The path to groundwater sustainability for lithium mining: the Salar de Atacama, Chile

Matt Floyd- 6857892
Contact: m.j.floyd@students.uu.nl
Water Science and Management
Course: GEO4-6004 Master's thesis (internship)
Supervisor: Thilo Behrends
Word count: 12838 (excluding references and table of contents)

Date: 26-07-2021
Faculty of Geosciences, Utrecht University

ACKNOWLEDGMENTS

Firstly, I would like to thank my supervisor, Dr. Thilo Behrends for his generosity in providing his time, advice and expertise towards this project. I would also like to thank Giovanni Cecchetto for the opportunity to join the Hidrosingeria project. Your guidance and support has made this internship an enjoyable one. A special mention also for Erik Young and Dr. Miguel Marazuela who were kind enough to advise me on the more technical aspects associated with this thesis.

ABSTRACT

The Salar de Atacama was used as a case study to understand to what extent freshwater pumping for lithium mining is impacting groundwater sustainability. The basin is one of the driest places in the world where freshwater is a critically limiting factor that provides economic and non-economic services for many different beneficiaries. In recent years, mining companies have been criticised for their pumping causing harm to the ecosystems and indigenous communities. With the increasing demand for lithium in electric vehicles, the current permitted pumping rate is expected to increase and impact groundwater sustainability. This evaluation encompassed both aquifer governance and aquifer performance components. The latter was determined using the groundwater balance method to quantify storage changes, the ratio between pumping rate and recharge rate and the renewal time. To account for short-term fluctuations of the flow components, the water table fluctuation method determines the impact of pumping on the groundwater table of the marginal zone. Aquifer governance was discussed through a legal-institutional perspective with a focus on how stakeholders are involved in governance and the current management of the system. There was poor consensus between stakeholders and a disregard towards indigenous rights and values characterised by inefficient state law. Indigenous communities were involved in governance through consultations, public meetings, and successful appraisals but conflict has been rife. For aquifer performance, the average recharge rate was superior to pumping indicating renewable groundwater availability for the current and future generations. This statement holds providing that pumping can be balanced by reducing the other outflow components. Supply decreased between the mining and natural period although the groundwater balance was not accurate. The water table fluctuation method was deemed more accurate since it had the most direct observation of changes in storage from monitoring well data with fewer assumptions and components. Low drawdown in the alluvial fans and marginal zone shows that freshwater pumping had minimal impact on the groundwater reserve. As a result, the aquifer governance of the basin was weak compared to aquifer performance and undermined overall groundwater sustainability. To improve sustainability, a river basin management plan should be implemented that recognises indigenous community needs in adaptable groundwater management. An expanded monitoring network with restrictions and more scientific research with a focus towards ecosystems impacts and climate influences were recommended.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

ABBREVIATIONS

Groundwater table depth (GTD)

Salar de Atacama (SdA)

Water table fluctuation (WTF)

External mixing zone (EMZ)

River basin management plan (RBMP)

Digital elevation model (DEM)

1 INTRODUCTION

1.1 Lithium mining

Worldwide demand for electric vehicles is expected to triple and reach a value of $100 billion by 2050 (Latham et al., 2019). This clean mode of transport has a reduced climate impact compared to internal combustion engines. Lithium batteries are currently the principal technology for electric vehicles and will account for 79% of lithium demand by 2030 (Staff, 2020). As a result, lithium demand is estimated to more than double from 47,300 tonnes in 2020 to 117,400 tonnes in 2024 (GlobalData, 2020). Failure to increase lithium supply could threaten global climate efforts. Therefore, it would be a mismatch to associate increased production of lithium for a more sustainable society with non-sustainable mining practices (Flexer et al., 2018). The main producers of lithium include Australia, China, Argentina, Zimbabwe, Portugal, and Chile. Lithium extraction in these countries is sourced from either the hard-rock mining of spodumene (ore containing high levels of lithium) or through the solar evaporation of saline groundwater (brine) The latter process mainly occurs in the South American Lithium Triangle (fig. 1.1).

Figure 1.1 The South American Lithium Triangle is made of Chile, Bolivia and Argentina. The main salars in this region are the Atacama and Uyuni. Lithium is extracted from these Salars (Jerez et al., 2021)

This region borders Bolivia, Argentina and Chile, and has an estimated 70% of the world's lithium reserves (Liu & Agusdinata, 2020). The brine occurs in continental saline desert basins known as salars and is pumped to the surface into large ponds, where through solar evaporation the liquid water content is removed until the brine reaches an ideal lithium concentration (fig. 1.2). The brine is then transported to a treatment plant to form lithium carbonate and further used to produce lithium hydroxide, useful for cathodic materials in lithium batteries (Grageda et al., 2020).

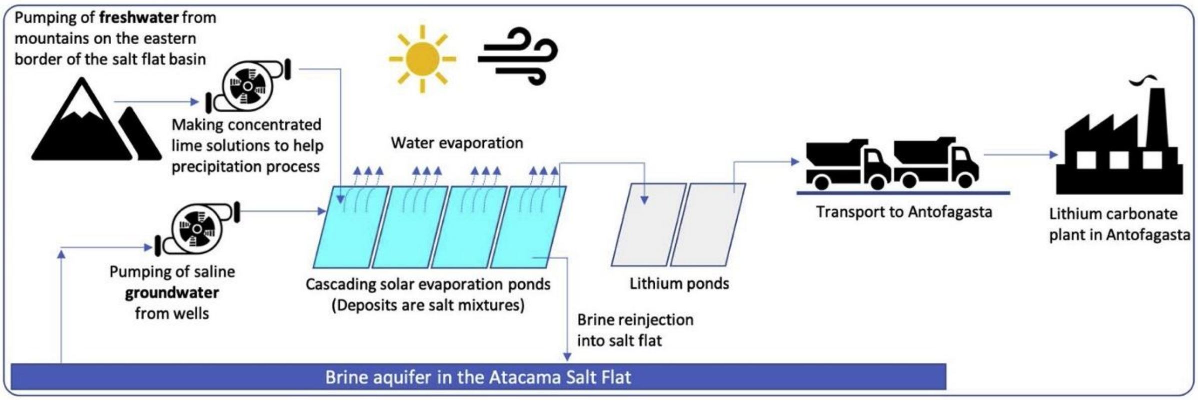

Figure 1.2 Current method for lithium extraction from brine pumping in the Salar de Atacama (Liu et al., 2019)

The high altitude and low rainfall of the South American Lithium Triangle provides unique conditions that results in some of the highest evaporation rates in the world (Bustos-Gallardo et al., 2021). This makes the region an effective location for lithium extraction since it has lower costs in the production stage compared to spodumene extraction. For example, production costs from spodumene in Australia costs an average of $5,000 per tonne compared to brine production in Chile at $1,800 per tonne (INN, 2018). This is why some of the world's most profitable lithium mining operations are from brine deposits such as the Salar de Atacama (SdA) in Chile.

1.2 Freshwater pumping in the SdA

Within the South American Lithium Triangle, the main producer of lithium brine is Chile, producing 23% of the world's total (Cabello, 2021). Home to the third largest Salar in the world, the SdA is of high economic importance with high concentrations of lithium (1500 ppm) (Garcés & Alvarez, 2020). For this reason, the mining companies of SQM and Albemarle started extracting this resource in the 1970's. From 1998, lithium production increased rapidly from 4500 ton/yr to 41,100 ton/yr in 2017 (Liu et al., 2019). This production on the SdA relies on the hydrogeological features of the endorheic basin (3,100 km^2). The basin is divided into 4 geomorphological zones: the nucleus, mixing zone, alluvial fans and volcanic rocks (fig 1.3). Water stored in the aquifer descends from rainfall falling over the volcanic rocks. In these high elevations, through lateral recharge and direct recharge, freshwater is transported and stored in the alluvial fans. Here, SQM extracts freshwater from 5 pumping wells (fig. 1.3). Freshwater then flows towards the marginal zone and meets the evaporated water (brine) resulting in a mixing zone. In the mixing zone, three hydraulic domains occur: the internal (IMZ), middle (MMZ) and external (EMZ) mixing zones (Marazuela et al., 2018). The Quelana, Peine and Tilopozo lagoons, wetlands and springs occur in the MMZ whereas the Soncor lagoon occurs in the IMZ (fig 1.3). The EMZ represents the boundary condition between the freshwater of the alluvial fans and saline water of the marginal zone.

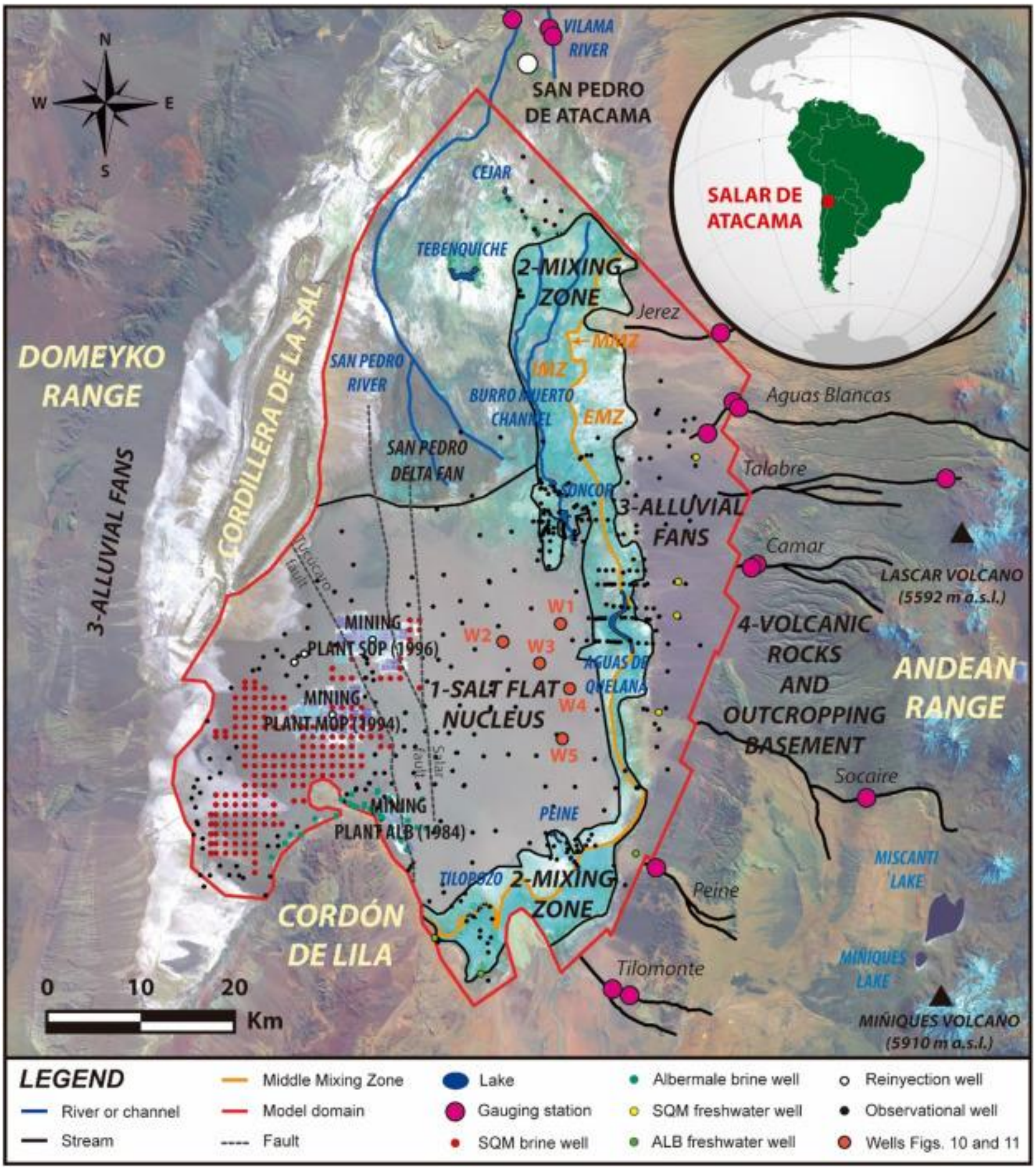

Figure 1.3 Map of the SdA basin showing the four zones of the nucleus, marginal zone, alluvial fans and volcanic rocks. The 5 SQM freshwater pumping wells (yellow dots) are located in the eastern alluvial fans (Marazuela et al., 2019a)

Under natural conditions, the groundwater table depth (GTD) was determined by a balance between inputs and outputs that were in a steady state. The rate of evaporation was controlled by the GTD. High groundwater results in high evaporation rates and the accumulation of salt deposits. As a result, the water cycle of the basin is highly sensitive to anthropogenic changes. Brine pumping in the Salar, decreases the groundwater table and increases surface evaporation. In addition, brine pumping creates a cone of depression, and the hydraulic head allows for greater mixing of brine and lesser saline water at the fringes of the nucleus. The reinjection of the excess brine also sinks due to its higher density, which alters the salinity gradient and encourages greater mixing. The pumping of freshwater in the alluvial fans increases the transportability of the brine and processes the obtained evaporates to produce the lithium salts, suitable for battery use (Guzmán et al., 2021). Freshwater pumping amounts to 260 l/s per annum and is set to increase with production expansion (SQM, 2018) . Therefore, it is important to understand how freshwater pumping from lithium mining is impacting the freshwater reserves of the alluvial fans, since ecosystems of the marginal zone and local communities rely on this resource.

