layers and their age relationships. This is known as the stratigraphy, which is explained below in Section 3.2, and provides the fundamental underpinning for the geological interpretation. In section 3.3 we visualise the three-dimensional geology, from the edge of the Silala basin groundwater catchment in Bolivia across the international border into Chile, where the difference in Chilean and Bolivian stratigraphy is shown to lead to important differences in the geological structure that underpins the hydrogeology of the basin. This misinterpretation of the stratigraphic succession leads to an incorrect interpretation of the geology and consequently an incorrect hydrogeological conceptual understanding and model.

There are also differences in interpretation regarding the faulting of the geological sequence and, in particular, the existence of a fault system in the area of the Bolivian wetlands and down the Silala River ravine from Bolivia into Chile, proposed by Bolivia (Section 3.4). Large faults like this can provide high permeability groundwater pathways or conversely may be barriers to transverse groundwater flow.

As we discuss below in more detail, we conclude that DHI's numerical models are based on a misunderstanding of the hydrogeology, which will inevitably lead to errors in model predictions.

Figure 3-2 also shows the outcrops of more recent volcanic deposits in Bolivia, the presence of which is agreed by the parties. Overlying these are alluvial deposits and glacial deposits (SERNAGEOMIN (Chile), 2017 and 2019; Arcadis, 2017). Within the alluvial deposits there are perched aquifers, which are important in feeding springs along the Silala River in Chile. These also outcrop in Bolivia, and hydrogeochemical evidence suggests they are important in supplying a proportion of the spring waters that support the Bolivian Cajones and Orientales wetlands.

3.2. Stratigraphy

3.2.1. Stratigraphy of the Silala basin developed by Chile

In Chile, five main bedrock geological units have now been recognized in the Silala topographic catchment. Further radiometric age determinations of the rocks in these units have been used to help construct the stratigraphy shown in Figure 3-3. A compilation of the radiometric ages available is listed in Table 1.

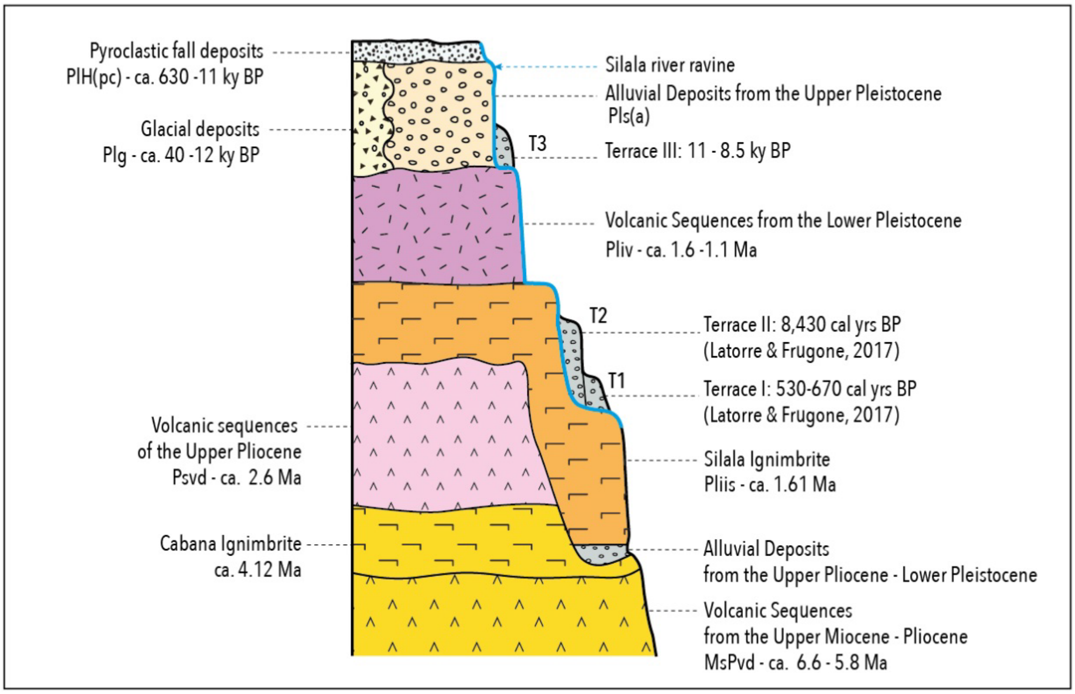


Figure 3-3. The updated integrated stratigraphic column of the Silala River basin as mapped in Chile (SERNAGEOMIN (Chile), 2019). The references for the radiometric dates are found in Table 1. (Here the debris flow, see below, is identified as "Alluvial Deposits from the Upper Pliocene-Lower Pleistocene").

In summary the stratigraphic succession of volcanic rocks, and including a debris flow, beginning with the oldest rocks outcropping in the Silala basin in Chile is as follows:

Volcanic Sequences from the Upper Miocene-Pliocene (MsPvd) ca 6.6 – 5.8 Ma (see Table 1). These comprise a series of volcanic rocks including domes, lava domes, lava flows and autoclastic breccia. This unit has been correlated with the older parts of the Inacaliri and Apagado volcanoes, which have been radiometrically dated at 5.8 Ma. They are less fractured than the Ignimbrites and are likely to be considerably less permeable.

Cabana Ignimbrite (Piic) ca 4.12 Ma (see Table 1). The Cabana Ignimbrite is a medium to poorly welded tuff of white and white-pinkish color with vesicular and dacitic pumice and subangular and angular lithics in an ash matrix. In Chile (SERNAGEOMIN (Chile), 2019) in borehole CW-BO at the international border, it was found to be over 53 metres thick. Recently an age date of 4.12 Ma (SERNAGEOMIN (Chile), 2017) has been determined. The Cabana Ignimbrite has been found, in an overflowing borehole (SPW-DQN) and in boreholes drilled in 2016, to support considerable groundwater flows (Arcadis, 2017).

Debris flow (date by stratigraphic position). A thin (20 cm) fluvial deposit can be seen at outcrop near the Inacaliri police station in Chile (SERNAGEOMIN (Chile), 2019) directly overlying the Cabana Ignimbrite and underlying the Silala Ignimbrite (see below). Borehole CW-BO, drilled very close to the international border was cored and a debris flow identified overlying the Cabana Ignimbrite (Arcadis, 2017; SERNAGEOMIN (Chile), 2017 and 2019). This was 13 metres thick but has been correlated with the fluvial deposits seen at outcrop, because a debris flow is a fluvial deposit and would be expected to become finer grained as it flows down gradient, while still occupying the same stratigraphic position in the geological succession. In a pumping test (Arcadis, 2017), the upper strata of the Cabana Ignimbrite and the debris flow were found to support groundwater flow.

Volcanic sequences from the Upper Pliocene (Psvd) ca 2.6 Ma (see Table 1). These dacitic lavas are of pale grey color and can be found at outcrop beneath the Silala Ignimbrite (1.61 Ma (see below)). They have been dated at 2.6 Ma and have also been found, in borehole MW-DQN, lying beneath the Silala Ignimbrite (SERNAGEOMIN (Chile), 2019). These lavas have low levels of fracturing and are likely to have low hydraulic conductivity.

Silala Ignimbrite (Pliis) ca 1.61 M (see Table 1). This ignimbrite is a welded tuff of andesitic composition. It is pink and has distinct cooling units or flow levels which can be seen dipping gently to the south west in the walls of the Silala River ravine in Chile. In SERNAGEOMIN (Chile), 2017, the age of deposits was bracketed at between 2.6 Ma and 1.48 Ma, since it overlies the dacitic lavas (2.6 Ma, see above) and is covered by an andesitic lava flow (Volcanic sequences of the Lower Pleistocene - 1.48 Ma, see Table 1) from the Inacaliri volcano in Bolivia. A new radiometric date of 1.61 Ma (see Table 1) confirms its stratigraphic position.

Pyroclastic Fall Deposits (PlH(pc)) ca 630 ka (see Table 1). These deposits comprise well-stratified fine to medium-grained ash found in the central and southern parts of the Chilean study area. Recently an age of 630 ka (see Table 1) has been determined for the ash deposits. These deposits form a thin capping to areas in the south of the topographic catchment and have a low hydraulic conductivity. Infiltration tests (Arcadis, 2017) gave a low infiltration capacity.

Age (Ma)	Unit	Reference
630±310 ka	Pyroclastic fall deposit	Blanco and Polanco, 2018
1.48 ± 0.02*	Volcanic sequences of the Lower Pleistocene	Almendras et al., 2002
1.612±0.018	Volcanic sequences of the Lower Pleistocene	Sellés and Gardeweg, 2017
1.61±0.08	Silala Ignimbrite (Chile)	Blanco and Polanco, 2018
1.74±0.02*	Nlsg-Volcanic sequences of the Lower Pleistocene	SERGEOMIN (Bolivia), 2003

Age (Ma)	Unit	Reference
2.6±0.4	Volcanic sequences of the Upper Pliocene	SERNAGEOMIN (Chile), 2017
3.2±0.4*	Ntpg-Ignimbritas Silala (Bolivian)	SERGEOMIN (Bolivia), 2017
4.12±0.08	Cabana Ignimbrite (Chile)	SERNAGEOMIN (Chile), 2017
5.84±0.09*	MPv2-Volcanic sequences of the Upper Miocene	Almendras et al., 2002
5.8±0.4*	MPv2-Volcanic sequences of the Upper Miocene	Almendras et al., 2002
6.04±0.07*	Volcanic sequences of the Upper Miocene	SERGEOMIN (Bolivia), 2003
6.63±0.06	Volcanic sequences of the Upper Miocene	Blanco and Polanco, 2018
6.6±0.5*	Nis-3-Silala Ignimbrites (Bolivian)	SERGEOMIN (Bolivia), 2017
7.8±0.3*	MPvl-Silala Ignimbrites (Bolivian Nis 1)	Ríos et al., 1997

Table 1. Compilation of the radiometric ages available from the Silala River area.