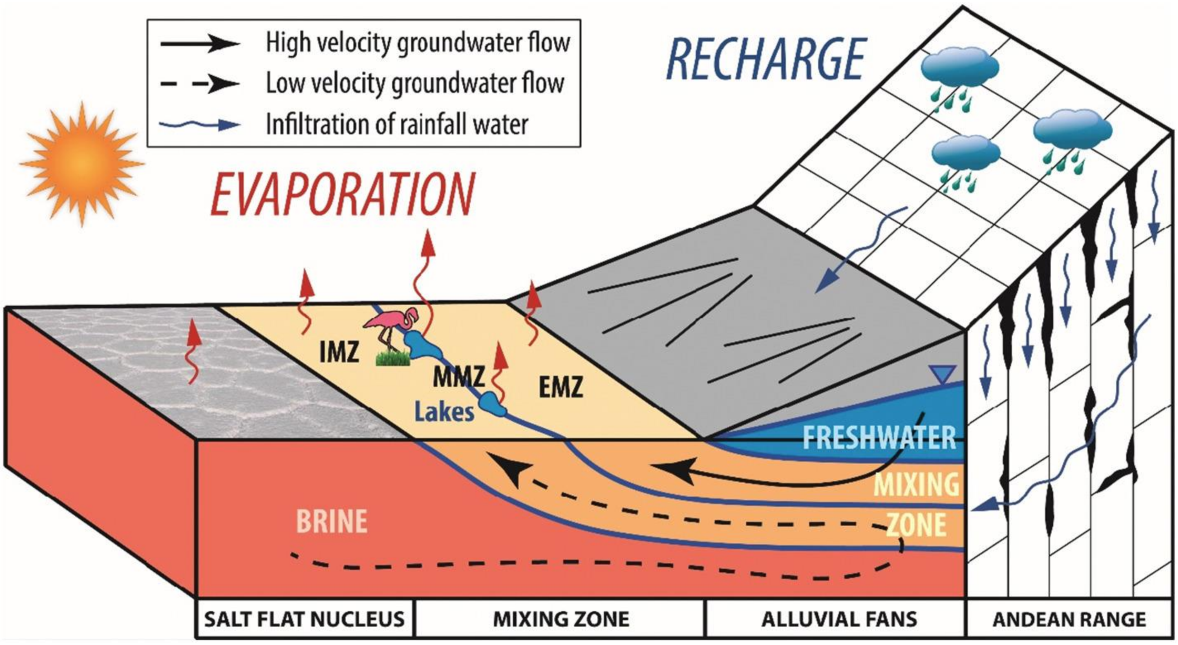

Figure 1.4 Conceptual *model of the SdA's hydrogeology. Freshwater is recharged from the alluvial fans and flows over the brine in the mixing zone. In the nucleus, the* evaporated brine sinks due to its higher density and later in the mixing zone, it retur*ns to the surface casing freshwater mixing* (Marazuela et al., 2019b)

1.3 Problem definition

Freshwater is a critically limiting factor needed for ecosystems to thrive, local communities to perform subsistence agriculture and livestock raising, and for tourism. Taken together, this resource provides economic and non-economic services for many different beneficiaries in the SdA, all of which depend on the quantity and quality of available freshwater. As a result, the major concern is over groundwater usage for lithium mining and the extent that this exploitation is sustainable.

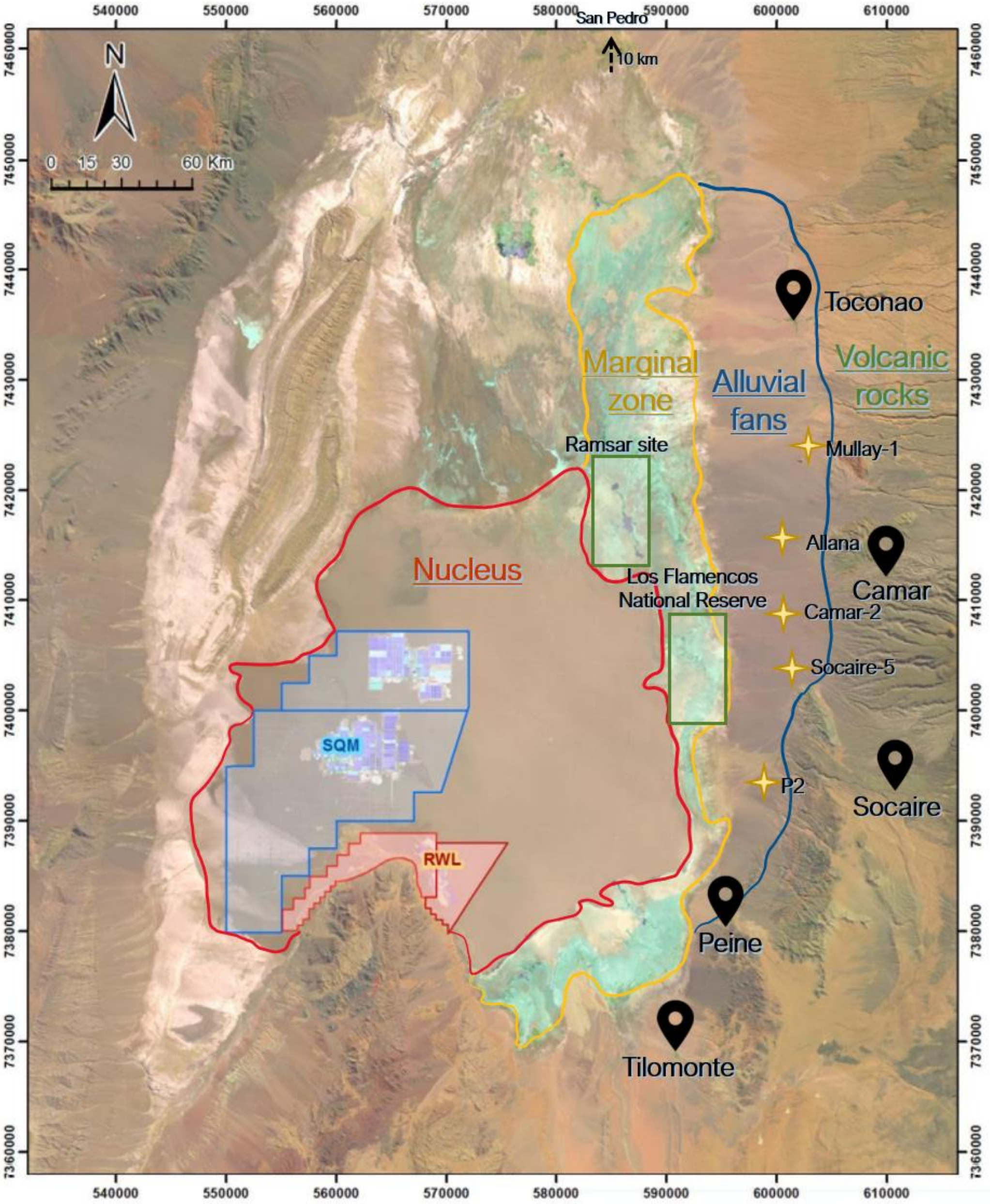

Figure 1.5 Map of the SdA showing the two mining companies SQM and Albemarle extracting brine in the nucleus (red area). To the east, the Ramsar site and Los Flamencos National Reserves are located in the marginal zone (yellow area). Freshwater is extracted from the 5 pumping wells in the Alluvial fans (blue area). A collection of towns are also in close proximity.

SQM and Albemarle have been criticised in the media due to their pumping causing harm to the ecosystem and local communities (BBC, 2019; Deutsche Welle, 2020; Mongabay, 2020). Valuable wetlands and lagoons with unique biodiversity are present in the marginal zone and are classified as a site of international importance, otherwise known as a Ramsar site (fig.1.5) (Ramsar, 2010). These ecosystems are highly vulnerable and thus require protection to maintain their intrinsic value (Gajardo & Redón, 2019). The Los Flamencos National Reserve was implemented as a protective measure in 1990 to protect the endangered migratory flamingos that feed and reproduce in the lagoons. These lagoons are also habitats for several migratory birds, halophytic shrubs/grass, some mammals, microalgae, and bacteria (Marazuela et al., 2019b). Preserving these natural ecosystems are of high economic importance since 100,000 tourists visit the Salar each year (OCMAL, 2018).

An increase in freshwater pumping, depletes freshwater supply and causes a loss of vegetation and fauna since less freshwater is discharged towards the marginal zone. In the last 20 years, satellite images show a decrease in vegetation in the marginal zone as a result of lithium mining (Liu et al., 2019). In the same time span, the extent of land occupied by lithium mining in the nucleus has increased 4 times over (Garcés & Alvarez, 2020). This expansion results in an increased pumping rate from the freshwater wells of P2, Socaire-5, Camar-2, Allana and Mullay-1, located in the alluvial fans (fig 1.5).

The current permitted pumping rate of 260 l/s is expected to increase since the Chilean government have granted SQM a new contract to expand lithium production from 70,000 ton/yr to 180,000 ton/yr by 2023 (SQM, 2018). An increased rate that exceeds the rate of replenishment from recharge causes excessive depletion of the groundwater table. This scenario is more likely to occur in consecutive dry years where rainfall is in short supply. As a result, the system is more prone to failure and less groundwater can replenish the sensitive ecosystems. The scientific challenge is determining an acceptable pumping rate that has no negative socio-economic impacts. The management challenge is more complicated. To achieve groundwater sustainability the aquifer storage must satisfy all stakeholders demands in an equitable manner whilst having a plan to ensure resilience if failure were to occur. This desired outcome is difficult to achieve since lithium mining companies in the SdA have different values towards groundwater compared to the indigenous communities. Babidge & Bolados (2018) describe this situation in terms of the struggle between '*David and Goliath'*. There is also limited state regulation that protects the groundwater resource. This exacerbates the tension between the mining companies and indigenous communities and causes water injustices for the local towns with a decrease in agricultural activities. San Pedro located in the eastern alluvial fans has historically been an agricultural oasis for the cultivation of corn, quinoa, vegetables, and fruit along with the livestock of guanacos, llamas, and alpacas (Jerez et al., 2021). With the advance of lithium mining, agriculture in San Pedro has been discouraged.

For this reason, the impact of freshwater pumping for lithium mining on groundwater sustainability should be scrutinised from a scientific and management perspective since different stakeholders rely on the groundwater of the alluvial fans.

1.4 HidroSinergia project

In the Netherlands and Chile, a project to develop a potential solution to improve the sustainability issue surrounding lithium mining in the SdA has been set up by HidroSinergia together with other partners including Ecoinvent, AFD Utrecht and EIT RawMateirals. The main goal of HidroSinergia is to assess the overall impact lithium mining is having on the basin and to provide solutions for this. The impact is being assessed from a multidisciplinary perspective. This research has been performed within the context of the HidroSinergia project and looks at the impact of lithium mining from a hydrogeological and management perspective. The aim of this research is to understand to what extent freshwater pumping for lithium mining is impacting groundwater sustainability. Recommendations will be suggested to improve the current management.

The research question that will be answered:

How is lithium mining impacting groundwater reserves and what can be done to improve the current groundwater management to achieve groundwater sustainability?

The research question will be answered through the following sub-questions:

1. What impact does freshwater pumping for lithium mining have on the natural groundwater balance?

2. What are the effects of freshwater pumping for lithium mining regarding the groundwater table?

3. Does freshwater pumping for lithium mining satisfy the conditions needed for groundwater sustainability and how can this be improved?

2 THEORETICAL FRAMEWORK

This section introduces the two concepts of groundwater storage changes and groundwater sustainability. Together, these two concepts enable this research to be centred around both a scientific and management perspective.

2.1 Groundwater storage changes

The quantification of groundwater storage changes for an aquifer can be challenging since local instruments cannot directly calculate this component. Storage changes are temporally and spatially variable and are often deduced from indirect approaches (Huet et al., 2016). Indirect approaches are associated with high uncertainties since there are a large number of assumptions.

Within the scientific literature, storage changes have been quantified through water balance approaches (Wang, 2012), streamflow analyses (Berghuijs et al., 2016), water table fluctuation (WTF) (Labrecque et al., 2020), chemical tracing (de Vries & Simmers, 2002) and numerical modelling (Abdelhalim et al., 2019). The two most popular and most widely used methods are the water balance and WTF approaches. The water balance approach is centred around the concept of mass conservation. This concept refers to the balance between inflows and outflows of an aquifer system being equal to the change in water storage. The inclusion of water balances in hydrological studies can be applied for both surface flows and groundwater flows. Since many aquifers have complex hydrological systems, it is necessary to identify the necessary components to form a water balance. For the purposes of this research, the components of a groundwater balance are included. For example, inflows include direct recharge (R_d) which is the quantity of water that replenishes an aquifer from rainfall. Similarly, indirect recharge (R_{id}) occurs from surface bodies such as rivers and lakes. Taken together, direct, and indirect represents total recharge (R_t). Inflow can also occur from irrigation return flow (RF) defined as the excess of irrigation water than is not lost through evapotranspiration (Jafari et al., 2012). Once in the saturated aquifer, groundwater flow occurs onto (Q_{on}) and off (Q_{off}) the basin (fig 2.1). Groundwater can be lost through a variety of different processes. Phreatic evaporation (E) occurs if a critical groundwater depth is reached whereby groundwater can directly evaporate through capillary rise (Brunner et al., 2008). Groundwater outflow also occurs through baseflow (Q_{bf}) which is groundwater discharge to streams or springs. Lastly, pumping (P_d) can influence the water table if water is withdrawn at a faster rate than it is replenished.

$$R_t + RF + Q_{on} = E + P_d + Q_{off} + Q_{bf} + \Delta S$$

Equation 2.1 Groundwater balance

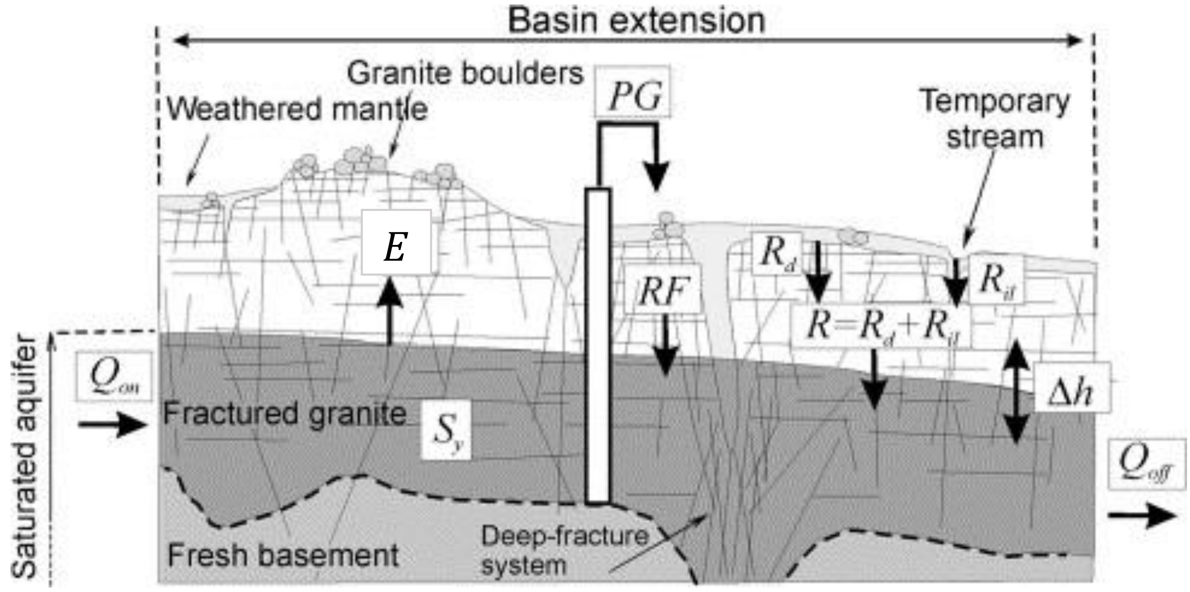

Figure 2.1 Diagram of input and output components of a groundwater balance in an unconfined aquifer (Maréchal et al., 2006)

Providing that the groundwater balance components are known with sufficient accuracy, the unknown storage quantity can be calculated. However, hydrological studies commonly have more than one unknown component to solve. Rezaei & Mohammadi (2017) used a groundwater balance in conjunction with the WTF method to quantify the unknowns of recharge and specific yield for a semiarid basin. This coupling of methods shows that components other than changes in storage can also be quantified with improved accuracy. The WTF method links the change in groundwater storage with groundwater table fluctuations (Δh). To apply the WTF approach, the specific yield (S_y) at the depth of groundwater fluctuation is needed. Koïta et al., (2018) defines the specific yield as the volume of water released per unit area for a unit decrease in hydraulic head. In other words, the specific yield is the fillable porosity of an unconfined aquifer.

$$\Delta S = S_y \cdot \Delta h \cdot A$$

Equation 2.2 Water table fluctuations relation

Since the specific yield is a dimensionless quantity and independent of time, the groundwater table fluctuations are multiplied by the aquifer area to transform the storage value into a volume measurement. Varni et al., (2013) describes the WTF method as simple and easy to apply. This is probably because groundwater table data is easy to access from monitoring well measurements. However, this approach is mostly suitable for shallow GTDs in unconfined aquifers that display sharp fluctuations (Healy & Cook, 2002). WTF are only representative of a small area whereas groundwater balances can be assessed for any size of area and for any period of time (Delin et al., 2007). As a result, the application of the WTF is more limited compared to a groundwater balance. For this reason, a plethora of studies have conducted groundwater balances for the SdA.

CORFO (1977) first identified the saline interface between the nucleus and marginal zone and divided the basin into 5 distinct hydrological sectors. In addition, a variety of evaporation rates corresponding to different surfaces for the marginal zone were determined (Mardones, 1986). DGA (1999) implemented a groundwater balance to assess if there was sufficient supply to constitute new rights to use groundwater. DGA (2010) confirmed that this supply had decreased, and water rights should be reassessed. DGA (2013) concluded that the management of the Salar must ensure that withdrawals do not exceed recharge, keeping in mind the ecological demands. Most recently, Marazuela et al., (2019a) concluded that brine pumping causes a reduction in the phreatic evaporation rate. This process is termed the damping capacity and suggests that brine pumping is indirectly reducing the outflows of the system. These groundwater balance studies do not include the impact of freshwater pumping in the alluvial fans nor specifically relate this to possible impacts in the marginal zone. This aspect could have been overlooked which has implications for the management of the SdA and the different stakeholders associated. Therefore, a management perspective that encompasses the concept of groundwater sustainability is required to compliment the scientific one.

2.2 Groundwater sustainability

To cope with the threats of groundwater exploitation, suitable decision tools are required to preserve groundwater for future generations. The factors of aquifer performance and aquifer governance collectively evaluate the concept of groundwater sustainability.

Firstly, pumping is considered safe provided the pumping rate does not exceed the rate of natural recharge. In this condition, groundwater is defined as renewable if the stored groundwater volume (stock) divided by the average recharge is less than 100 years (Bierkens & Wada, 2019). This is called the average renewable time and indicates if groundwater can be replenished for the current generations. Only the usage of renewable groundwater can be deemed sustainable. This concept ignores the potential changes in recharge that may occur during capture with increased recharge and decreased discharge. This condition is referred to as the ‘water-budget myth’ (Bredehoeft, 1997; Devlin & Sophocleous, 2005). If more discharge is captured, there is a lesser amount of groundwater available for environmental purposes further downstream. This environmental flow is the groundwater contribution needed to maintain ecosystems in the marginal zone. The pumping rate is only considered sustainable if the pumping does not cause unacceptable consequences to these ecosystems.

Instead, sustainable groundwater development recognises that the maintenance and protection of groundwater resources will not cause unacceptable economic, environmental, and social consequences (Hiscock et al., 2002). For example, pumping should not cause the depletion of surface water for ecosystems nor cause a deep cone of depression that runs dry and becomes economically unfeasible. Pumping should adhere to existing water rights and be equally distributed among water users. To meet these constraints, the aquifer performance basis of sustainable groundwater development should be extended to include aquifer governance (fig. 2.2).

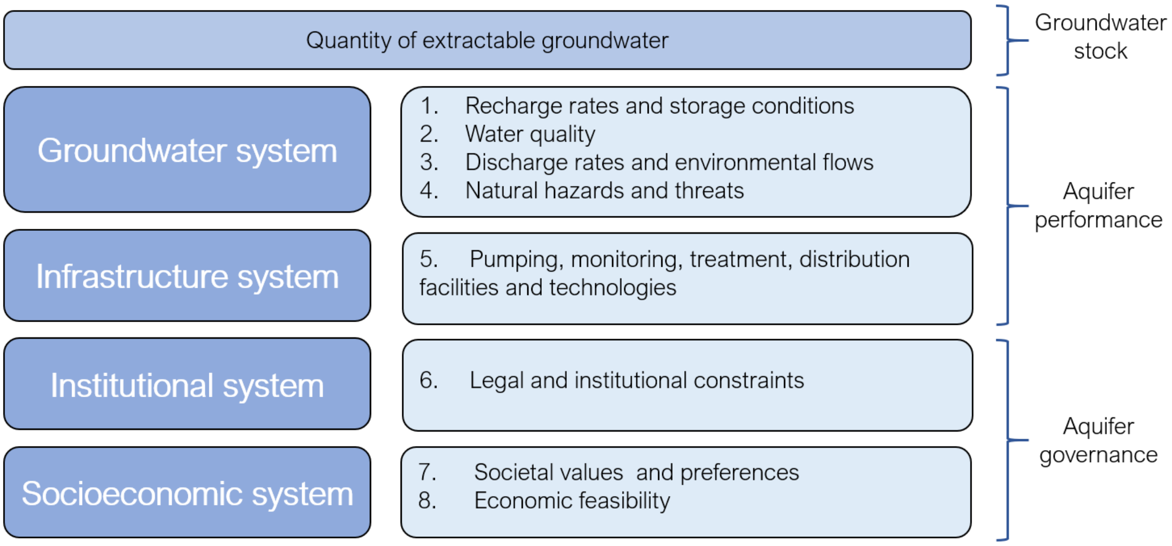

Figure 2.2 Eight sustainability factors to evaluate groundwater sustainability as a function of aquifer performance and aquifer governance. (Elshall et al., 2020)

Gleeson et al., (2020) states that aquifer governance involves decision making amongst various stakeholders that define and meet resource goals. Legal and institutional constraints include water rights for the indigenous communities of the SdA. This sustainability factor also includes restrictions on pumping, regulations on water efficiency and tariffs (Rahimi-Feyzabad et al., 2021). In addition, the socioeconomic system considers trade-offs between different societal values and their preferences towards groundwater use as well as the estimation of costs relating to groundwater development.

Different stakeholders have contrasting societal goals in relation to groundwater management. To achieve groundwater sustainability, their values towards groundwater should be acknowledged. Haileslassie et al., (2020) states that groundwater values are reliant on who defines it since different perspectives can cause diverging values. As a result, the decision-making process is challenging to incorporate and encompass all values within groundwater management. For example, the indigenous communities of the SdA believe that their water is a spiritual force, and they have a responsibility to protect it (Babidge & Bolados, 2018). This intangible value cannot be seen or touched, so how can this be included within groundwater management? For pumping to adhere to groundwater sustainability, this value must be upheld. However, groundwater management usually favours towards economic and aesthetic aspects compared to societal and cultural needs (Rudestam et al., 2018). This idea of inclusivity is needed, whereby together different stakeholders can participate and reach an agreement that is fair for all. Therefore, groundwater sustainability is defined as *'maintaining long-term, dynamically stable storage (and flow) of high-quality groundwater using inclusive, equitable and long-term governance and management'* (Gleeson et al., 2020).

Defining groundwater sustainability in this manner is important because it extends beyond the physical definitions and quantitative basis of storage changes and groundwater table drawdown that are too narrow to also include socio-economic consequences and societal values. These methods are still useful to assess aquifer performance but should be integrated with the concept of aquifer governance to holistically assess groundwater sustainability.

3 METHODOLOGY

Focusing on the alluvial fans, groundwater sustainability was evaluated based on aquifer performance and governance. Two groundwater balances were compared to determine the change in storage between the natural and mining state and identify the magnitude of the induvial flow components. To account for short-term fluctuations of the flow components, the WTF method determines the impact of pumping on the GTD of the marginal zone. An exceedance probability analysis allowed for a greater understanding of the freshwater pumping impact. As for the impact of freshwater pumping on the alluvial fans, a spatial analysis was conducted to understand complex trends. In addition, aquifer governance was discussed through a stakeholder and legal-institutional perspective. If freshwater pumping for lithium mining does not satisfy the conditions needed for groundwater sustainability, then recommendations to improve the current groundwater management were suggested to achieve groundwater sustainability. An overview of this approach is provided (fig. 3.1). A more detailed explanation is given in this chapter.