** Indicates a Bolivian radiometric date (SERGEOMIN (Bolivia), 2017), all other dates detailed in SERNAGEOMIN (Chile), 2019.*

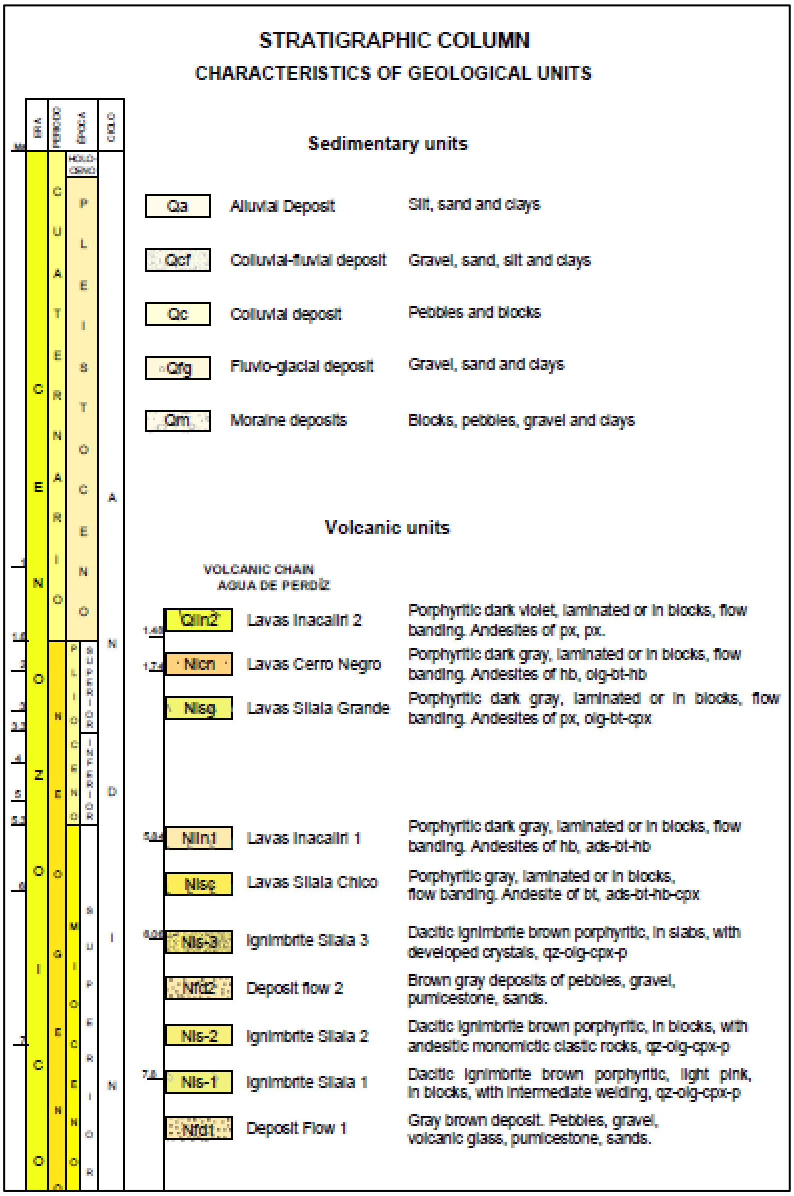
3.2.2. Stratigraphy developed by Bolivia

The details of the stratigraphy developed by SERGEOMIN (Bolivia) in 2017 are described below for comparison with the stratigraphy determined by geological mapping and analysis in Chile. The stratigraphic column shown in Figure 3-4 and

Table 2 is from SERGEOMIN (Bolivia), 2017, Annex A, Map area 1. Map area 1 is highlighted since it pertains to the DHI near field model (DHI, 2018).

SERGEOMIN (Bolivia) have identified three Ignimbrite deposits (labelled Nis 1, Nis 2 and Nis 3), and two debris flows, one occurring at the base of Nis 1 and the other between Nis 2 and Nis 3. It should be noted that SERGEOMIN (Bolivia) and DHI in their reports refer to all three ignimbrites in Bolivia as Silala Ignimbrite. This is potentially confusing, because SERNAGEOMIN (Chile) refer to two ignimbrites in Chile, the upper of which they have named the Silala Ignimbrite and the lower the Cabana Ignimbrite, as detailed in Section 3.2.1. DHI in their report (DHI, 2018) divide the ignimbrites into different lithological types depending upon whether they are highly welded or less welded, but these currently cannot be correlated directly with the Chilean divisions of Silala and Cabana Ignimbrites.

Bolivia reports three dates for ignimbrite rocks in the Silala extended groundwater basin, in Bolivia. These are 7.8 Ma, 6.6 Ma and 3.2 Ma (see Table 1). The oldest of these dates (7.8 Ma) is stated to be from the base of an outcrop of Bolivian Silala Ignimbrite Nis 1 in the Silala ravine (in Bolivia), the 6.6 Ma date is from rocks much further to the north and stated to be from Bolivian Silala Ignimbrite Nis 3. The 3.2 Ma date is from ignimbrite located towards the northern edge of the extended groundwater catchment and has not been correlated with the Bolivian Silala Ignimbrites (Nis 1, Nis 2 and Nis 3) (SERGEOMIN (Bolivia), 2017). For comparison, the date for the Chilean Silala Ignimbrite is 1.61 Ma and the date for the Chilean Cabana Ignimbrite is 4.12 Ma.



STRATIGRAPHIC COLUMN

CHARACTERISTICS OF GEOLOGICAL UNITS

Sedimentary units

Qa	Aluvial Deposit	Silt, sand and clays
Qcf	Colluvial-fluvial deposit	Gravel, sand, silt and clays
Qc	Colluvial deposit	Pebbles and blocks
Qfg	Fluvio-glacial deposit	Gravel, sand and clays
Qm	Moraine deposits	Blocks, pebbles, gravel and clays

Volcanic units

VOLCANIC CHAIN
AGUA DE PERDÍZ

QIIn2	Lavas Inacaliri 2	Porphyritic dark violet, laminated or in blocks, flow banding. Andesites of px, px.
NIcn	Lavas Cerro Negro	Porphyritic dark gray, laminated or in blocks, flow banding. Andesites of hb, olg-bt-hb
NIsg	Lavas Silala Grande	Porphyritic dark gray, laminated or in blocks, flow banding. Andesites of px, olg-bt-cpx
NIIn1	Lavas Inacaliri 1	Porphyritic dark gray, laminated or in blocks, flow banding. Andesites of hb, ads-bt-hb
NIsc	Lavas Silala Chico	Porphyritic gray, laminated or in blocks, flow banding. Andesite of bt, ads-bt-hb-cpx
NIs-3	Ignimbrite Silala 3	Dacitic ignimbrite brown porphyritic, in slabs, with developed crystals, qz-olg-cpx-p
Nfd2	Deposit flow 2	Brown gray deposits of pebbles, gravel, pumicestone, sands.
NIs-2	Ignimbrite Silala 2	Dacitic ignimbrite brown porphyritic, in blocks, with andesitic monomictic clastic rocks, qz-olg-cpx-p
NIs-1	Ignimbrite Silala 1	Dacitic ignimbrite brown porphyritic, light pink, in blocks, with intermediate welding, qz-olg-cpx-p
Nfd1	Deposit Flow 1	Gray brown deposit. Pebbles, gravel, volcanic glass, pumicestone, sands.

Figure 3-4. Stratigraphic column from SERGEOMIN Map 1 (SERGEOMIN (Bolivia), 2017).

Map Abbreviation	Age dates	Volcanic Unit	Lithology
Qlin2	1.48 Ma	Lavas Inacaliri 2	Andesite
Nlcn	1.74 Ma	Lavas Cerro Negro	Andesite
Nllsg		Lavas Silala Grande	Andesite
Nlin1	5.84 Ma	Lavas Inacaliri 1	Andesite
Nlsc		Lavas Silala Chico	Andesite
Nis-3	6.6 Ma	Ignimbrite Silala 3	Ignimbrite
Nfd-2		Deposit flow 2	Pebbles, gravel, pumice, sand
Nis-2		Ignimbrite Silala 2	Ignimbrite
Nis-1	7.8 Ma	Ignimbrite Silala 1	Ignimbrite
Nfd1		Deposit flow 1	Pebbles, gravel, pumice, sand, volcanic glass

Table 2. Stratigraphic column for Volcanic rock units from SERGEOMIN (Bolivia) in Figure 3-4 (SERGEOMIN (Bolivia), 2017, Map 1). Radiometric dates are taken from Table 1.

SERGEOMIN (Bolivia), 2017, identify lavas from the Cerrito Silala (Chico in Bolivia) and the early lavas from Volcán Inacaliri and lavas from Volcán Apagado (Silala Grande in Bolivia). All of these rocks date from approximately 6.6 – 5.8 Ma (see Table 1). They have taken the earlier two radiometric dates for the Ignimbrites (Nis 1 and 3) to place them stratigraphically below the lavas of the Cerrito Silala and the earliest lavas of the Volcán Inacaliri and Volcán Apagado. This is in conflict with the interpretations of Chile. Based on the Chilean evidence, the Silala Ignimbrite (in Chile) and the Cabana Ignimbrite are younger than the lavas from Cerrito Silala (Chico in Bolivia) and lie stratigraphically above these lavas.

There appear to be no lavas outcropping in Bolivia in the extended groundwater basin with ages comparable with the Volcanic Sequences of the Upper Pliocene (dated 2.6 Ma, see Table 1). However, SERGEOMIN (Bolivia) and DHI agree with Chile that the more recent lavas from Inacaliri and Volcán Apagado of Pleistocene age overlie all the above-mentioned older volcanic rocks (see Figure 3-2).

3.2.3. Discussion

The main differences in geological interpretation between Bolivia and Chile are focused on the ignimbrite deposits. It is clear that there is a thick succession of separate ignimbrite deposits that have filled the Silala basin in Bolivia and that only some of these outcrop in Chile. Ignimbrites with ages as found in Chile, of 1.61 Ma and 4.12 Ma, have not been found in Bolivia. There are five age dates for the Ignimbrites (see Table 1), which represent separate volcanic events, over a large time range:

a. 7.8 Ma – Bolivian Silala Ignimbrite Nis 1
b. 6.6 Ma – Bolivian Silala Ignimbrite Nis 3
c. 4.12 Ma – Chilean Cabana Ignimbrite
d. 3.2 Ma – Bolivian Silala Ignimbrite (Ntpg)
e. 1.61 Ma – Chilean Silala Ignimbrite

Also, there are identified debris flows that lie between various ignimbrite deposits, one in Chile and two in Bolivia, but these do not appear to be correlated. However, they are important, because in Chile there is drilling evidence and pumping test results that show that they contribute to strong groundwater flow horizons (Arcadis, 2017). There is more or less agreement between the parties on the stratigraphy of the Pleistocene and more recent deposits.

It would seem highly unlikely that the Silala (Chilean) Ignimbrite outcropping in Chile with a well-defined, recently analyzed, radiometric date of 1.61 Ma, which is continuously traceable in the Silala ravine walls in Chile to the international border, should, further upstream in the ravine in Bolivia, have an age of 7.8 Ma. This is implausible and would require a large geological structure such as a fault with a throw of many tens if not hundreds of metres, for which no evidence has been presented by SERGEOMIN (Bolivia) or DHI (see section 3.4). The age of the Chilean-named Silala Ignimbrite is well defined by several radiometric dates from underlying deposits. The lavas of the Volcanic Sequences of the Upper Pliocene, which can be seen in outcrop underlying the Silala Ignimbrite, as shown on Figure 3-5, have been dated recently (Table 1) at 2.6 Ma. Also, the underlying Cabana Ignimbrite (in Chile), found in several boreholes drilled in 2016 (Arcadis, 2017), has a recent radiometric age date of 4.12 Ma, all considerably younger than 7.8 Ma. The outcrop of the Silala Ignimbrite (named in Chile) clearly crosses the international border, and more generally there is very strong evidence that the Ignimbrite succession in Chile also occurs across the border in Bolivia. The Chilean ignimbrite dates confirm that, in Chile, the oldest rocks are the Volcanic Sequences of Miocene/Pliocene, which underly the Cabana Ignimbrite. If, as dated in Bolivia, there are older Ignimbrites outcropping in the basin, these must underly the younger Miocene/Pliocene lavas, but the higher and younger ignimbrites (in Chile, Silala and Cabana Ignimbrites) overlie these lavas. For clarity, a conceptual cross-section at the international border has been constructed on the basis of the radiometric dates and outcrop relationships discussed above, is shown in Figure 3-6.

For comparison, Bolivia’s conceptual cross-section through the geology at the International border is reproduced from DHI, 2018, in Figure 3-7. The differences in interpretation of the geology can be clearly seen. On DHI’s cross-section a fault zone is depicted (see also section 3.3) but there appears to be no displacement of the rocks either side. Geological faults occur when great pressures built up in the earth's crustal rocks are relieved, and this results in movements of the rocks on either side of a fault plane. Movements can be as small as a few centimeters or very large, and they might be horizontal movements or vertical movements or low angle movements. Clearly when the rocks move they are split along the fault plane and a displacement occurs. On the DHI conceptual diagram (Figure 3-7), a horizon of welded ignimbrite is shown crossing the ravine. Even though a major fault zone is depicted on the Figure, the welded ignimbrite is shown at the same level in both walls of the ravine, implying that the DHI-inferred major fault zone has caused no displacement. This is so unlikely that we believe it impossible.

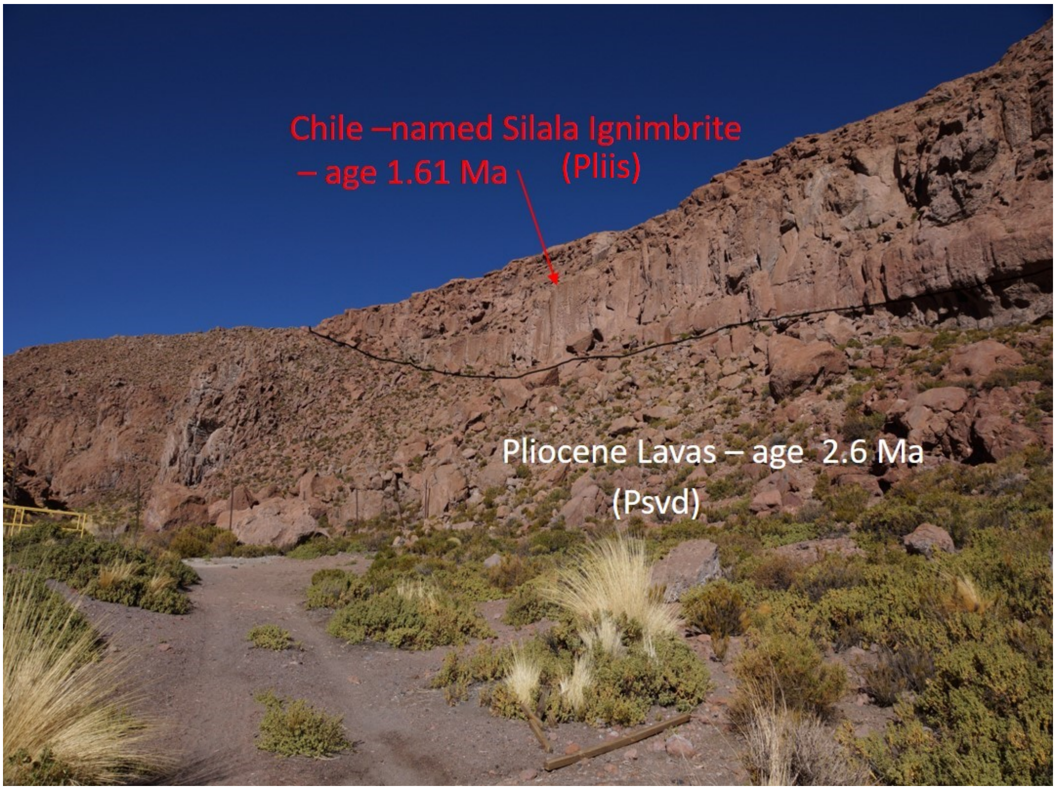


Figure 3-5. Disposition of Silala Ignimbrite (1.61 Ma) overlying Pliocene dacitic lavas (2.6 Ma) (SERNAGEOMIN (Chile), 2019).

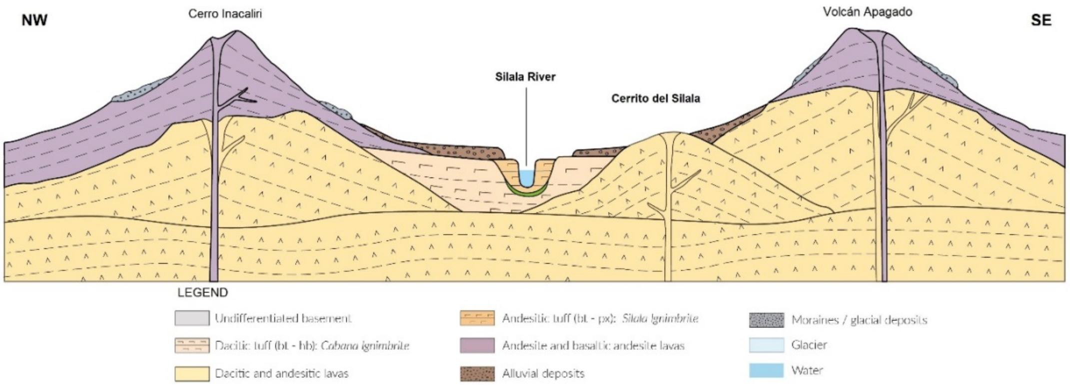


Figure 3-6. Schematic profile of Inacaliri-Apagado volcanic chain at the border of Chile and Bolivia, including Cerrito Silala, Cerro Inacaliri and Volcán Apagado, showing the Silala Ignimbrite underlain by the Cabana Ignimbrite, which is in turn underlain by Miocene/Pliocene lavas of Cerrito Silala, Volcán Apagado and the Volcán Inacaliri. Beneath all are earlier Ignimbrite deposits. The purple shows the Pleistocene lavas of Inacaliri and Apagado, (SERNAGEOMIN (Chile), 2019).

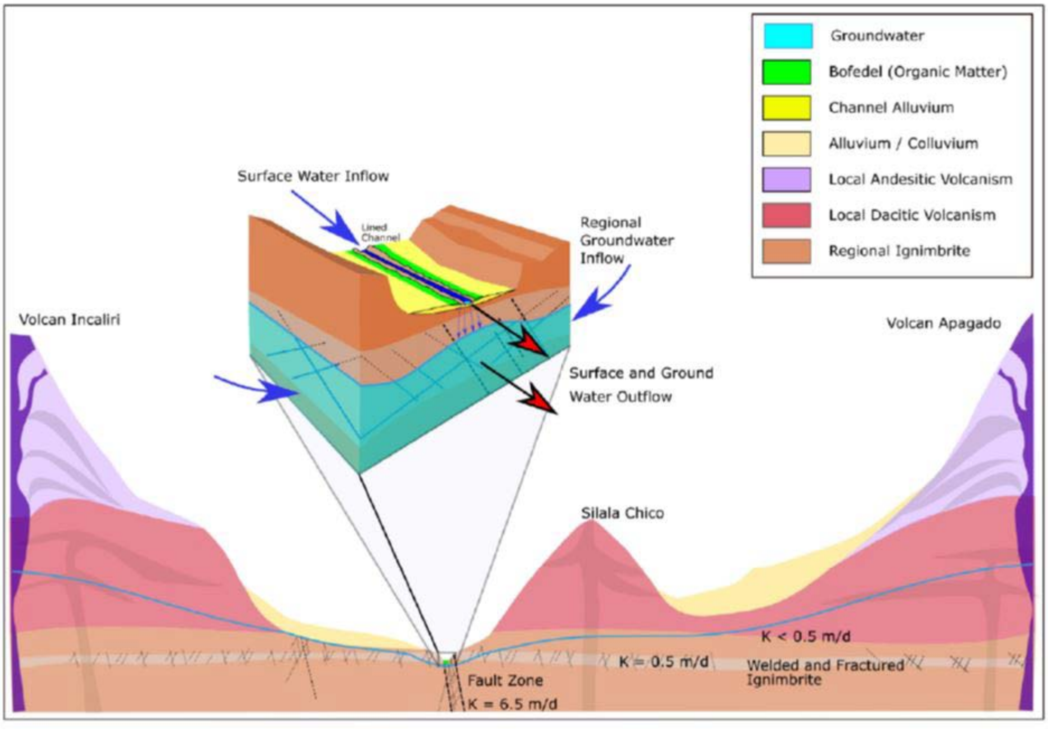


Figure 3-7. DHI conceptual cross-section reproduced from DHI, 2018 (BCM, Vol. 4, p. 88, Figure 36).

3.3. Three-dimensional geology of the extended Silala groundwater catchment

In order to visualize the geology of the extended groundwater catchment so that a good understanding of both the regional and local hydrogeology might be gained, the map shown in Figure 3-2 was compiled and the profile A-B (cross section) in Figure 3-8 was constructed. This was achieved by studying the geological maps and reports of SERGEOMIN (Bolivia), 2003 and 2017; SERNAGEOMIN (Chile), 2017 and 2019, including all the radiometric ages available (see Table 1), and satellite images from Google Earth. The map (Figure 3-2) is very similar to the version of SERGEOMIN (Bolivia), 2003. This compilation has been enabled after the submission of the BCM and the associated DHI, 2018 report, which referred to various SERGEOMIN (Bolivia) reports (2003 and 2017). These were subsequently requested from, and provided by, Bolivia. Field studies and observations in Bolivia, further petrographic study and radiometric dating have not been possible.

Volcanic centres, including Cerrito Silala, align in an approximate North-South direction (SERNAGEOMIN (Chile), 2017 and 2019). These volcanic centres are aligned in this way in response to a local crustal extension (i.e. pulling apart of the earth’s crust) which produced a plane of weakness that upwelling magma (molten rock) under pressure took advantage of, allowing the formation of a line of volcanoes (volcanic centres). These centres have ages of 6.6-6.0 Ma (see Table 1). The volcanoes of Inacaliri and Apagado form a topographic high, which together with the north-south alignment mentioned above have meant that the pyroclastic flows that deposited the Silala and Cabana Ignimbrites in Chile had a topographic high to overtop in order to flow downgradient to the south west into Chile.

The geological cross section A-B, shown in Figure 3-8, visualizes the geology with depth. The line of the section (see Figure 3-2) goes from the edge of the groundwater catchment in Bolivia to the south west, approximately along the line of the Silala River. The paucity of borehole information limits the three-dimensional accuracy of geological knowledge and understanding. Nevertheless, the compilation of Chilean and Bolivian data (radiometric dates in Table 1, field observations that where available in Bolivian reports, and the Chilean mapping observations) is expected to give the best understanding to date of the geology of the extended catchment.

If the Bolivian 7.8 Ma ignimbrite age date is valid then there must be ignimbrite deposits beneath the Miocene/Pliocene lavas of Cerrito Silala, since these are younger, and this has been shown on Figure 3-8. The Chilean evidence shows that there are at least two Ignimbrite deposits overlying the Miocene/Pliocene lavas in Chile. Since the Bolivian stratigraphy does not include ignimbrite deposits overlying the Miocene/Pliocene lavas, it is incorrect. The Bolivian geological succession beneath the Pleistocene lavas of the Inacaliri and Apagado volcanos cannot be correlated with the Chilean geological succession.

A cross-section through the Cajones and Orientales wetland areas, Figure 3-8, shows Chile’s geological interpretation with depth. This clearly shows the Chilean-named Silala and Cabana Ignimbrites overlying the Miocene/Pliocene volcanics of the Cerro Silala (Chico in Bolivia). This three-dimensional geological configuration has not been used by DHI in the construction of their models. Instead they use a stratigraphy in their models that results in different hydrogeological layers and they invoke a fault system which perhaps justifies their hydraulic parameter distribution. The restricted region of Chilean Silala and Cabana ignimbrite, through which groundwater must flow beneath the Silala River, can also be seen in Figure 3-8.