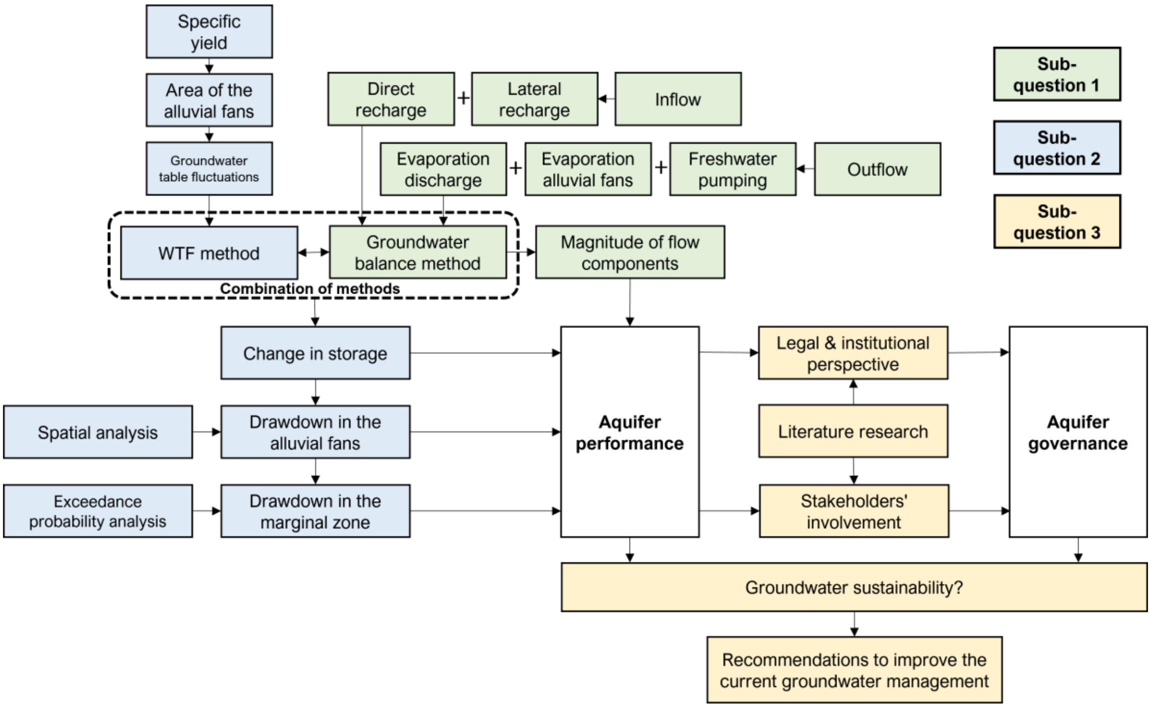

Figure 3.1 Methodology flowchart showing the steps for the evaluation of groundwater sustainability

3.1 System boundaries

This research will be for a section of the alluvial fans (347km^2) that receives freshwater from the Talabre sub-basin (852.6km^2) (fig 3.2). The system boundaries represent the alluvial fans. There are three main intermittent streams: the Camar, Talabre and Aguas Blancas flow from the Talabre sub-basin before infiltrating in the alluvial fans due to the high permeability. There are three weather stations located in close proximity: the Camar, Socaire, and Talabre Station. The Camar

Station is located at a lower altitude (2700m) compared to the Talabre Station (3300m). The altitude difference results in Talabre having higher rainfall of 73 mm/yr than Camar (37 mm/yr) (DGA, 2021). The alluvial fans have four pumping wells including Mullay-1 (Q_M), Allana (Q_A), Camar-2 (Q_C) and Socaire-5 (Q_S) (equation. 3.2). 7 monitoring wells are also located in the alluvial fans and are used to monitor the groundwater table response to pumping. The 1027 monitoring well is located in the marginal zone. Groundwater table data for this well is used to calculate the evaporation discharge. Negligible phreatic evaporation occurs in alluvial fans because the groundwater is stored further away from the surface as the average GTD is 40m. In contrast, the evaporation zones of the marginal zone have a higher rate due to shallower GTD. The two protected areas of the Los Flamencos protect the sensitive ecosystem of the flamingos.

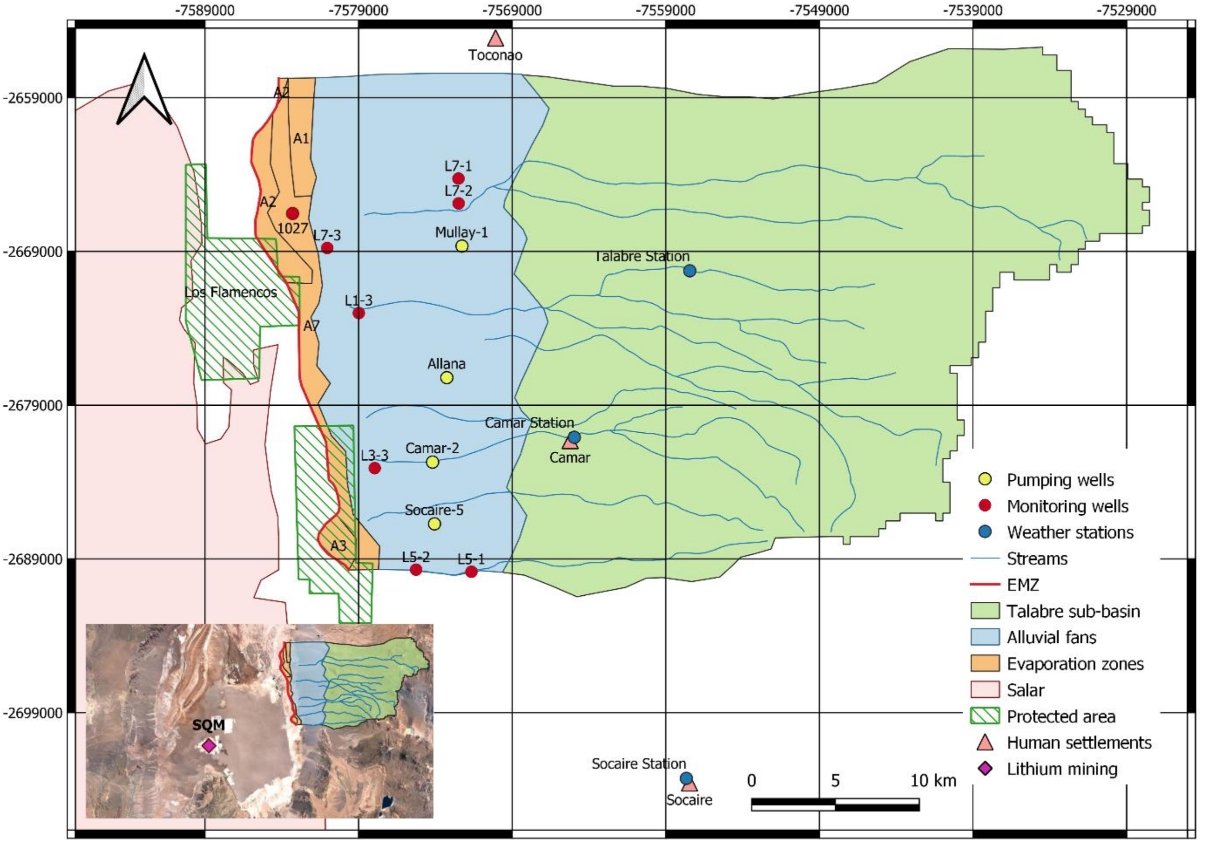

Figure 3.2 The alluvial fans (blue shade) showing streams flowing from the Talabre sub-basin (green shade). 7 monitoring wells (red circles) located in the alluvial zone and 1 in the marginal zone (orange shade). 4 pumping wells (yellow circles), 3 weather stations (blue circles) and 3 human settlements (pink triangles) are located. Two protected areas (green boxes) are located in the marginal zone next to the Salar (red shade). The EMZ (red line) represents the boundary condition where freshwater first mixes with brine.

3.2 Natural groundwater balance components

The natural groundwater balance represents the flow components before lithium mining from 1975 to 1997. The same method to calculate direct recharge, lateral recharge, stream discharge, evaporation, and evaporation discharge of the marginal zone was also used for the mining groundwater balance from 1998 to 2020.

3.2.1 Direct recharge

The calculation of direct recharge (R_d) for the alluvial fans is an important first step to compute the groundwater balance. The sparse vegetation and intermittent streams suggest that a large extent of rainfall infiltrates in the eastern mountains. Detention is where a fraction of rainfall will not infiltrate nor recharge an aquifer. Marazuela et al., (2019a) claims that approximately 35% of water is detained in the soil and returns to the atmosphere after a rainfall event for the alluvial fans. This value is justified since rainfall events lower than 5mm do not affect the groundwater table. Therefore, for each monthly rainfall event, 65% of the rainfall contributes to direct recharge. There are three weather stations in close proximity to the alluvial fans: Camar, Talabre and Socaire Stations. Using the Thiessen polygon approach in QGIS Desktop 3.16.3 the area of influence for each station was calculated. For the alluvial fans, the Camar Station had a higher weighting (75%) compared to Talabre (25%) and the Socaire (0%). The rainfall measurement was then multiplied by the area of the alluvial fans to determine the recharge volume. Direct recharge was then computed for the years of 1975 to 2020 at the yearly timestep.

3.2.2 Lateral recharge

The lateral recharge (Q_l) for the Talabre sub-basin was calculated using the same approach as the direct recharge calculation but with some adjustments. Firstly, Marazuela et al., (2019a) had a lower detention value of 25% for the Talabre sub-basin. Secondly, the Talabre Station had a higher weighting (77%) than Camar (23%) and Socaire (0%). It is assumed that all infiltrated rainfall that falls on the Talabre sub-basin flows to the alluvial fans. The combination of the lateral recharge and direct recharge represents the total recharge for the alluvial fans for the years of 1975 to 2020.

3.2.3 Evaporation of the alluvial fans

Phreatic evaporation data for the alluvial fans (E_a) was sourced from Marazuela et al., (2019a). Evaporation values were based on 3 different evaporation zones (A12b, A12d and A12e) in the alluvial fans. The evaporation values ranged from 0-1 mm/yr. Through QGIS, the evaporation zones were dissected for the area of interest. Per zone, the evaporation rates were multiplied by the zone's area to give an evaporation volume and totalled for the alluvial fans. No time series data could be collected, so the evaporation value was constant for the years 1975 to 2020.

3.2.4 Evaporation discharge of the marginal zone

It should be noted that the evaporation discharge of the marginal zone (E_m) is a separate component to the evaporation of the alluvial fans. To calculate the discharge of the alluvial fans, it can be assumed that the volume of water lost in the marginal zone through evaporation equates to the same quantity of water needed to replenish it. This assumption holds since the marginal zone is endorheic and the only exit is through evaporation. The boundary condition for this is at the EMZ, whereby the majority of water to the east of the EMZ is from the alluvial fans. In this location, 4 evaporation zones occur. Through QGIS, the A1, A2, A3 and A7 zones are dissected to the area of interest. For the calculation of the phreatic evaporation rate, the methodology of Philip (1957) was used. This method relates the potential evaporation rate at the surface (E_0) with the phreatic evaporation (E_m) for a certain GTD (z).

$$E_m = E_0 \cdot e^{(-b \cdot z)}$$

Equation 3.1 Phreatic evaporation of the marginal zone (Philip, 1957)

The adjustment parameter (b) is calculated by setting a line of best fit for the relationship between the experimental phreatic evaporation and GTD data points (fig 3.3). This approach is only possible with a lysimeter which measures the variation in GTD due to evaporation. Due to time constraints and limited resources, this type of data could not be collected. Instead, the adjustment parameter value (5.58) and evaporation rate at the surface (5.84 mm/yr) was sourced from Marazuela et al., (2020). These constant values were then multiplied by the monthly GTD data points from the 1027 monitoring well located in A7, to calculate the corresponding phreatic evaporation rate.

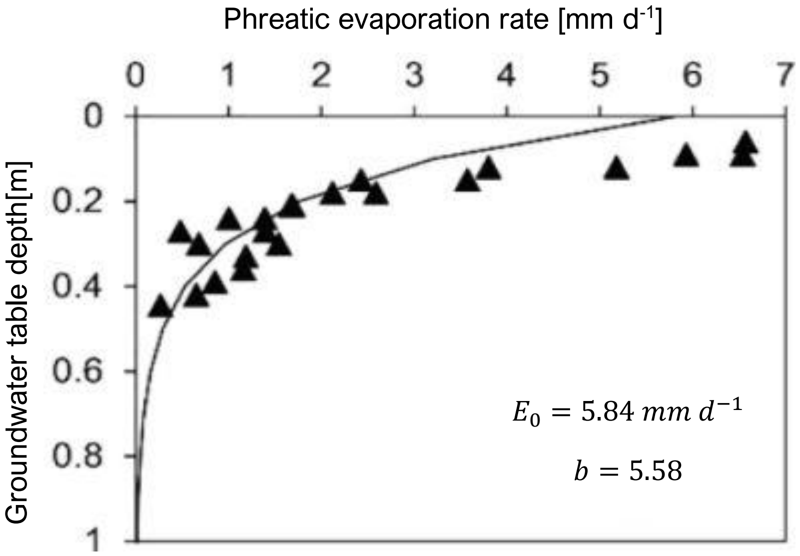

Figure 3.3 Exponential relationship between phreatic evaporation rate and GTD for the lysimeter located in evaporation zone A7 (Marazuela et al., 2020)

These monthly values were then summed into annual values and multiplied by the area of A7 to give an evaporation volume. This approach was only applicable for A7 since there were no other lysimeters in the other evaporation zones. 1027 had data points from 1998 to 2020. For the remaining evaporation zones, the constant evaporation rates for A2 and A3 in 1986 and 2018 was used (Marazuela et al., 2020) and multiplied by each area to calculate the evaporation discharge. The 1986 and 2018 values represented the natural and mining state equivalent. The A7 evaporation rate for 1986 was also used for the natural groundwater balance. There was no evaporation rate for A1. Instead, the A7 evaporation rate for this zone was used.