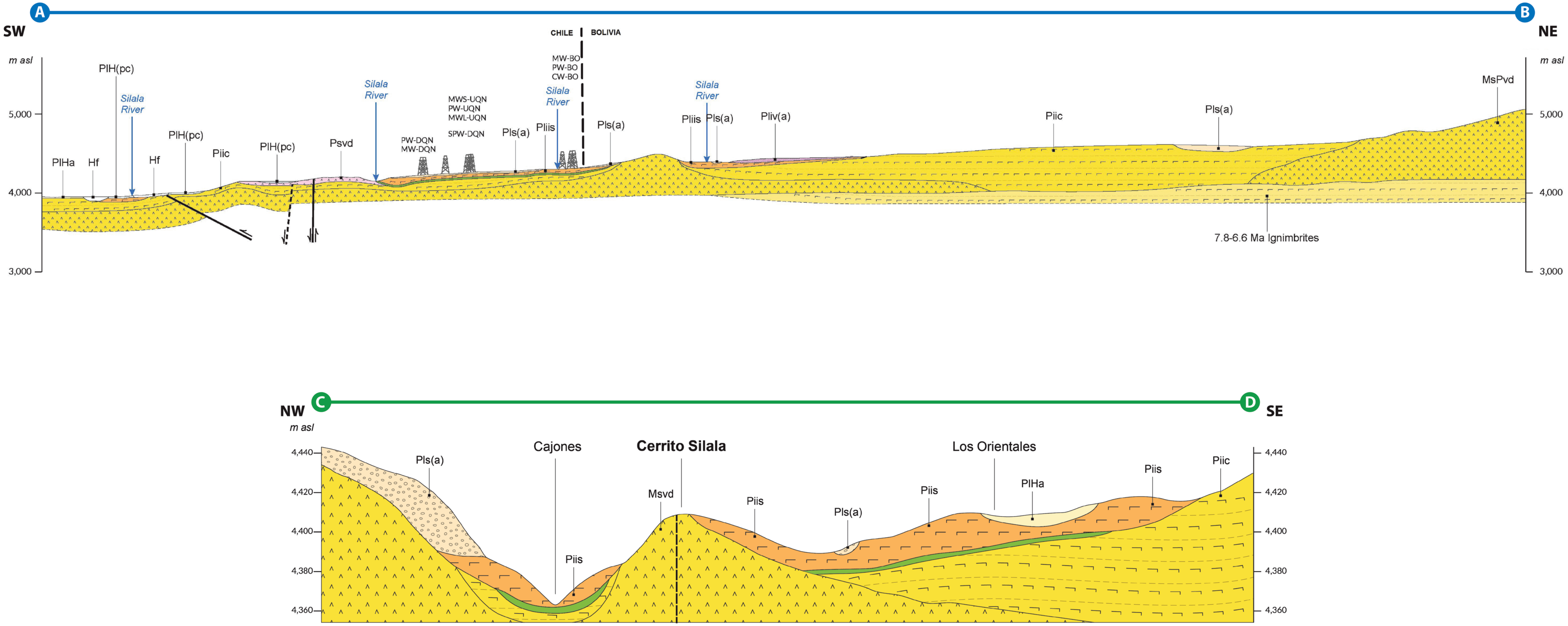


Figure 3-8. Geological cross section A-B from South West – to North East through the Silala extended groundwater catchment showing the distribution of lithological units and their stratigraphic positions (for legend see Figure 3-2) and a cross-section C-D from north west to south east through the Cajones and Orientales wetlands. The black dashed vertical line represents the North – South volcanic centre alignment through Cerrito Silala (SERNAGEOMIN (Chile), 2019).

The DHI Near Field model does not incorporate the Chilean Silala and Cabana Ignimbrite with the interbedded debris flow. These deposits, which form the main deep aquifer in Chile, overlie the Miocene/Pliocene lavas, and must continue to the north east over the International border into Bolivia. The DHI model representation of the geology and hydrogeology does not incorporate this geological configuration, proven in Chile, and is therefore inherently flawed.

There is agreement between the parties that the major regional aquifer is formed by the ignimbrites, but in Chile these are underlain by much less permeable Miocene/Pliocene lavas. Therefore, the groundwater flow path in the Silala and Cabana Ignimbrites through to Chile is restricted, although both these deposits are known to support high groundwater flows (Arcadis, 2017).

Another facet of the three-dimensional geology that can impact significantly on the groundwater flow regime is the presence of geological faults. Geological faults cause displacement of rock sequences, bringing strata of different nature to lie next to each other. They can cause extensive fracturing or grind up the rocks to a fine powder, which can line the fault planes, producing a region of low permeability. Thus, they can form high permeability pathways for groundwater or low permeability barriers to groundwater flow.

The modelling that was carried out in support of the BCM (DHI, 2018) has employed high hydraulic conductivities along an alleged fault zone, which is shown on their maps (SERGEOMIN (Bolivia), 2017) as running from the Orientales wetland to the Cajones wetland and bending around to follow the line of the Silala River to cross the international border into Chile (see Figure 3-9). However, no evidence, including displacements, fault gouge deposits or rock shattering has been found in Chile to support the presence of such a fault. No evidence of large displacement is provided by SERGEOMIN (Bolivia) in their 2003 or 2017 reports and DHI, in their conceptual cross-section (Figure 3-7), show no displacement across the fault. SERGEOMIN (Bolivia), 2017 provide evidence of fractures and their directions and some minor faulting with minor displacements in Bolivia, but nothing of such a major character as the major fault system introduced by DHI.

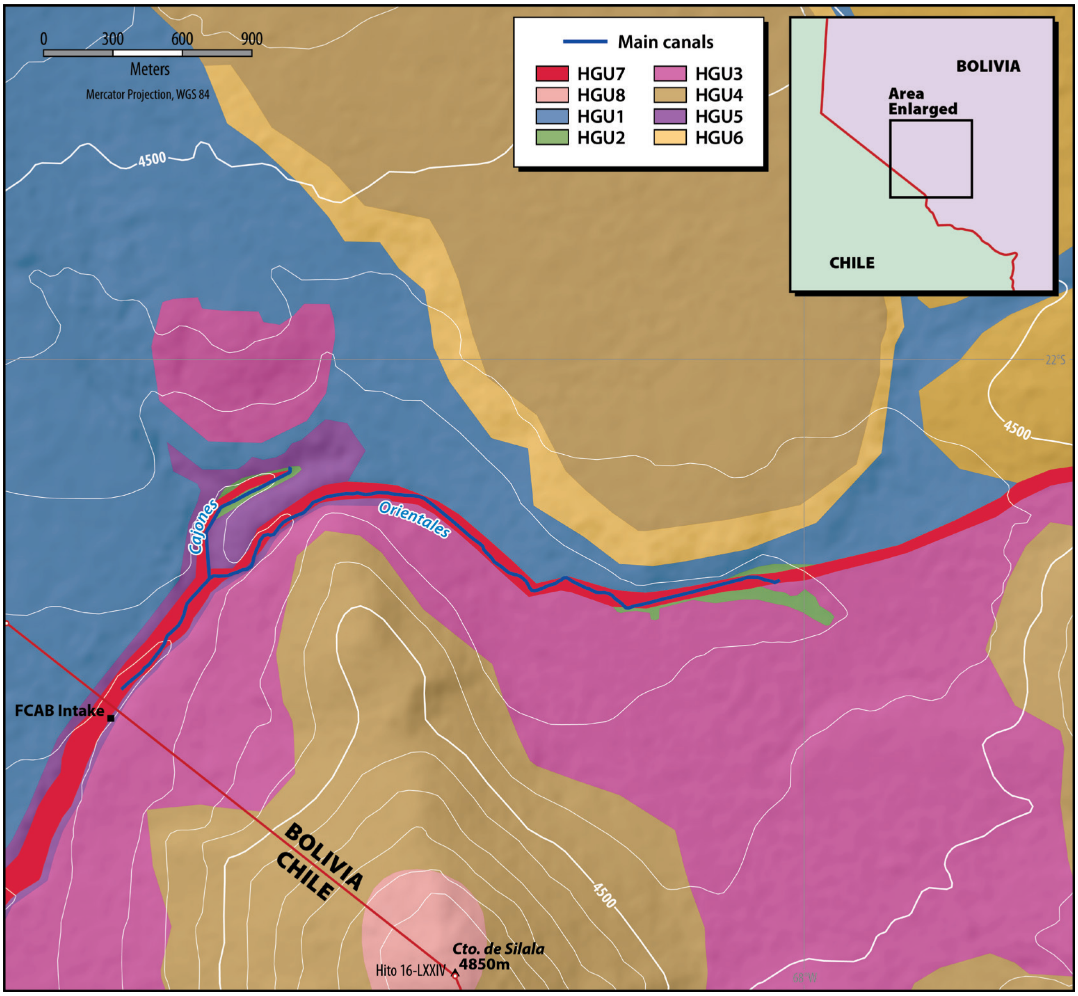


Figure 3-9. Amended map from DHI, 2018 (BCM, Vol. 4, p. 76, Figure 29) showing in red (HGU7) the DHI postulated fault system (SERNAGEOMIN (Chile), 2019).

This fault system has been assumed to be vertical by DHI, 2018, yet such a fault system showing such outcrop sinuosity could only geometrically occur in the manner assumed by DHI, 2018, if it had a very low angle. DHI specify this fault system to be 400 metres deep and 50 metres across and provide it an elevated hydraulic conductivity down to 200 metres depth (DHI, 2018). On the geological maps provided with SERGEOMIN (Bolivia), 2017, the faults appear as inferred. However, they have not been found at outcrop in Bolivia by SERGEOMIN (Bolivia), 2017, or by SERNAGEOMIN (Chile), 2019, in Chile. Furthermore, the morphology of the walls of the Silala ravine at the international border and downstream of the border which are composed of Silala (Chilean notation) Ignimbrite shows no signs of displacement, and major joints can be seen at approximately the same level on each side of the ravine (see Figure 3-10), clearly continuous across the ravine.

Figure 3-10. Approximately horizontal jointing in the Silala Ignimbrite crossing the Silala ravine with no displacement. Photo taken looking upstream at the junction with the Quebrada Negra (SERNAGEOMIN (Chile), 2019).

In short, there appears no evidence for this fault system introduced by DHI, yet it is a dominant feature of the hydrogeology used by DHI to model the Near Field system.