3.3 Mining groundwater balance

The mining groundwater balance represents the inclusion of the freshwater pumping component from 1998 to 2020. This section will help answer sub-question 1.

3.3.1 Pumping wells

The mining period was from 1998 to 2020. To conduct a groundwater balance, pumping rates (P_d) for the four pumping wells (Q_A, Q_C, Q_S, Q_W) was obtained from the SQM website, for the groundwater year 2019 to 2020.

$$P_d = Q_A + Q_C + Q_S + Q_W$$

Equation 3.2 Total pumping rate of pumping wells

The pumping rates for 1998 to 2019 were approximated from fig. 3.4. This approach obtained an average pumping rate with a resolution of 10 l/s per year. As a result, there was a higher degree of uncertainty with this data compared to the pumping rates sourced from SQM. Units were converted from litres to cubic meters for each year.

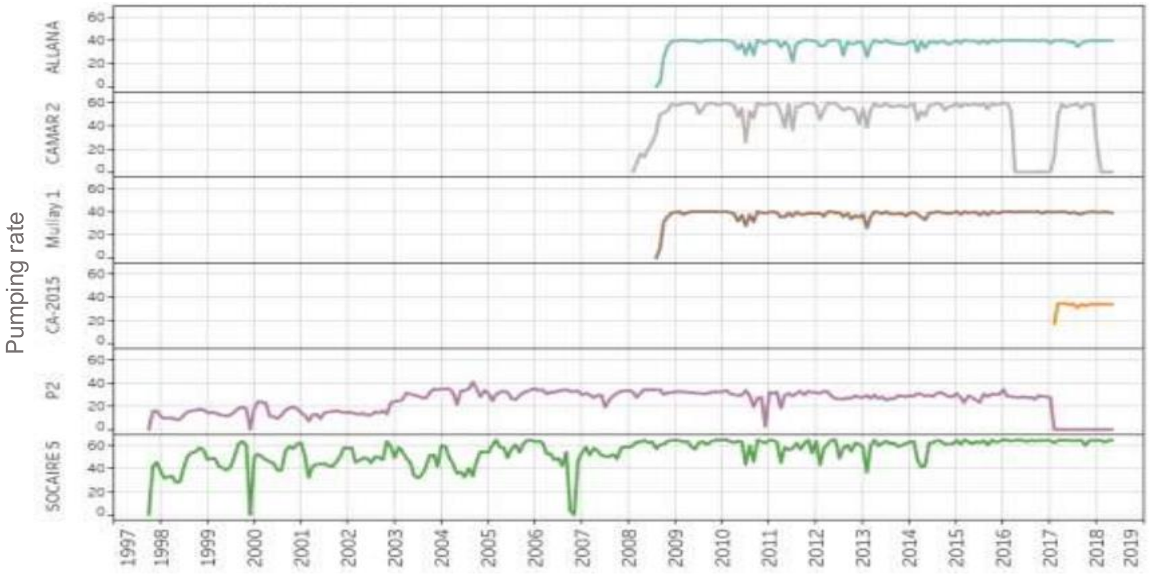

Figure 3.4 Freshwater pumping rates [l/s] for Mullay-1, Allana, Camar-2, Socaire-5 pumping wells (Albemarle, 2018).

3.3.2 Groundwater balance simplifications

Due to the large thickness of the unsaturated zone overlying the unconfined aquifer in the alluvial fans (~40m), one can assume that the groundwater discharge to surface water (Q_{bf}) is negligible. This same argument holds for transpiration since the roots of flora are unable to access the aquifer. All groundwater discharge is from pumping (P_d), phreatic evaporation of the alluvial fans (E_a) and the evaporation discharge from the marginal zone (E_m). Inflows can also be simplified. Irrigation data was not available. However, the indigenous communities use freshwater for irrigation. The quantity that could theoretically be returned is assumed negligible since this type of irrigation is small scale. The groundwater onflow to the alluvial fans represents the lateral recharge (R_l). The stream discharge was not included since the source of the streams were located in the Talabre sub-basin and was represented by lateral recharge. These streams have a small water surface and thus direct evaporation was assumed negligible. Direct recharge (R_d) was the remaining inflow. Therefore, equation 2.1 can be simplified to give the mining groundwater balance.

$$R_d + R_l = E_a + E_m + P_d + \Delta S$$

Equation 3.3 Mining groundwater balance

The only difference between the natural and mining groundwater balance is the inclusion of the freshwater pumping component (fig 3.5).

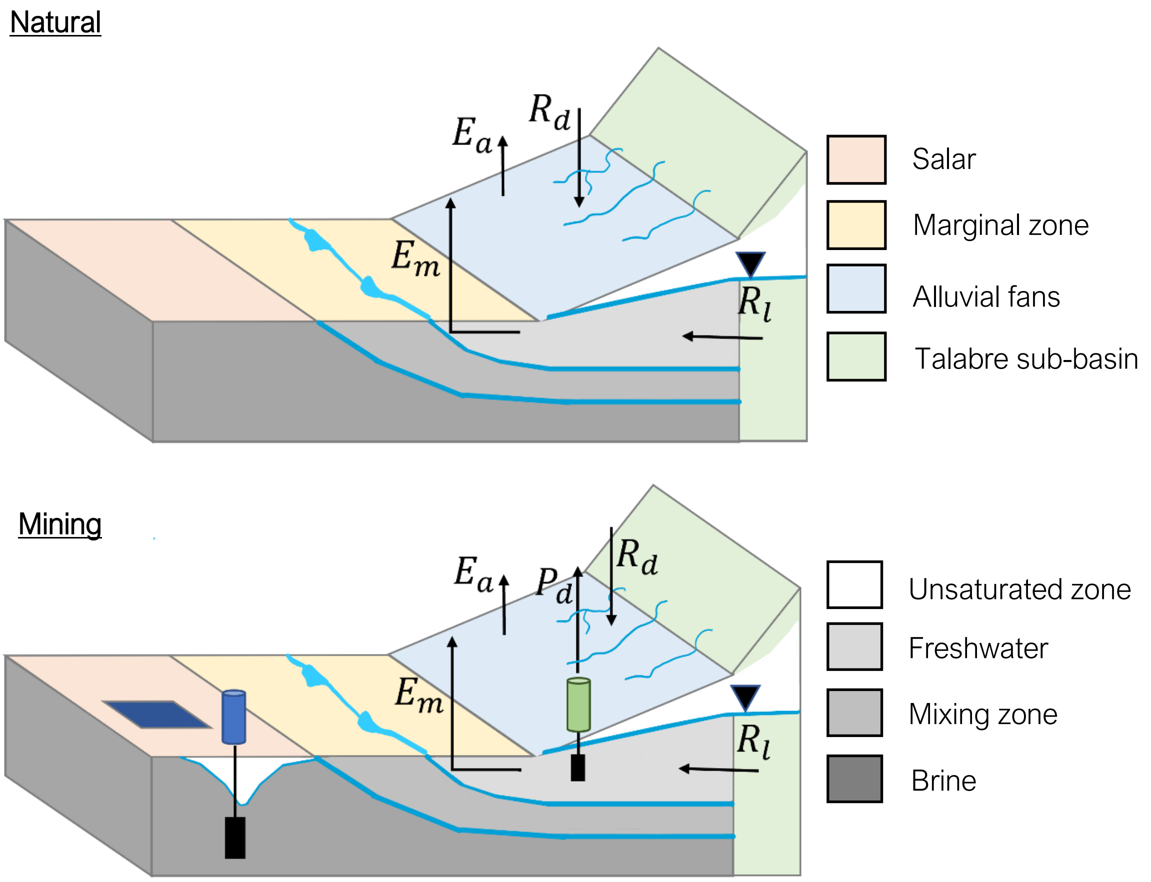

Figure 3.5 Conceptual model of natural and mining groundwater balance for the alluvial fans. In the natural system direct recharge (R_d) and lateral recharge (R_l) is in balance with phreatic evaporation from the alluvial fans (E_a) and marginal zone (E_m). In the mining period, freshwater pumping (P_d) occurs in the alluvial fans.

3.4 Groundwater table fluctuations

This section describes a different approach for calculating the change in storage of the alluvial fans. Alongside this, the procedure for a spatial analysis of the GTD and an impact assessment of altered pumping rates will be discussed. This will help answer sub-question 2.

3.4.1 Spatial analysis of drawdown in the alluvial fans

Spatial analysis is a useful technique to understand the impact pumping is having on the groundwater table of the alluvial fans. This is important since it allows for better-informed decision-making processes to target vulnerable areas at risk from pumping. The outcome of this analysis is to produce 4 groundwater table maps:

a) Map of drawdown at a low pumping rate
b) Map of drawdown at a high pumping rate
c) Map of changes between high and low pumping rate
d) Map of average groundwater table

Firstly, the low and high pumping rates were determined from the average groundwater table fluctuations results, where two pumping regimes were identified. A gradual decline occurred from March 2000 to December 2007 at a pumping rate of 54 l/s whereas a sharper decline occurred from January 2009 to December 2017 at a pumping rate of 183 l/s. The drawdown for the two regimes was taken as the difference between the start and end of these two durations. Map c represents the relative change in drawdown between these two pumping regimes. Map d was the average groundwater table for 2000 to 2020.

In QGIS, for each map a Digital Elevation Model (DEM) was stylised with a single band pseudocolour and hill shade layer to make trends clear to observe. The monitoring well's vector points were interpolated with the DEM to form a raster. The Inverse Distance Weighting (IDW) interpolation was deployed which assumes closer values are more related than further values with its function. Red colours indicate high drawdown whereas green colours indicate low drawdown. The colour ramp for the low and high pumping maps was then synced for comparison.

3.4.2 Changes in storage: the WTF approach

To calculate changes in storage, the average GTD for the alluvial fans was determined. 7 monitoring wells were selected to show a good representation of the basin that were not in close proximity to the pumping wells. If in close proximity, this could distort the results and not be a true representation of the basin since the monitoring wells further away are less affected. The monitoring wells data was obtained from the SQM (2021) database and spanned back to 2000 at the monthly time step. In total, there was 1936 data points with 314 months missing. Since the GTD per monitoring well showed a repeating seasonal pattern, a moving average was computed to fill in the missing values. The monitoring wells were inputted into QGIS. Using the Thiessen polygons method, the contributing area for each well on the overall basin was calculated (fig 3.6). The units of the GTD were meters above sea level. Using a DEM, the GTD was computed as the difference between the surface and groundwater table at a certain point. The weighting of each polygon was then multiplied by the GTD of each monitoring well and summed to get the average basin GTD. Since the fluctuations in GTD is a function of time, the storage was calculated by multiplying these fluctuations (Δh) by the specific yield (S_y) and the area of the alluvial fans (equation 2.2).

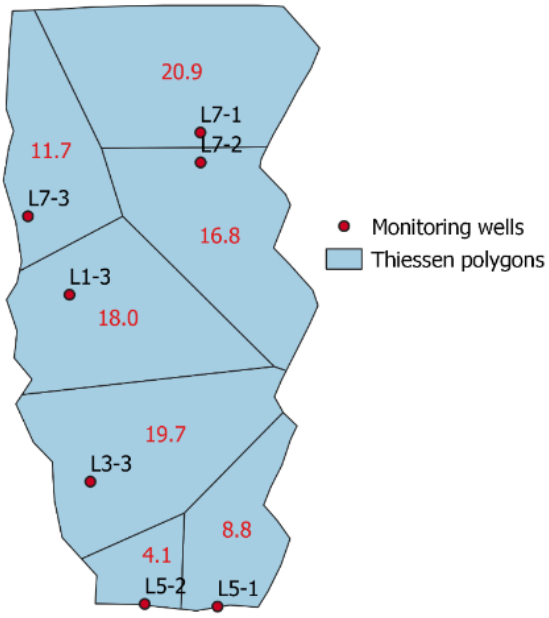

Figure 3.6 Thissen polygon of the alluvial fans. The contributing area of each monitoring well of the total area is shown in red. L7-1 had the highest contribution of 20.9%.

Groundwater fluctuations are calculated as the difference in GTD between two following months. The specific yield values were obtained from Marazuela et al., (2019b) and the alluvial fans had an average value of 0.008. From this the changes in storage were quantified.

3.4.3 Average renewal time

The groundwater stock was calculated in a similar way as section 3.4.2 but instead of multiplying by fluctuations, the saturation thickness (b) of the aquifer was used (fig 3.7). The average saturation thickness was calculated as the difference between the average GTD and average bedrock depth.

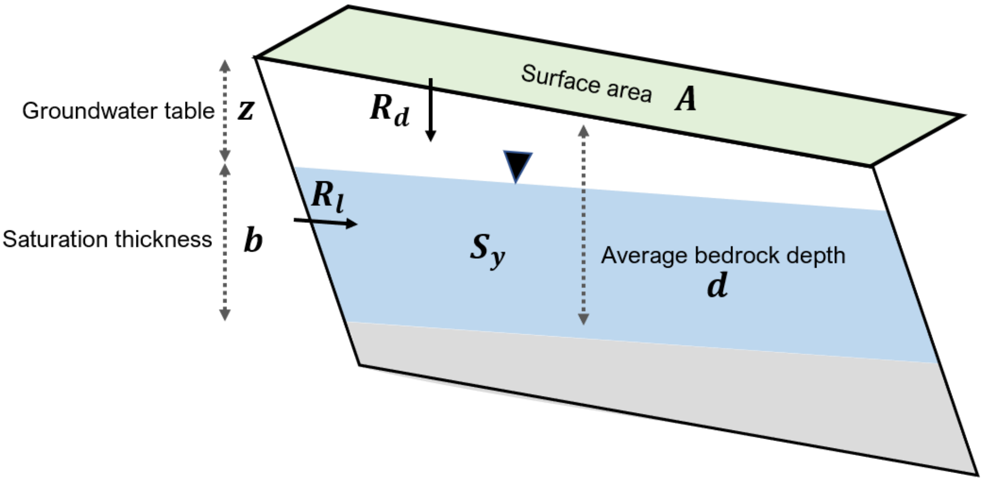

Figure 3.7 Components required to calculate the groundwater stock and average renewal time of the alluvial fans

A value of 300m was used for the bedrock depth (IDAEA-CSIC, 2017). The groundwater stock was then divided by the average total recharge for the average renewal time. Units were changed from seconds to years. The change in storage was also computed as the difference between the average GTD for the low and high pumping regimes. This was then compared against the groundwater stock to determine the impact of pumping on storage changes.

3.4.4 Drawdown in the marginal zone

The impacts of pumping are not just limited to the alluvial fans but can also have an impact on the GTD of the marginal zone. For a given pumping rate, a new average evaporation discharge value in m^3/s was calculated at the yearly time step from 2000 to 2020. This was achieved by setting all other components in the groundwater balance constant. The WTF storage value was used instead of the groundwater balance storage value since it was deemed more accurate. The evaporation discharge was converted from volume units into mm by dividing by the area of the A7 evaporation zone of the marginal zone and multiplying by the number of seconds in a year. This represented the yearly average phreatic evaporation rate of A7. The evaporation rate was transformed into the corresponding GTD using the exponential relationship (fig 3.3). In total there were 189 GTD data points in response to the pumping rates of 0 (natural), 54, 183, 200, 260, 300, 400, 500 and 1000 l/s per year from 2000 to 2020. Increasing the pumping rate can be at the expense of the evaporation discharge and without information on the GTD under various scenarios, the effect of pumping is uncertain. For this reason, it is important to compare the GTD between scenarios to understand the effect of pumping. This comparison was implemented through an exceedance probability analysis (equation 3.4). This type of analysis examined how often a certain GTD was equalled or exceeded for a percentage amount of time per pumping rate.

$$Exceedance\ probability = \frac{m}{n+1}$$

Equation 3.4 Exceedance probability (USGS, 2008)

Where m is the rank of the GTD and n is the total number of data points. For each scenario, the exceedance of the GTD per year was calculated from 2000 to 2020. For each scenario, an average regression line was fitted. The purpose of the regression lines was to understand the drawdown between the different scenarios at the same exceedance. Therefore, the effect of pumping on the GTD of the marginal zone was determined.

3.5 Groundwater governance

For sub-question 1 and 2, the aquifer performance aspect of the alluvial fans was quantitatively investigated. However, in accordance with Gleeson et al., (2020) definition of groundwater sustainability, the aquifer governance aspect must also be considered to determine if pumping adheres to groundwater sustainability. The aquifer governance aspect of sub-question 3 will be of qualitative nature and critically discussed through a stakeholder and legal-institutional perspective.

3.5.1 Legal and institutional perspective

The legal and institutional perspective is central for aquifer governance. Chile water and indigenous laws relating to groundwater use was discussed. For resilience against disaster, the management of the basin was analysed with particular focus on contingency plans. Data sources for this included environmental audits from SQM and reports from DGA. Water rights were discussed concerning the distribution amongst lithium mining companies and indigenous communities. As for restrictions in place, the SNIFA website was an important source for records of environmental instruments and sanctions implemented towards SQM.

3.5.2 Stakeholder involvement

Indigenous laws were identified to understand the effectiveness of encouraging inclusivity in governance. From this, collaborations and conflicts were identified. All societal values need to be considered to adhere to groundwater sustainability. If a particular stakeholder is more impacted than another, this does not indicate sound groundwater governance. Focus was on the indigenous communities' intangible value towards groundwater and its importance in groundwater management. Once areas of weaknesses were identified, recommendations were made to improve overall groundwater sustainability. Groundwater governance consisted entirely of literature research. This was obtained from academic, institutional, and industrial articles and reports. The search engines of Google Scholar and Scopus licenced by Utrecht University was used.

4 RESULTS

4.1 Groundwater balance

In this section, the magnitude of the groundwater balance components, associated uncertainties and temporal oscillation of flows are analysed for sub-question 1.

4.1.1 Magnitude of groundwater balance components

During the mining period, the average annual contribution of the different inflow components varied slightly from the period before mining. In the natural period, lateral recharge was 80.3% and direct recharge was 19.7%. In the mining period, the lateral recharge decreased to 78.2% and direct recharge increased to 21.8%. The outflows in the natural period were composed almost entirely of evaporation discharge from the marginal zone (99.8%). In contrast, evaporation from the alluvial zone was negligible (0.2%) in the natural and mining period. With the influence of lithium mining, pumping made up 10.4% of the total outflow compared to 89.4% from evaporation discharge.

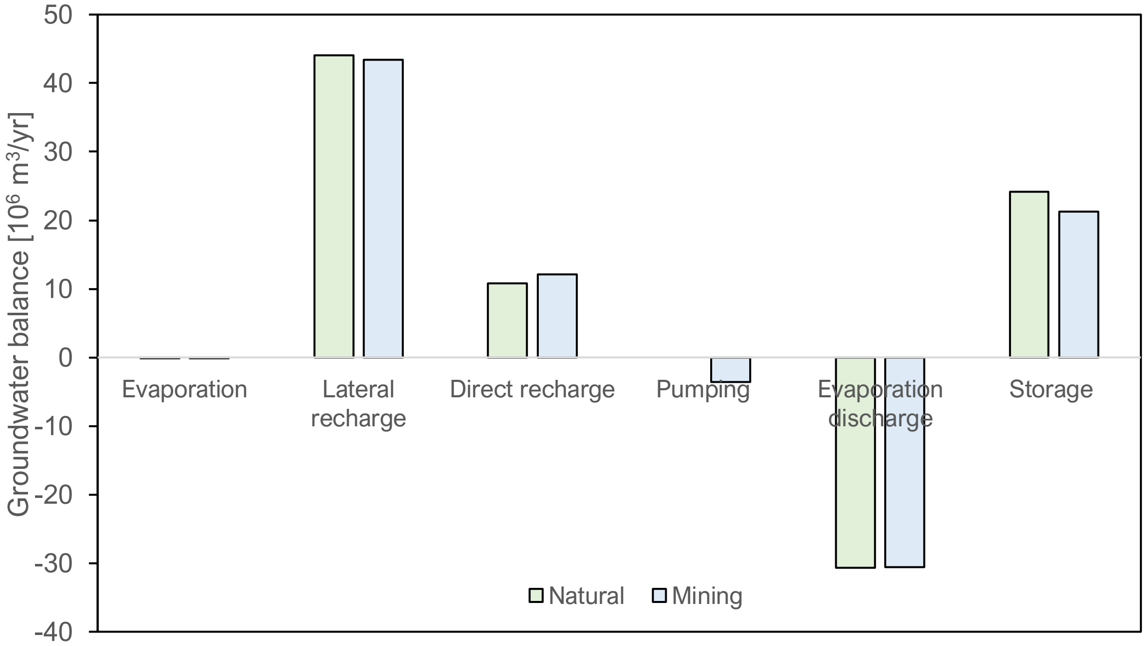

Figure 4.1 Average magnitude of groundwater balance components per year for natural and mining. Storage decreased between natural and mining.

Pumping was 16 times lesser than total recharge. Therefore, pumping was a minor component in the groundwater balance. The storage was postive in magnitude and showed a decrease between the natural and mining periods (fig. 4.1). The groundwater stock for the alluvial fans was 7.18 x 10^8 m^3 with an average total recharge for the natural and mining period of 1.75 m^3/s. This equated to an average renewal time of 13 years. The average GTD during low pumping (42.8m) and high pumping (43.3m) amounted to a storage change of 1.15 x 10^6 m^3. The change in storage between the two regimes was 0.16% of the total groundwater stock. This trend represents the average but the components in the groundwater balance change considerably throughout time.

4.1.2 Temporal oscillations of flows

The change in storage decreased on average by 3.0 x 10^6 m^3 per year between the natural and mining periods (table 8.1). Even though the storage was overwhelmingly high in magnitude, a decrease still occurred. One reason for this decrease was due to consecutive dry years from 2003 to 2010 (fig. 4.2). The average rainfall of the Camar Station during this period (11.2 mm/yr) was significantly less than the 20-year average of 45.3 mm/yr. In 2008, the pumping rate also increased from 60 l/s to 200 l/s corresponding to an increase in outflow of 4.42 x 10^6 m^3. In this same duration, the inflow increased by 1.45 x 10^7 m^3 and the change in storage remained constant before reaching an all-time low in 2010. Storage values were negative in 19 years, 8 in the natural period and 11 for mining. Outflow in the mining period can be lower than the natural since the outflows are constant due to a lack of groundwater table data.

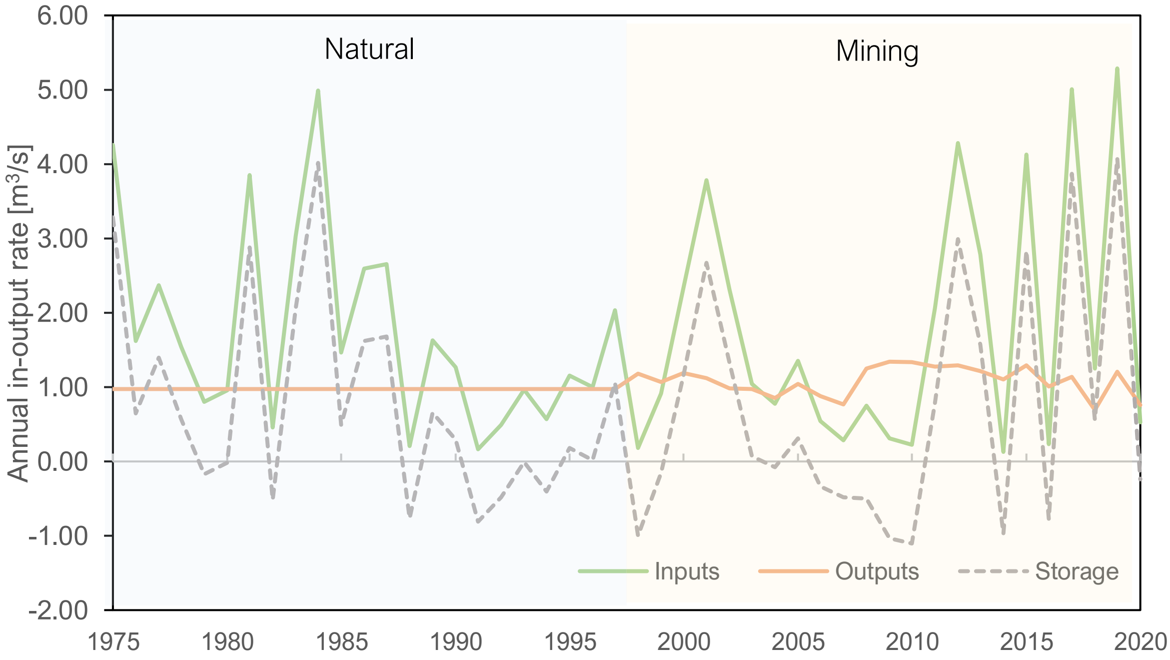

Figure 4.2 Temporal oscillations of inflows (orange line) and outflows (green line) for the alluvial fans in the natural (blue shade) and mining period (yellow shade). The difference in these flows is the change in storage (grey dotted line)

The sharp rises in inflow were caused by rainfall in January to March where average monthly rainfall exceeded 10 mm (fig. 4.3). The remaining months had an average monthly rainfall of less than 3 mm and had a lesser impact on the inflow and storage changes. From 2011 onwards, these oscillations were more frequent with fluctuations ranging between 0.69 m^3 s^{-1} and 1.34 m^3 s^{-1}. The outflow oscillations from 2013 to 2020 also run synchronously with the inflow oscillations, whereby for each year an outflow peak or trough was identical to the inflow's peak or trough equivalent. This occurred because evaporation discharge was calculated based on GTD and implies that during wet years higher discharge rates coincide with increases in groundwater table for the alluvial zone.