A vertical normal fault has been mapped in Chile (SERNAGEOMIN (Chile), 2019), trending N-S, which affects the front of the dacitic lava flow dated 2.6 Ma (Table 1, Volcanic sequences of the Upper Pliocene) but does not displace the overlying Chilean Silala Ignimbrite. This tectonic event (fault) occurred between 2.6 to 1.6 Ma (see Figure 3-11). This structural configuration and the presence of the low permeability Pliocene lavas under which the Cabana Ignimbrite occurs, and the thinning of the Silala Ignimbrite to only the upper 8 metres (SERNAGEOMIN (Chile), 2019), causes a reduction in the transmissivity of the Ignimbrite aquifer. As a consequence, an elevated groundwater piezometric surface is observed at the borehole SPW-DQN (Suárez et al., 2017) from which groundwater overflows to the Silala River at rate of approximately 90 l/s (Suárez et al., 2017). The overflow began during the drilling and did not begin until the borehole depth was 28 metres (pers com. Muñoz, 2017). This clearly indicates a considerable variation of permeability with depth, since here the upper several metres of the Chile-named Silala Ignimbrite act as a low permeability layer that confines groundwater in the lower layers and in the Cabana Ignimbrite, which is found at depth (SERNAGEOMIN (Chile), 2019). The groundwater flows down-gradient to the south west are very much reduced due to the existence of the fault, the presence of the Pliocene lavas beneath the Chilean Silala Ignimbrite and the underlying Cabana Ignimbrite being at greater depth. In consequence, the groundwater levels in the Cabana Ignimbrite are very low, as evidenced in borehole EW-PS (SERNAGEOMIN (Chile), 2019; Arcadis, 2017). Hence, there are important geological features in Chile that significantly affect groundwater flows across the border, but these are not recognized by Bolivia, or included in DHI's modelling.

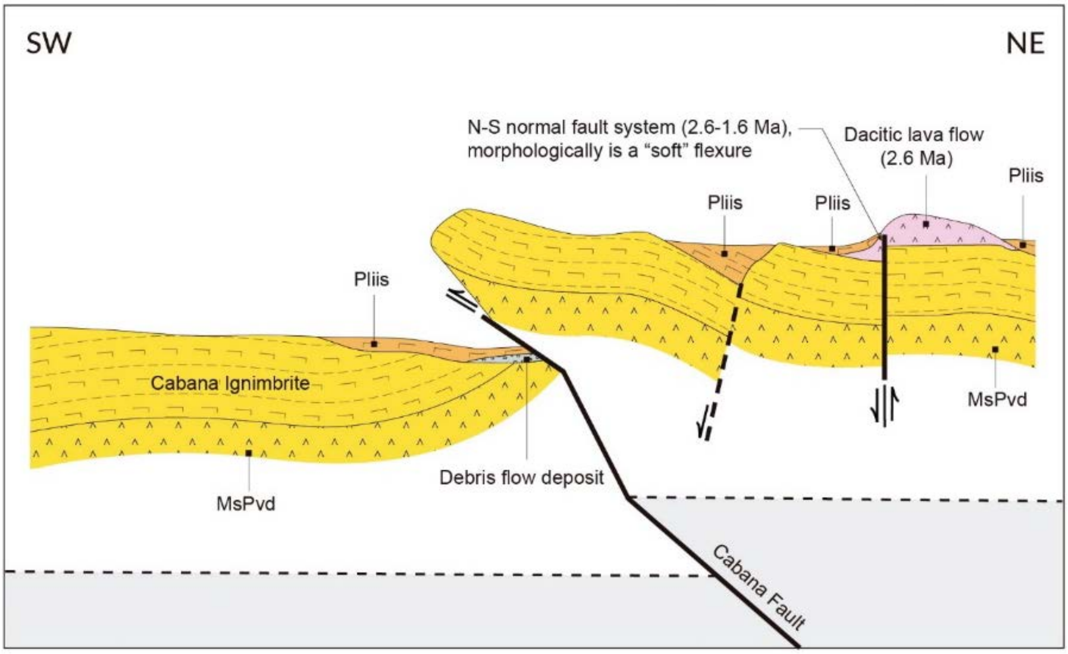


Figure 3-11. Schematic structural profile in the SW sector of Silala River. (SERNAGEOMIN (Chile), 2019).

3.4. Conclusions

The geology of the extended groundwater catchment of the Silala River is highly complex. Clearly there has been a succession of volcanic pyroclastic flow events over several million years with intervening erosive periods during which sediments in the form of debris flows and minor fluvial deposits have been laid down. The thickness of these ignimbrite deposits is unknown but likely to be large, perhaps over 200 metres, but this has not been proven by drilling.

There are four main differences in the Chilean interpretation of the geology to that in the DHI report (DHI, 2018), which have impacts on the hydrogeological conceptual model that DHI, in their models, are attempting to represent numerically.

The first is the stratigraphic position of the two ignimbrite deposits recognized along the Silala River in Chile. The contact relationships observed in Chile, as discussed above, and the ages obtained (Table 1) are consistent with the schematic cross-section at the International border shown in Figure 3-6 and the geological cross-sections shown on Figures 3-8 (SERNAGEOMIN (Chile), 2019). This is significantly different from the DHI, 2018 cross-section drawn to represent schematically the geology along the same section across the Silala River ravine at the international border. The DHI interpretation is not supported by the Chilean data. This means that the layering incorporated in their models, which is used to represent the hydrogeological configuration, is not supported by the Chilean evidence. DHI have used the degree of welding in the ignimbrites and their proposed fault system (see below) to determine their layering and parameter distributions in their models, which include areas at the international border. The likely effect of this is that the distribution of hydraulic parameters, both with depth and laterally, will be wrong, thus affecting the groundwater flow regime downstream and possibly upstream of the Bolivian wetlands. This would be highly likely to affect spring flows and the driving groundwater heads in their models.

The second is that there is no evidence for a major vertical fault running down the line of the Silala ravine into Chile. DHI assume a vertical fault system, which provides high hydraulic conductivities to great depth, and has an apparently arbitrary width, approximately the same as the width of the Silala River ravine at the international border. This is a major control on groundwater flows in their model but, as noted, is unsupported by evidence.

The third is that although we recognize that the ignimbrite deposits, where seen at outcrop in the Bolivian wetlands or in cores, may be highly fractured, and this would be likely to provide high fracture permeability, the DHI modelling takes no account of the vertical variability of permeability, as demonstrated by the artesian flowing conditions at Chilean borehole SPW-DQN, which implies a significant confining layer.

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

The numerical model constructed by DHI was used to make predictions of surface water and groundwater flows so that they might understand what these flows might have been before construction of the channels in the Bolivian wetlands. The flaws in the representation of the hydrogeology by this model are clear. It does not represent the geology correctly either stratigraphically or structurally and invokes a fault system that is both unmapped and geometrically highly unlikely. Thus, DHI assume in their model a distribution of high hydraulic conductivity in the region of this assumed fault system that has no basis.

The effects of these flaws on the performance of a groundwater numerical model are unknown but they would undoubtedly mean that actual groundwater flow paths and the distribution of high and low hydraulic conductivity would be significantly different to those modelled by DHI. Further evidence of an incorrect understanding of the hydrogeology is provided by hydrogeochemistry, which is discussed below in Section 4.

4 HYDROGEOCHEMISTRY OF THE SURFACE AND GROUNDWATERS OF THE SILALA BASIN

In this section we discuss the importance of the interpretation of the hydrogeochemistry data for understanding the origins of the groundwater feeding the various springs in the Silala groundwater catchment and particularly highlight the differences between the chemistry and isotopic compositions of

Bolivia's Cajones and Orientales spring waters. These indicate different origins, which, though accepted by DHI in their report (BCM, Vol. 4, p. 94), have not been represented in their modelling.

4.1 Introduction

The study of the chemical and isotopic evolution of surface and groundwaters can contribute to the understanding of the complex interactions between the river and the groundwater and the mechanisms of local and regional recharge to the river flow, differentiating the origins of waters and the residence times that groundwaters may have spent within the aquifers.

For instance, the chemistry of groundwaters depends on the flow path and the chemistry of the rocks the water is flowing through. Groundwaters are usually more mineralized than waters that have run off down a hillslope, reaching rivers after flowing short distances overland within a short time frame. In the case of the Silala catchment, the dominant origin for the surface water found in the Silala River is from groundwater emerging from springs. Groundwaters may spend many years flowing very slowly through an aquifer. If the spring water has its origins in one particular aquifer or another, this will often be reflected in the chemistry of the water. Additionally, groundwater recharge may have isotopic signatures that reflect the elevation of the precipitation that generated the recharge.

In this context, the hydrogeochemical study of groundwater has been an important approach to understand the flow of groundwater and to validate or discard hypotheses about the conceptual hydrogeological model. In the case of the Silala basin the study of the hydrogeochemistry has assisted in determining two different aquifer types and most importantly a differentiation between the spring water of the Cajones and Orientales wetlands.

Below we discuss the results of chemical analyses, including isotope studies, of the Silala River water, spring water and groundwater samples in Chile. These are presented in detail in Herrera and Aravena, 2019a and 2019b. The samples were mainly collected over three sampling campaigns during 2016 and 2017 (Herrera and Aravena, 2019a), to cover both wet and dry seasons. A further smaller campaign of sampling and analysis of surface and groundwaters was carried out in 2018 in the Quebrada Negra wetland (Herrera and Aravena, 2019b), in which one spring water, two surface water samples and four groundwater samples from piezometers were analyzed for the main ion chemistry. There was insufficient time to carry out isotope analyses on samples collected in this latter campaign.

The results cited by DHI in their report (DHI, 2018) in support of the BCM are also used to establish the character and origins of the waters of the Silala basin. The data provided in DHI (BCM, Vol. 4, pp. 89-94) comprise 14 chemical analyses of water samples from springs and shallow groundwater (sampled from piezometers) in the Silala River basin in Bolivia. No analyses were reported for Silala River water. The samples were collected during campaigns carried out for different studies between the years 2000-2001 and 2016-2017 (BCM, Vol. 4, pp. 539-542).

Herrera and Aravena (2019a), only considered analyses that had less than 10% ionic balance error (Custodio and Llamas, 1983). This is common practice for quality control (Herrera and Aravena, 2019a) and so only 6 of the 14 Bolivian analyses could be used for comparison with the Chilean data. These included samples from the Cajones ravine and the Orientales area.

The spatial variation of the chemical composition of the waters can be visualized using Stiff diagrams. These consist of a polygonal shape of three parallel horizontal axes extending on either side of a vertical zero axis. Cations are plotted in milliequivalents on the left side of the zero axes, one to each horizontal axis, and anions are plotted on the right side. Stiff diagrams were plotted on Figure 4-1 for all the chemical analyses of the dry season for Chile (the wet season data are similar) and all Bolivian analyses with satisfactory ionic balance errors.

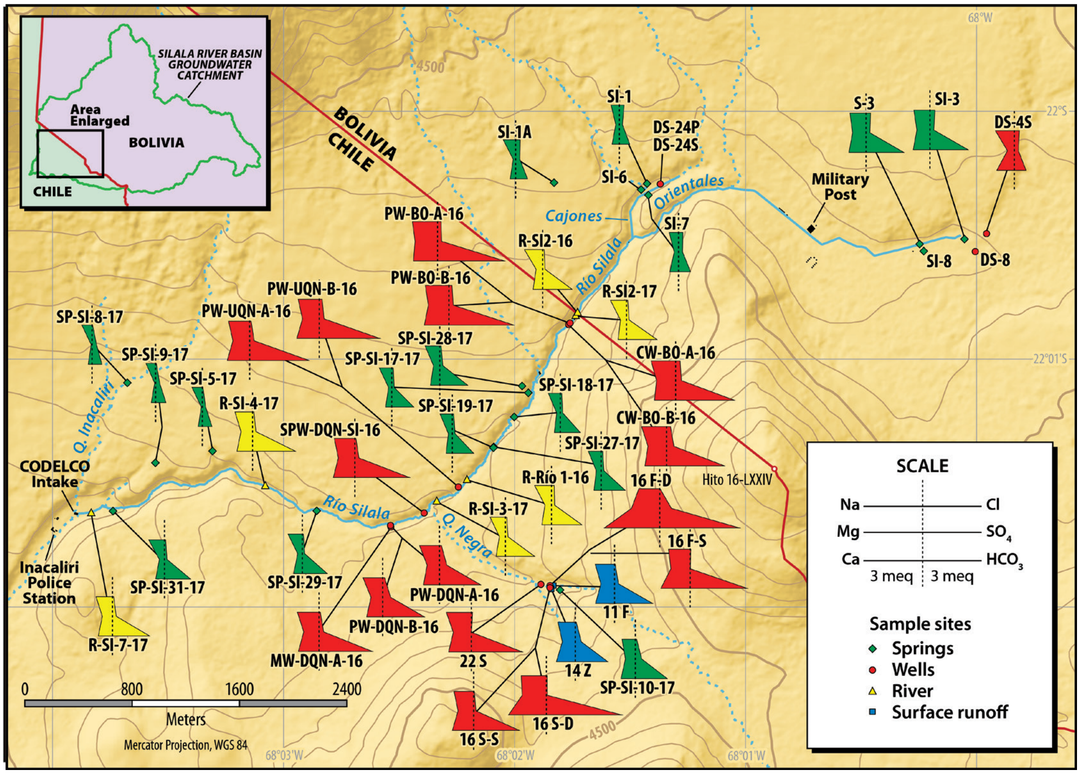


Figure 4-1. Modified Stiff diagrams of the waters from Silala River area in Chile (rainy season) and Bolivia (Herrera and Aravena, 2019b).

4.2 Discussion of chemistry analytical results

All the water analyses presented in Herrera and Aravena (2019a) have a relatively low salinity, though there are significant salinity differences between different waters.

Figure 4-1 shows that the waters from springs in the northern part of the Silala River in the Bolivian territory (Cajones ravine and slopes of Cerro Inacaliri) are characterized by low salinity, ranging between 113 and 129 µS/cm (Herrera and Aravena, 2019a), similar to that of the springs located in the northern part of the

Silala River in the Chilean territory. The groundwater in the Cajones ravine, collected from shallow piezometers, also has a low salinity, similar to the spring waters in Chile (Herrera and Aravena, 2019a). All these samples can be seen in Figure 4-1 to be Na-Ca bicarbonate type.

In contrast, more saline spring waters, ranging between 254 and 394 µS/cm, are found in the Orientales wetland in Bolivia (Herrera and Aravena 2019a). Similarly, the groundwater in the Orientales wetland, collected from shallow piezometers, has a relatively high salinity, similar to that of the Orientales springs. It is notable that the Orientales spring waters have much higher salinity than the springs in Chile or in the Cajones area of Bolivia and their conductivities are in the same salinity range as the groundwater in Chile (including those groundwaters from the Quebrada Negra wetland). These waters also tend to be Ca-bicarbonate water type, as do the groundwaters sampled in the Chilean territory.

In Chile, the springs on the northern side of the Silala ravine show similar chemistries to the river waters and are distinctly different from the deep groundwater sampled in Chile or the spring water samples in the Orientales wetland. Downstream of the confluence of the Quebrada Negra with the Silala River, the river water chemistry has a significantly higher Magnesium content (see Figure 4-1 and Herrera and Aravena, 2019b). This reflects the contribution of Magnesium-rich waters found in groundwater samples from the Quebrada Negra valley and is significantly different to the other waters, including the Bolivian samples, indicating the extreme complexity of the hydrogeology and origins of these waters.

Further inspection of Figure 4-1 shows that the spring waters and groundwaters of the Cajones and slopes of Inacaliri have very similar Stiff diagram shapes, and salinity, to those springs on the downstream northern side of the Silala River ravine.

4.3 Isotope analyses

This section focuses on the evaluation of environmental isotope data collected from springs, river and wells in Chile in the Silala River topographic catchment. The stable isotopes referred to in this section are ^{18}O (Oxygen-18), ^{2}H (Deuterium) and ^{13}C (Carbon-13), together with the radioactive isotope of ^{14}C (Carbon-14).

4.3.1. Interpretation of Oxygen-18 and Deuterium ($\delta^{18}O$ and $\delta^{2}H$) data

The methodology for the interpretation of the $\delta^{18}O$ and $\delta^{2}H$ data (Oxygen-18 and Deuterium) is explained in detail in Herrera and Aravena (2019a). The results are shown in Figures 4-2 and 4-3, where data for rainy and dry seasons are plotted with the global meteoric water line (GML) and the local meteoric water line (LML).

A clear pattern can be seen in these plots. The springs located in the upper course of the river in Chile (upstream of the junction of the Quebrada Negra with the Silala River) have a different isotopic fingerprint from the springs located in the northern part of the lower course of the river (downstream of the junction of the Quebrada Negra with the Silala River). The data from the latter plot near the local meteoric water line, which indicates local recharge, whereas the data from the former plot below the local meteoric water line, indicating recharge from higher elevations. The results also show that some springs located in the southern part of the lower river course (downstream of the junction with the Quebrada Negra) in Chile have a similar isotopic fingerprint to those from the upper river course. This pattern suggests that these springs are part of the same (or similar) hydrogeological system as that which feeds the springs in the upper course of the river in Chile. This is important when the chemistry and isotope data are integrated for Chile and Bolivia, in terms of the origins of the waters from the Bolivian springs.

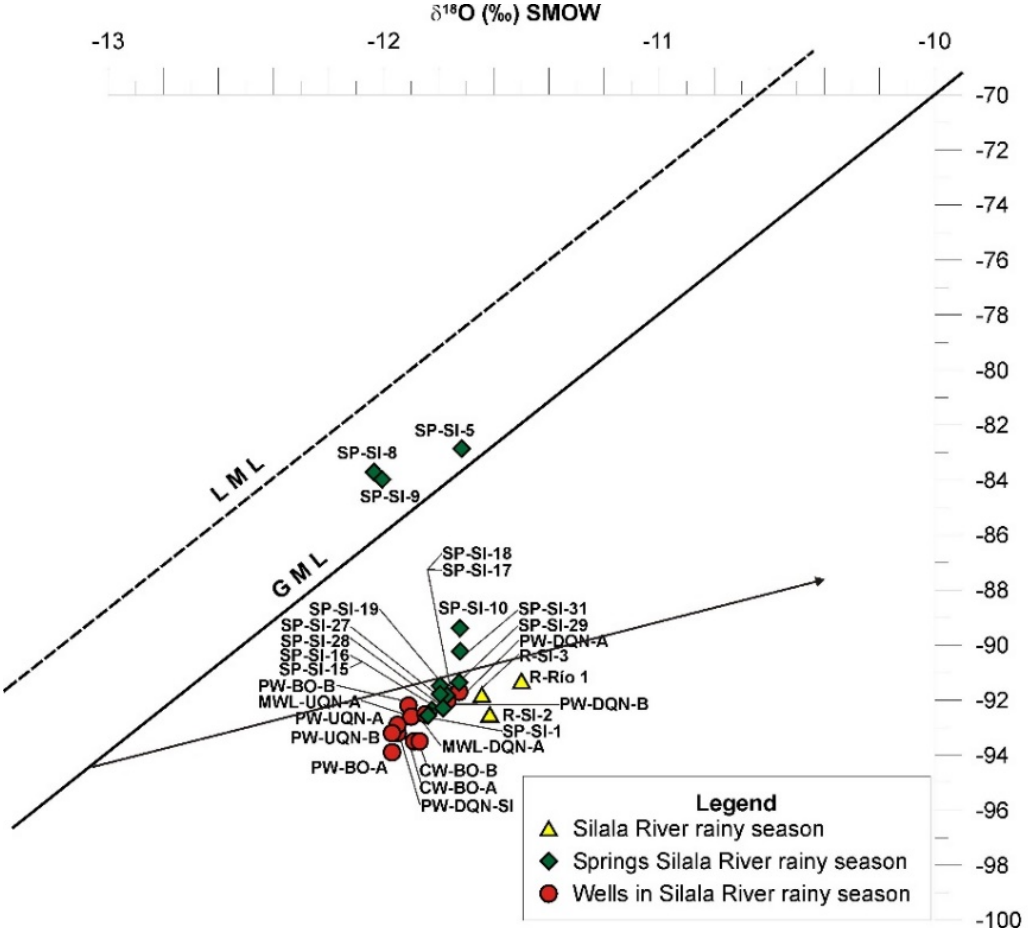


Figure 4-2. Plot of $\delta^{18}O$ and $\delta^{2}H$ for river, spring water and wells water in the rainy season (Herrera and Aravena, 2019a).

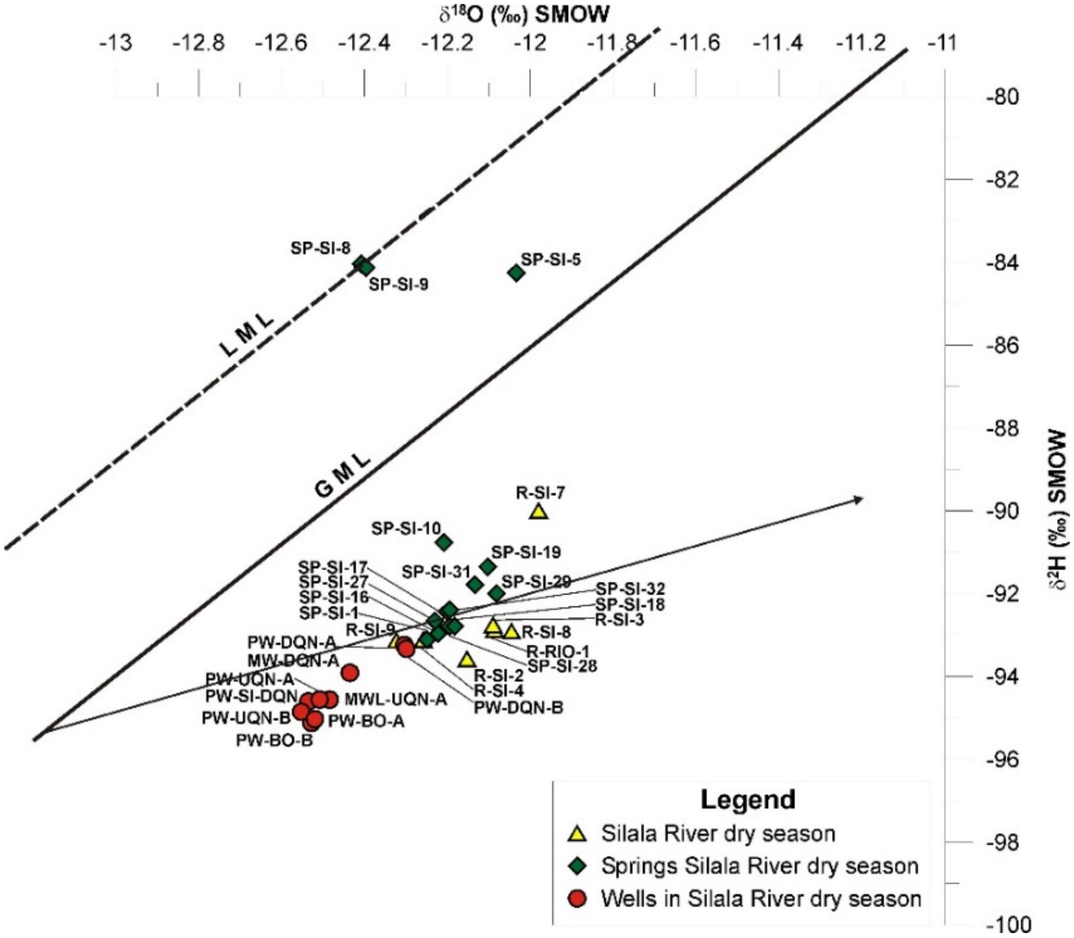


Figure 4-3. Plot of $\delta^{18}O$ and $\delta^{2}H$ for river, spring water and wells water in the dry season (Herrera and Aravena, 2019a).