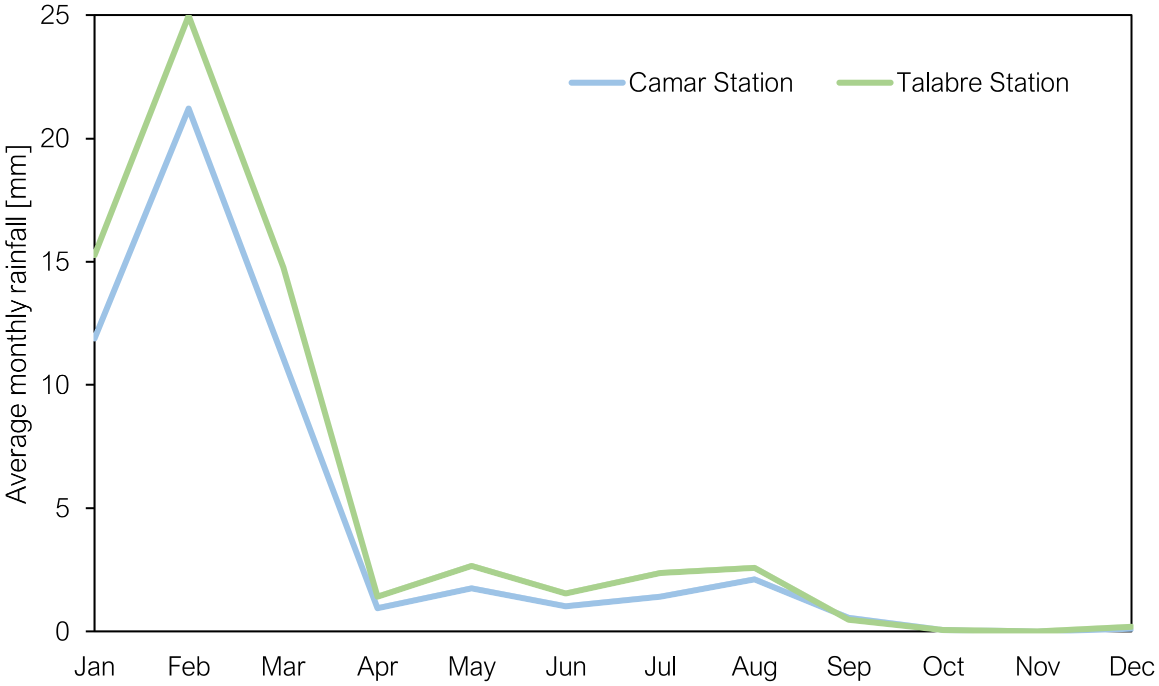

Figure 4.3 Average monthly rainfall from 1995 to 2020 for the Camar (blue line) and Talabre (green line) Weather Stations. Jan-March had higher rainfall than the remaining months. Talabre had higher rainfall because it was located at a higher altitude.

4.2 Groundwater table fluctuations

This section analyses the results of the WTF method with specific focus on how the influence of low and high pumping regimes impact the GTD of the alluvial fans. Results are analysed for sub-question 2.

4.2.1 Low vs high pumping regime

The topography of the alluvial fans was steep, and the GTD did not follow the steep slope of the mountain ridges. As a result, the depth increased from east to west from 104m in L5-1 to a shallower depth of 4m in L7-3 (fig 4.4, map D). During the low pumping rate (map A) from March 2000 to December 2007, Socaire-5 was the only pump in operation.

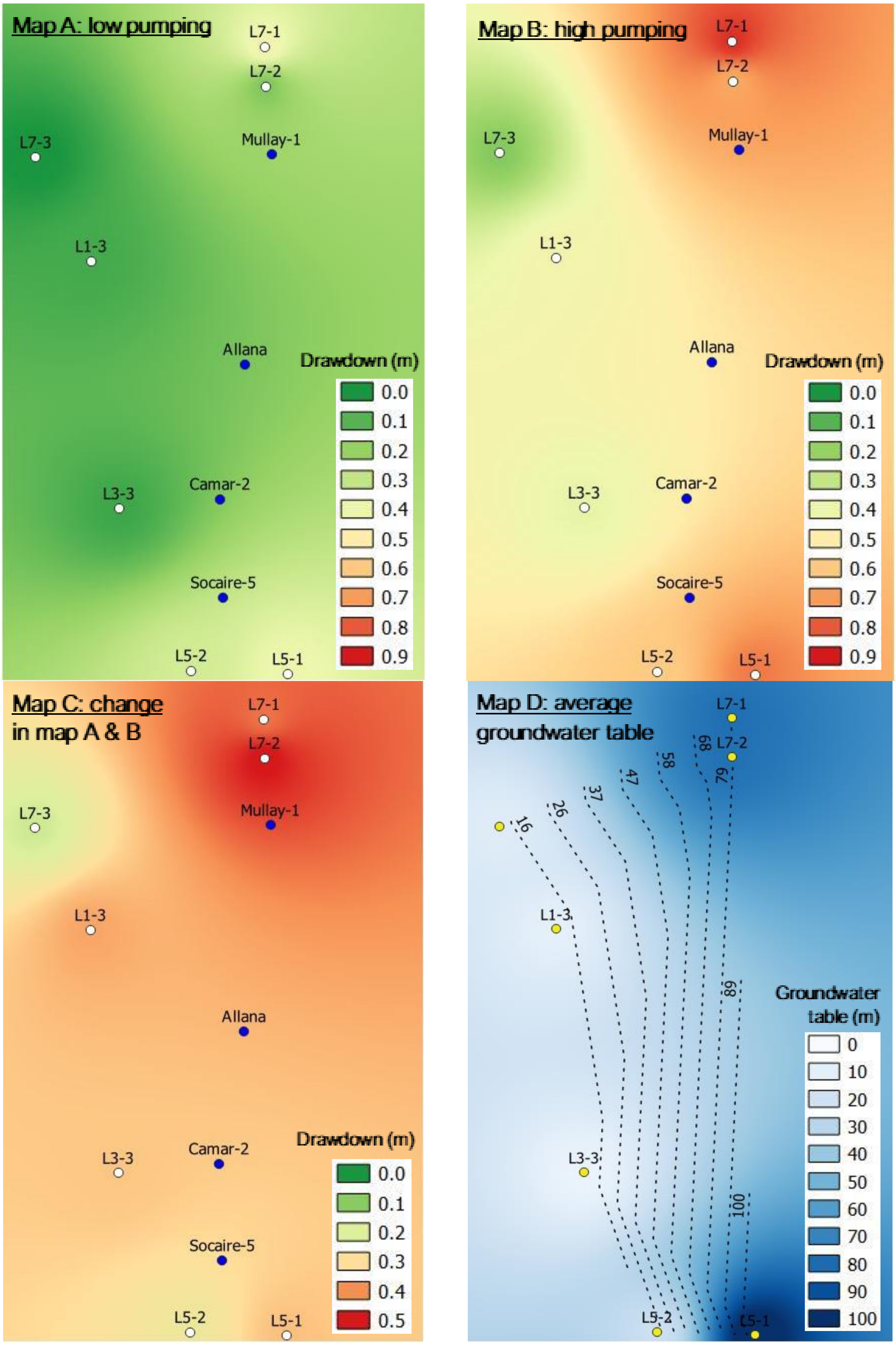

Figure 4.4 Spatial analysis of drawdowns in the alluvial fans. Drawdown obtained by comparing GTD Map A shows the drawdown in the low pumping regime whereas map B shows the drawdown for the high regime. Map C represents the difference between the low and high regime. Map D shows the average GTD of the alluvial fans.

When comparing the average drawdown values, the L5-2 and L5-1 monitoring wells had the greatest drawdown of 0.4m. L3-3 was also in close proximity to Sociare-5 but had negligible drawdown. L7-1 had a drawdown of 0.4m whilst L7-2 remained unaffected to a large extent. L7-1 and L7-2 were the furthest monitoring wells away from Socaire-5 and the GTD might have been independent of the pumping rate. Generally, the alluvial fans showed low drawdown in response to an average pumping rate of 54 l/s. In contrast, from January 2009 to December 2017, Allana, Camar-2 and Mullay-1 pumps were switched on to a rate of 183 l/s leading to larger drawdowns (map B). All monitoring wells had a larger drawdown compared to low pumping. L7-1 and L5-1 had a drawdown of 0.8m and 0.7m, whereas L7-3 was again unaffected to a lesser extent with a drawdown of 0.2m. With the influence of Mullay-1, L7-2 responded with a drawdown of 0.6m alongside the continual decrease of L7-1. Camar-2 had the highest individual pumping rate. However, the neighbouring monitoring well of L3-3 did not have the largest drawdown.

In order to illustrate the effect of changing pumping rates, map C shows the change in drawdown between the low and high pumping regimes. Since Socaire-5 remained constant between the two regimes, L5-2 had a moderate change of 0.3m. In contrast, the red shades surrounding L1-3 and L3-3 in map C were impacted by Camar-2 and Allana to a greater extent than in map B. L7-2 experienced the greatest drawdown of 0.5m. Mullay-1 had an impact on this monitoring well and a lesser impact on L7-1. The change in drawdown between low and high pumping for L7-3 remained low at 0.2m.

4.2.2 Effect of pumping rate on groundwater table

The relative GTD fluctuated but showed a gradual declining trend (fig. 4.5). This trend changed once the pumping rate increased. In 2008, the pumping rate increased to 140 l/s producing a large drop in the GTD (0.12m). After this sharp decrease, the GTD responds to a level that fits the average rate of decline before the change in pumping. This sharp increase was independent of a recharge event. This indicates that the response was caused by the stabilisation of the pumping rate at 140 l/s. The rate then increased to 200 l/s and this caused the coupling of another steep drop of 0.27m accompanied with a quick response once the pumping rate stabilised at 200 l/s. These sharp increases in pumping rate caused short-term drawdown values that were greater than the yearly average drawdown of 0.04m. Consequently, a decreasing GTD can be attributed to pumping. The rate of decline was higher for an average pumping rate of 183 l/s (high regime) compared to 54 l/s (low regime) (fig 4.5). Abrupt increases in GTD coincided with high levels of rainfall. During the high regime, three notable recharge events occur in 2012, 2015 and 2019. In all of these wet years, over 97% of the rainfall fell between January to March. Therefore, this indicates that rainfall in these months was the driver of short-term groundwater fluctuations. The lowering of the pumping rate to 125 l/s in 2017, alongside higher than average rainfall beyond March produced further stabilisation of the GTD.

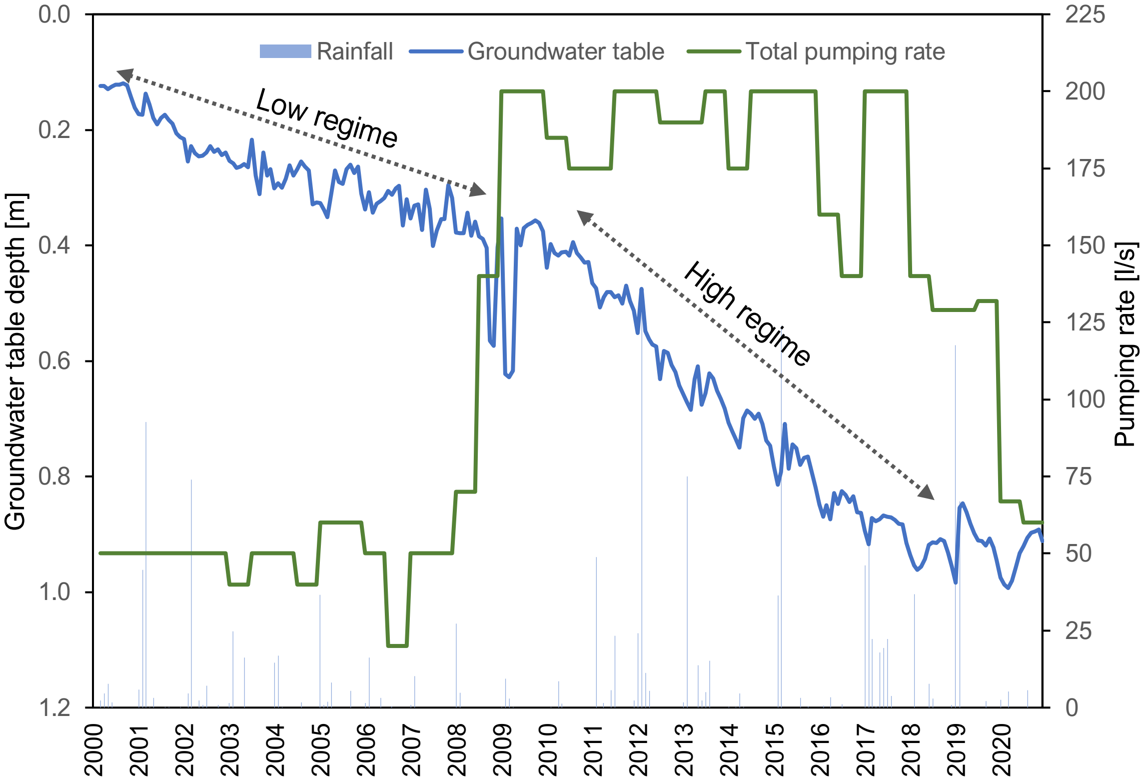

Figure 4.5 Relative GTD of the alluvial fans from 2000 to 2020 in response to pumping and rainfall. The GTD was capped at 42.6m and data points show the relative difference from this. Low regime refers to a low pumping rate of 54 l/s and high regime equalled 183 l/s

5 DISCUSSION

In this section the reliability of the methods, impacts from pumping and aquifer governance are discussed.