Spring water from a Quebrada Negra spring, SP-SI-10, has an isotopic composition in the range of the spring water issuing from the northern side of the river course upstream of the junction with the Quebrada Negra.

The isotopic data for the groundwater in both seasons also have a similar fingerprint, which suggests that all these waters are associated with recharge areas at similar altitudes. However, in the dry season the group of groundwaters tends to be somewhat separate from the spring waters, so it may be that the regional aquifer is recharged at higher altitude than the river and springs in Chile.

It is clear from these isotope data and the chemical analyses (Herrera and Aravena, 2019a and 2019b) that both river water and springs in Chile upstream of the Quebrada Negra are likely to be closely related. Electrical tomography (Arcadis, 2017) has shown the likelihood of perched aquifers in the Alluvial deposits (Herrera and Aravera, 2019a; Arcadis, 2017) on the southern side of Cerro Inacaliri. It seems likely that recharge to these perched aquifers in the Alluvial deposits, which overly the Chilean Silala Ignimbrite, and possibly the Cabana Ignimbrite, supplies shallow groundwater to the Silala River springs in Chile upstream of the Quebrada Negra. The alluvial deposits in which these perched aquifers are found are undoubtedly contiguous with similar deposits in Bolivia that would similarly be expected to support perched aquifers. Similarly, perched aquifer(s) in the widespread andesitic lava flows (SERNAGEOMIN (Chile), 2017) that outcrop in Bolivia to the north west of Cajones wetland and to the north of the Orientales wetland are likely to supply the groundwater feeding the springs in the Cajones and in part the Orientales wetlands in Bolivia.

4.3.2. Carbon-14 and Carbon-13 data

There is detailed discussion in Herrera and Aravena (2019a), of the basis for Carbon-14 dating and the use of Carbon-13 in correcting for several complicating features, namely carbon input to groundwater from the soil zone, dissolution of carbonate minerals and from carbon dioxide from volcanic rocks. Because of the complications and uncertainty attached to such corrections, Herrera and Aravena restricted their interpretation of the ^{14}C content of the groundwaters sampled in the Silala River groundwater catchment area to the use of the percent modern carbon (pMC) as a tracer to evaluate the river-groundwater interactions and river-springs interactions. In general, the higher the pMC value the younger the water will tend to be. The Bolivian dates (BCM, Vol. 4, Table 14, p. 92) are not believed to be credible, because of these complications.

The Chilean sampling sites and pMC data for the dry season are shown on Figure 4-4 together with the Bolivian sites and data. The Bolivian data were taken from DHI (BCM, Vol. 4, Table 14, p. 92).

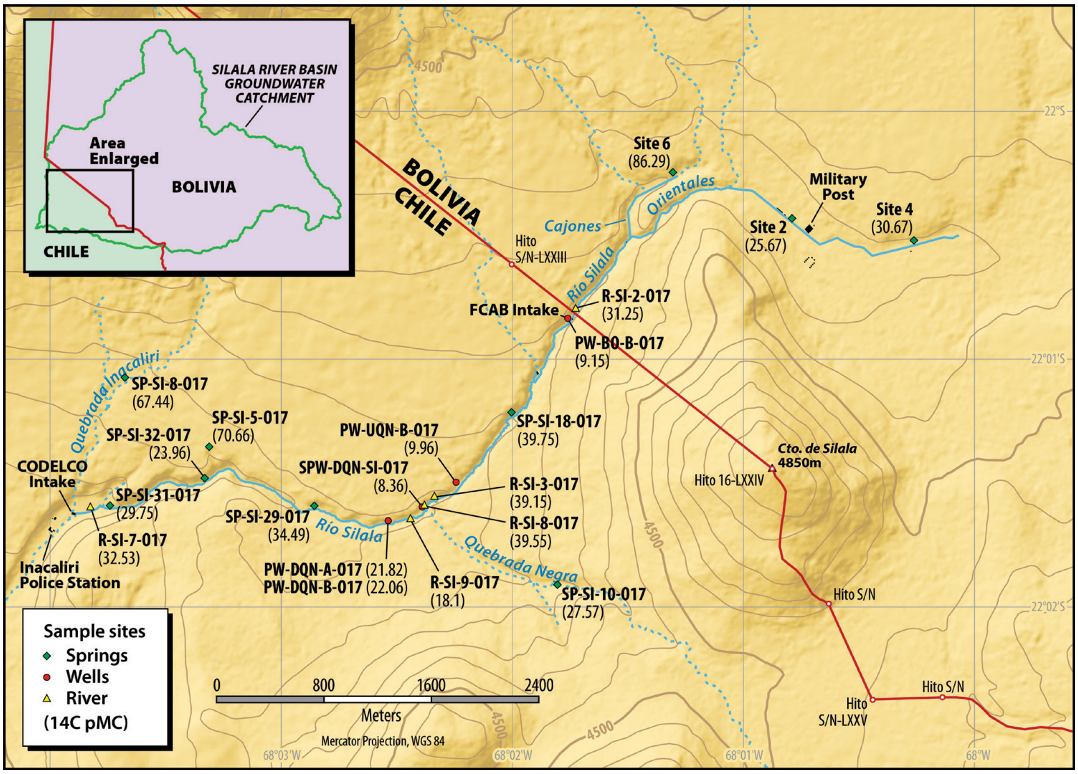


Figure 4-4. Distribution of ^{14}C sampling points in the Silala River basin in Chile (in the dry season) and Bolivia together with values of percent modern carbon (^{14}C pMC) (Herrera and Aravena, 2019a).

From a pMC value of 31.25 (Figure 4-4) at the international border, ^{14}C increases as the water flows downstream in the Silala River in Chile. This is attributed to lateral groundwater contributions from the springs flowing into the river from the north side of the ravine. Further down-gradient beyond the junction with the Quebrada Negra, the ^{14}C content of the river decreased to 18.1 pMC. This is caused by a contribution from groundwater discharge from the artesian well, sample SPW-DQN-SI-O17, which has a ^{14}C content of 8.36 pMC, i.e. much older water (Figure 4-4). Downstream of this well, further groundwater contributions from springs from perched aquifers cause an increase in pMC in the river. There is no information on ^{14}C from river samples given in DHI, 2018.

In contrast, much higher ^{14}C values were found in samples from the springs to the north of the ravine downstream of the Quebrada Negra in both the dry and rainy seasons, ranging between 67.44 and 70.66 pMC. These values are comparable to the ^{14}C value of 86.29 pMC that was reported for a spring located in Bolivia, supplying the Cajones wetland. Lower ^{14}C values of 25.67 and 30.67 pMC, similar to the springs in the Chilean sector, are observed in the springs located in the Orientales wetland in Bolivia. These springs have higher salinity than the northern (Cajones) wetland springs, similar to that of groundwaters sampled in Chile, suggesting that the springs are associated with groundwater discharge of a regional groundwater flow system. The spring located in the Quebrada Negra (sample SP-SI-10-O17), which may represent discharge of a regional flow system, perhaps recharged at higher altitude in Bolivia, has a pMC similar to those springs in the Orientales wetlands.

The deep groundwaters sampled in Chile have much lower ^{14}C values (Figure 4-4) than the springs, the Silala River or Bolivian samples. As noted above, the lowest ^{14}C value of 8.36 pMC was obtained from groundwater discharging from the artesian borehole, sample SPW-DQN-SI-O17. The groundwater flowing from this borehole would normally be confined beneath the upper layers of the Chilean Silala Ignimbrite.

DHI (BCM, Vol. 4, p. 103), based on the Bolivian ^{14}C data, suggest an "***old age in the southern wetland (up to ~ 11,000 years) and a significantly younger age in the northern wetland (up to ~ 1,000 years)"***. While it is certainly correct that these waters have different origins and chemistries, as shown above, these age estimates are not correct since they do not take into account the dilution effect due to dissolution of carbonates along the groundwater flow system and the potential input of volcanic CO_2 (Herrera and Aravena, 2019a).

4.4 Conclusions concerning the origins of the spring waters in the Silala groundwater catchment

Clearly, the Silala River water that crosses the International border is closely related to the spring flows emerging from the Bolivian wetlands. Nevertheless, the chemical and isotopic analyses reveal that the groundwater flow systems are complex. The proposal of a perched aquifer or aquifers, which supply the springs in the area to the north of the Silala River ravine, upstream of the junction with the Quebrada Negra, is justified considering the difference between the chemistry of the springs and the deep groundwaters and the fact that the deep groundwater levels in Chile are well below the elevation of the river. The groundwaters and surface waters that are found in the Quebrada Negra wetland present further complexity. They are higher in magnesium than any other others analyzed in the Silala River basin and seem to influence the chemistry of the Silala River downstream of the junction with the Quebrada Negra ravine, but their high salinity would indicate that they may be related to a regional deep aquifer.

The difference in salinity, major ion chemistry and ^{14}C pMC values between the Cajones spring waters and the Orientales spring waters are marked and indicate different origins for the two sets of springs in Bolivia.

The chemical and isotope analyses of the spring waters in the Cajones area show strong similarities to those of the springs found on the northern side of the Silala River ravine, downstream of the junction with the Quebrada Negra. These latter waters have $\delta^{18}O$ and $\delta^{2}H$ consistent with a locally recharged origin.

The chemical and isotope analyses of the spring and shallow groundwaters from the Orientales wetland indicate a different origin, which seems likely to be a mixture of shallow, locally recharged groundwater (probably from the alluvial deposits or Pleistocene lavas of the Inacaliri and Apagado) and groundwater from a regional aquifer. Some of the samples showed great similarities to the deeper groundwaters analyzed in Chile.

It is evident that the chemical character of the spring waters of Orientales and of Cajones is distinctly different. However, in the DHI Near Field model no account appears to have been taken of these differences and of the differing origins for the two sets of spring discharges, so the performance of the model in representing the spring discharges is likely to be flawed. Hence simulated scenarios to predict what these spring flows might have been in a natural condition, without channelization or with a restored wetland, are also likely to be flawed. The recharge to one set of springs finds its way via groundwater flow paths that are distinctly different from the other, and hence it is highly likely that the residence times for groundwaters discharging from these springs would be quite different. Therefore, they cannot sensibly be modelled as if they are the same and have the same recharge areas and the same origins. This leads to the conclusion that the modelling is based on an incorrect conceptual understanding of the groundwater flow regime and will therefore produce flawed results and predictions.

5 SUMMARY OF THE HYDROGEOLOGY OF THE SILALA GROUNDWATER CATCHMENT - AREAS OF AGREEMENT AND DISAGREEMENT BETWEEN CHILE AND BOLIVIA

In this section we summarize the hydrogeology of the Silala groundwater catchment and hence indicate the deficiencies in DHI's modelling, which fails to correctly represent the hydrogeology. This matters because unless the hydrogeology is represented properly the results of various scenario predictions are likely to be incorrect.

In briefly describing the hydrogeology of the Silala basin we bring together the evidence from the geological mapping, radiometric dating and drilling with the interpretations of hydrogeochemical analyses in both Chile and Bolivia, which provide convincing support to Chile's hydrogeological understanding of the groundwater flow regime in the Silala basin.

It is clear that there are at least two aquifer types that are active in the catchment in Chile:

a. A perched aquifer system that is present in the alluvial deposits overlying the bedrock volcanic formations found in the Silala basin (Arcadis, 2017).

b. A regional aquifer system formed by a succession of ignimbrite deposits that is interbedded with fluvial debris flow deposits in Bolivia and Chile and is recharged from the Silala River groundwater catchment (Arcadis, 2017; DHI, 2018).

It is also clear that recharge to the groundwater catchment, most of which lies in Bolivia, that enters the ignimbrite regional aquifer either emerges at the Bolivia wetland springs or flows within the ignimbrites (in Chile, the Chilean-named Silala Ignimbrite or the Chilean-named Cabana Ignimbrite). There is a clear groundwater level gradient to Chile from Bolivia in the ignimbrites (Arcadis, 2017), as agreed by the Bolivian experts. The only way that groundwater in the regional aquifer provided by ignimbrite succession can reach Chile is either as surface flow from springs in Bolivia's Near Field area, in particular the Bolivian Cajones and Orientales wetland springs, or by flowing as groundwater beneath the area of the Bolivian Near Field model down the hydraulic gradient to Chile. There is no other possible route for such groundwater flows because of the edifices of Cerro Inacaliri and Volcán Apagado, whose roots are built upon low permeability Miocene Volcanic deposits (SERNAGEOMIN (Chile), 2019).

The hydrogeochemistry analyses have provided strong evidence to support the existence of these two distinct aquifer systems, which, for the most part, are not well connected (Arcadis, 2017; Herrera and Aravena, 2017; Herrera and Aravena, 2019a and 2019b). However, DHI do not include these as separate aquifer systems in their Near Field model, even though they agree that ^{14}C isotope data show distinct differences between the waters of the Orientales wetlands and the Cajones wetlands. The configuration of the geology and hydrogeology of the Silala groundwater catchment, as developed with strong evidence by Chile, is not incorporated into the DHI Near Field model.

Recharge from precipitation (both rainfall and snowmelt) infiltrates both aquifer systems, and groundwater flows to a number of spring systems in Chile (some of which support the Quebrada Negra wetland (Muñoz and Suárez, 2019) and in Bolivia, where they support the Cajones and Orientales wetlands (Arcadis, 2017; Muñoz et al., 2017; DHI, 2018).

This recharge provides the flow to the spring and wetland systems. However, the detail of the geology is highly complex (SERNAGEOMIN (Chile), 2019). This means that the groundwater flow paths, the distribution of permeability and origins of recharge to different spring systems are also complex and not precisely known.

Although there is agreement between the experts on the existence of a regional aquifer in ignimbrite rocks, the Bolivian interpretation of the three-dimensional nature of this aquifer system has been shown to be incorrect in several respects:

- It is clear that the ignimbrite aquifer system identified in Chile (the Chilean Silala and Cabana Ignimbrites), together with an interbedded fluvial debris flow (section 3, above) has not been recognized by DHI in their report (DHI, 2018), nor incorporated into their models.

- The evidence presented shows that the existence of a major fault system located beneath the Silala River ravine is wholly implausible. DHI incorporate this fault system as a particular distribution of high permeability in their Near Field model, which consequently is based on an incorrect conceptual understanding of the geology and hydrogeology.
- The DHI modelling takes no account of the vertical variability of permeability in the regional ignimbrite aquifer, as clearly demonstrated by the artesian flowing conditions at the Chilean borehole SPW-DQN, which implies a significant confining layer.
- The impact on the groundwater flow system in the catchment due to the faulting at the downstream end of the Silala topographic catchment has not been considered by DHI in their modelling.
- Finally, the difference in origins of the recharge to the Bolivian wetland spring systems has not been incorporated in DHI's Near Field model (section 4.4 above).

It is clear that the hydrogeology of the groundwater catchment is highly complex and many of the features identified in Chile have not been taken into account by DHI in their modelling. Given in particular the subtle nature of the changes associated with the channelization in Bolivia, and lack of recognition of key features of the hydrogeology, DHI's scenario predictions must be seen as severely flawed.

6 DISCUSSION ON THE ENHANCEMENT OF SPRING FLOWS IN THE CAJONES AND ORIENTALES WETLANDS BY THE USE OF EXPLOSIVES

In this section we briefly discuss the assertion made in the BCM that explosives were used to develop the spring sources in the Bolivian wetlands. We conclude that enhancement of spring flows by explosives methods as described in the BCM would not be possible.

Bolivia refers to the use of explosives to enhance spring discharges ('Many of the spring discharge points in Bolivia still clearly evidence the use of explosives'; BCM, Vol. 1, p. 47).

The only evidence to substantiate this claim is a single photograph (BCM, Vol. 4, p. 101, Figure 44), which includes the bracketed phrase "(precipitates on rock)". This is entirely insufficient for DHI to make the statement 'Based on the rock blasting in the area of the many of the springs, the current hydraulic gradients may have been altered from natural conditions' (BCM, Vol. 4, p. 101). If rock blasting had been used to excavate the channels at the spring emergences, it is our opinion that the effects on the hydraulic gradients would be insignificant.

While rock blasting has been used elsewhere to enhance pumped well yields, it is in our opinion highly unlikely, given the long history of spring discharges (over centuries and potentially millennia) and associated natural processes of erosion, that any blasting, had it occurred, would have had a significant impact on spring discharges. The BCM cites Driscoll, F.G., 1978 (BCM, Vol. 1, p. 47) as evidence that blasting can enhance water flows by a factor of 6 to 20. The article they refer to, concerns the development of deep borehole water supplies in poorly fractured granites, quartzites and slates, not springs. These rocks are metamorphic and have undergone considerable changes due to high pressure and temperature. They are normally very poorly permeable. The ignimbrites of the Silala wetlands, by

Bolivia's own evidence, are highly fractured, and have major and minor jointing (SERGEOMIN (Bolivia), 2017).

The deep (well over 100 metres) boreholes undergoing the cited blasting development were plugged with sand to direct the blast horizontally. Significant development of spring flow would not be possible using these methods. Bolivia's assertion that explosives have been used to enhance spring discharges is therefore not credible.

7 CONCLUSIONS

(i) What new evidence has been produced, since Chile submitted its Memorial in July 2017, concerning the understanding of the geology and hydrogeology of the Silala River?

New investigations in the Silala River topographic catchment have included field observation, re-logging of borehole drill cuttings, geological mapping and radiometric dating of the Chilean-named Silala Ignimbrite and Pliocene lavas. This new information has revealed a more detailed understanding of the stratigraphy in Chile and the extensive presence of a debris flow that lies at the base of the Chile-named Silala Ignimbrite and the upper boundary of the Chilean-named Cabana Ignimbrite. It has also revealed a major fault in Chile, a few hundred metres below the junction of the Silala River and the Quebrada Negra tributary valley. The stratigraphy and this structure have not been considered in the Bolivian hydrogeological conceptual understanding or incorporated into their numerical models. DHI introduce a new fault system running through the Bolivian wetlands and down the Silala River ravine into Chile (DHI, 2018), but no evidence to support this has been found in Chile.

New hydrogeochemical investigations have revealed the distinct character of the spring and groundwater of the Quebrada Negra. And in conjunction with the

Chilean data, Bolivian chemical and isotopic analyses have revealed: a) the distinctly different recharge origins of the spring water of the Bolivian wetlands, Cajones (referred to in DHI, 2018 as the North Wetland or Bofedal) and Orientales (referred to in DHI, 2018 as the South Wetland or Bofedal), and b) the close similarities of the Chilean spring waters, recharged from perched aquifers, to the spring and groundwaters of the Cajones wetland in Bolivia. As with the geological structure and stratigraphy, above, this important difference in recharge to the two Bolivian springs is not incorporated in DHI's modelling.

(ii) Does the hydrogeological conceptual understanding and parameterisation of the numerical models of Bolivia's expert, the Danish Hydraulic Institute (DHI), provide an adequate basis to quantify the effects of channelization on the surface water and groundwater flows from Bolivia to Chile?

The DHI numerical models incorporate an incorrect stratigraphy and an implausible fault system and take no account of the down-gradient Chilean geological structure or the difference in origin of the Cajones and Orientales springs waters. In particular,

a. The ignimbrite aquifer system identified in Chile (the Chilean Silala and Cabana Ignimbrites), together with an interbedded fluvial debris flow has not been recognized by DHI in their report (DHI, 2018), nor incorporated into their models, neither has the vertical heterogeneity in permeability. This will undoubtedly mean that the groundwater flowpaths that they simulate as a result of their models' permeability distribution will be wrong.

b. The fault system that they propose will also affect the groundwater flowpaths and the ease with which groundwater can move in their invoked fault system region.

c. The different origins of the Cajones and Orientales spring waters are due to the two distinct aquifer systems identified by Chile (with considerable supporting evidence (sections 3, 4 and 5), but these have not been included in the DHI models.

d. The faulting mapped at outcrop downgradient in Chile and the presence of Pliocene lavas (sections 3 and 5) between the two (Chilean) ignimbrites (in Chile) which cause a decline in the permeability of the Cabana and Silala Ignimbrites in Chile has similarly not been considered.

We conclude that the DHI models do not simulate the groundwater system properly and are unfit to quantify the effects of channelization in the Bolivian wetlands or accurately represent the current hydrological system.

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

The evidence for showing that the groundwater-fed springs of the Cajones and Orientales wetland has been enhanced by explosives is flimsy and the reference to development of deep borehole yields by explosive methods is inapplicable. The springs could not have been developed significantly to increase yields by the explosive methods suggested by Bolivia.

In summary, we have shown that the numerical modelling results that have been presented by Bolivia to demonstrate the alleged effects of channelization in the Bolivian wetlands are incorrect. Their models are based on a misrepresentation of the current hydrological system and the proposed scenarios. In short, with this conceptual basis, their models could only produce implausible predictions.

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Statement of Independence and Truth

1. The opinions I have expressed in my Reports 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 Report.

2. I understand that my overriding duty is to the Court, both in preparing the two Expert Reports that accompany the Reply of the Republic of Chile 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 Reports, to be accurate and complete in answering the questions posed by the Republic of Chile in the terms of reference which are reproduced in the Reports. I consider that all the matters on which I have expressed an opinion are within my field of expertise.

4. In preparing these Reports, 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

24 January 2019

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Dr. Denis Peach
Hydrogeologist

24 January 2019

LIST OF ANNEXES TO THE REPLY OF THE REPUBLIC OF CHILE

VOLUME 2

ANNEXES 92 - 99

LIST OF ANNEXES TO THE EXPERT REPORTS

VOLUME 3

ANNEXES XI - XIV

CERTIFICATION

I certify that the annexes and reports filed with this Reply are true copies of the documents referred to and that the translations provided are accurate.

Ximena Fuentes T.
Agent of the Republic of Chile
15 February 2019