5.1 Critical evaluation of methods

The groundwater balance indicates an increase in storage however decreasing groundwater tables were recorded for the WTF method. This implies that the two approaches lead to inconsistent results.

5.1.1 Groundwater balance

Pumping is significantly less than total recharge implying that it is feasible to pump without changing the storage but only if the pumping can be balanced by reducing the other outflow components. In the natural period, storage changes are expected to be close to zero since no major changes have occurred. In other words, steady state should be reached whereby inflows equal outflows. However, since both the natural and mining periods had higher inflows compared to outflows, the change in storage was postive (fig. 4.1). This indicates that one or several components were either underestimated or overestimated. The groundwater balance has a high number of components associated with a variety of assumptions that caused the level of uncertainty per component to differ. Since evaporation and pumping are small in magnitude, their influence on the change in storage accuracy is lesser than lateral recharge, direct recharge, and evaporation discharge. The error propagation of these components determines the error of storage changes. Since lateral recharge was the greatest in magnitude (1.39 m^3/s), the accuracy of the change in storage values depends on the accuracy of the lateral recharge value to a great extent. Marazuela et al., (2019a) had a lateral recharge value of 1.48 m^3/s for the Talabre sub-basin. For the same area, the value was 6.1% less than the calculated lateral recharge value and was not overestimated. This strengthens the reliability of the average lateral recharge value and indicates that the evaporation discharge of the marginal zone has the highest uncertainties.

Calculating the evaporation discharge using a depth-dependent term has the advantage of relating the GTD and phreatic evaporation rate. However, Marazuela et al., (2020) views this approach as not the most advanced and scientific way to estimate phreatic evaporation but there are not many alternatives. The main limitation is due to the strong reduction of phreatic evaporation within the first decimetres whereby the accuracy of the estimation of GTD is critical. Marazuela et al., (2020) demonstrates that an error of 0.5m in GTD reduces the evaporation output by more than 60%. This could be one reason why the evaporation discharge is underestimated, although the large number of assumptions associated with this component is more likely. For example, it was assumed that the evaporation zones of the marginal zone outside of the EMZ (fig 3.2) is equal to the discharge of the alluvial fans. In reality this is not strictly true for two reasons: (1) a small amount of groundwater from the alluvial fans surpasses the EMZ and reaches the nucleus and (2) there is groundwater flow contribution from the North. Whilst these two factors undermine the accuracy of this component, they are relatively small in magnitude. The limited network of lysimeters also meant that phreatic evaporation is only calculated for evaporation zone A7. A larger network of lysimeters in all evaporation zones would have served as a better representation of the true evaporation discharge. Due to the large number of assumptions and associated error of the depth-dependent term, the accuracy of changes in storage for the groundwater balance is low. However, evaporation is key in assessing the impact of pumping in the marginal zone

5.1.2 WTF method

The rate of GTD decline is high for a high pumping rate and demonstrates asymptotic development. In other words, after an adjustment in pumping rate the groundwater table approaches a limit, and a new steady state can be reached with a lower groundwater table. Sharp increases in pumping rate causes short-term drawdown values that are greater than average annual drawdown. As a result, sharp increases in pumping rates should be closely monitored to assess if drawdown rates are unsustainable. Rainfall is also a cause of short-term groundwater fluctuations. The amount of rainfall is controlled by climatic cycles such as the El Nino Southern Oscillation (ENSO) that occurs from 5 to 10 or more years (Houston, 2006). In recent years, the influence of these cycles could have a contribution to the decreased rate of decline in groundwater table.

The WTF method uses the most direct observation of changes in storage from monitoring well data. Since the GTD data is accurate, the accuracy of storage changes is dependent on the accuracy of the specific yield and calculation of groundwater fluctuations. The main challenge of quantifying the specific yield is the sparseness and reliability of available data as well as the complex nature of drainage during aquifer tests (Gehman et al., 2009). The value used from Marazuela et al., (2019b) was deduced from hydraulic tests performed by mining companies. For the purposes of this research, one can assume that the specific yield is reliable.

Groundwater table fluctuations are not calculated in the conventional way as stated in the scientific literature. Usually, the calculation of fluctuations is related to natural recharge and no other factors such as pumping and evaporation. The standard application relies on short-term events whereby daily fluctuations are estimated between the peak of the groundwater table rise and the extrapolated antecedence recession curve at the time of the peak (USGS, 2017). In this research, long-term fluctuations are calculated as the difference between the groundwater table at the beginning and end of each month, with no extrapolation. The fluctuations also include the influence of pumping and evaporation. This non-standard approach decreases the reliability of the results to a certain extent. However, the WTF results are still robust providing the interpolation of the monitoring wells are correct. To obtain a regional average GTD, the point source of the 7 monitoring wells is spatially interpolated. The accuracy depends on the number of monitoring wells used and if this is a good representation of the alluvial fans. Increasing the number of monitoring wells would reduce the spatial sampling error. However, due to limited data availability and the proximity to pumping wells, only 7 are selected.

In the alluvial fans, L7-3 has the lowest drawdown since it is the furthest away from the pumping wells. As a result, monitoring wells with a large contributing area towards the average GTD and were close to the pumping wells have great potential to skew the results. For example, L7-1 has the largest contributing area (20.9%) towards the average and is in close proximity to Mullay-1. L7-1 causes the sharp increase and decrease of the average GTD in 2008 (fig 4.5). Therefore, the storage changes of the WTF method are sensitive towards pumping. One limitation is that GTD data is only available from 2000 onwards. A comparison between the natural and mining period for the WTF method is not possible.

5.1.3 Combination of methods: comparison and benefits

The groundwater balance assesses whether pumping impacts groundwater sustainability. Important aspects relating to sustainability include the ratio between the pumping rate and recharge rate as well as determining the renewal time. Storage is used as a proxy and should tend towards zero if all flow components are calculated accurately. The WTF storage values tend more toward zero indicating that at least one of the groundwater balance components is inaccurate. Since the lateral recharge is close to literature values, the evaporation discharge most likely has the largest error. The GTD in the marginal zone in response to pumping is most relevant for the evaluation of groundwater sustainability. The effect of pumping is based on the relationship between phreatic evaporation and GTD. To determine this long-term effect, one could assume steady state whereby storage changes are equal to zero. In this regard, the WTF method is not necessary. However, the temporal oscillations of the flow components show that annual dynamics occur in wet and dry years causing perturbations and deviations from steady state. If you assume steady state for a dry year, the evaporation and GTD in the marginal zone becomes low. For exceptionally dry years, the lack of inflow can be buffered by storage. Therefore, the response of the groundwater table is delayed because changes in pumping rates are compensated by either increases or decreases of storage. The WTF method is used to account for these short-term fluctuations and to determine the impact of pumping on the GTD of the marginal zone.

5.2 Pumping impact in the marginal zone

In this section, the pumping impact on the GTD of the marginal zone is discussed.

5.2.1 Groundwater table response

The WTF long-term average steady state storage value is -0.04 m^3/s. In the following results, the GTD response to pumping accounts for changes in evaporation discharge and also the compensation due to the storage changes for a period of 20 years. For dry years, an increased pumping rate reduces the GTD of the marginal zone to a greater extent compared to wet years. An increased rate of 300 l/s in the dry year of 2010 causes a drawdown of 0.38m (fig. 5.1). In contrast, the drawdown difference between the pumping rates in the wet years of 2012, 2015, 2017 and 2019 is negligible and the GTD is close to the surface.

Table 5.1 Groundwater table that was equalled or exceeded for 10% of the time in response to different pumping rates in the marginal zone. 0 l/s = natural, 54 l/s = low pumping regime, 183 l/s = high pumping regime, 260 l/s = max permitted rate

Exceedance analysis	Pumping rate [l/s]								
	0	54	183	200	260	300	400	500	1000
Q10 Groundwater table depth [m]	0.43	0.45	0.56	0.58	0.58	0.64	/	/	/

The calculation of the corresponding GTD in the marginal zone is only possible if the evaporation term is postive. This condition is met providing that the recharge and the contribution of change in storage is larger than pumping rates. If this is not the case, the evaporation term becomes negative implying that water from the marginal zone flows towards the alluvial fans. The exceedance probability analysis examined evaporation discharge further. With no pumping (natural period) the GTD of 0.43m is equalled or exceeded for 10% of the time (fig. 5.2). For the pumping rate of 300 l/s at the same exceedance, the groundwater table decreased by 48.6% to 0.64m (table 5.1). For exceedances between 70-90%, the groundwater table is similar between pumping rates.

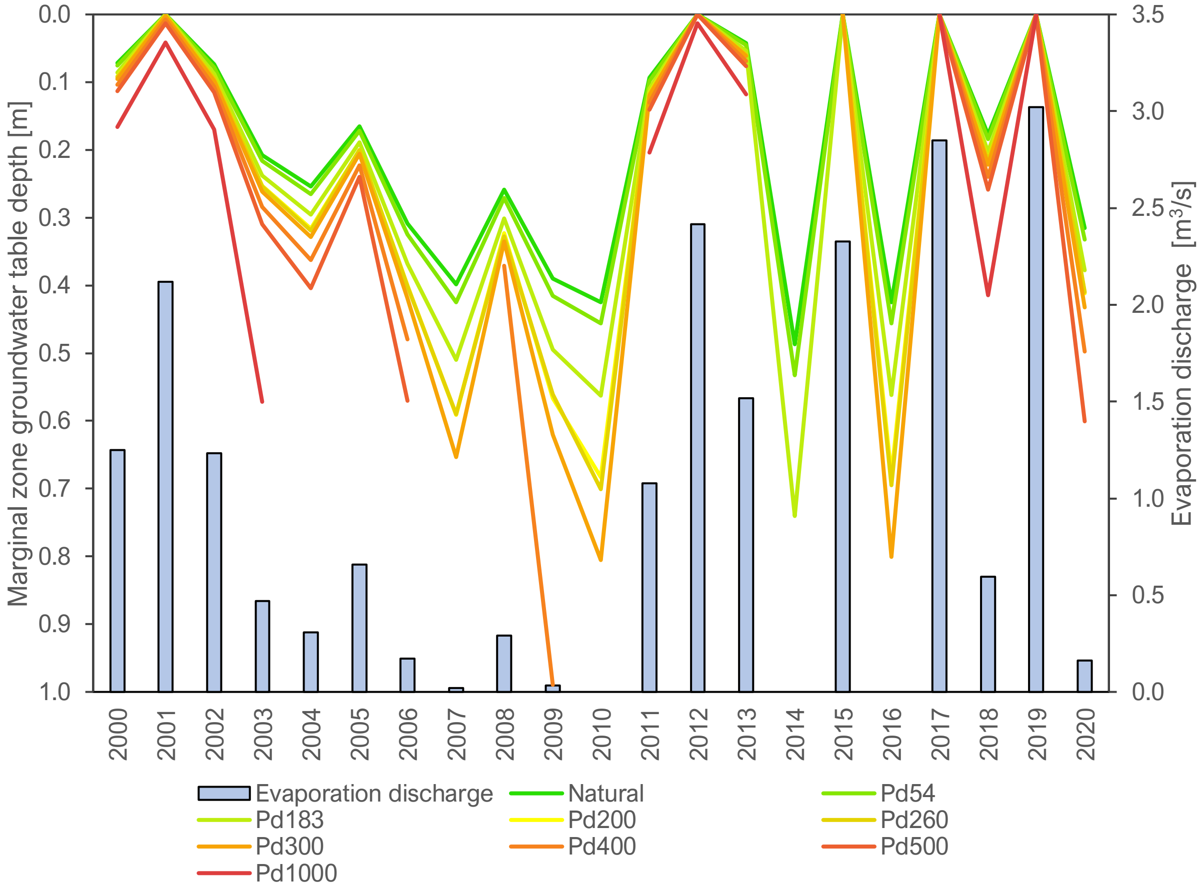

Figure 5.1 Groundwater table of the marginal zone in natural conditions (dark green) and in response to low (green), medium (yellow) and high (red) pumping rates. The evaporation discharge (blue bar) represents the environmental flow from the alluvial fans.

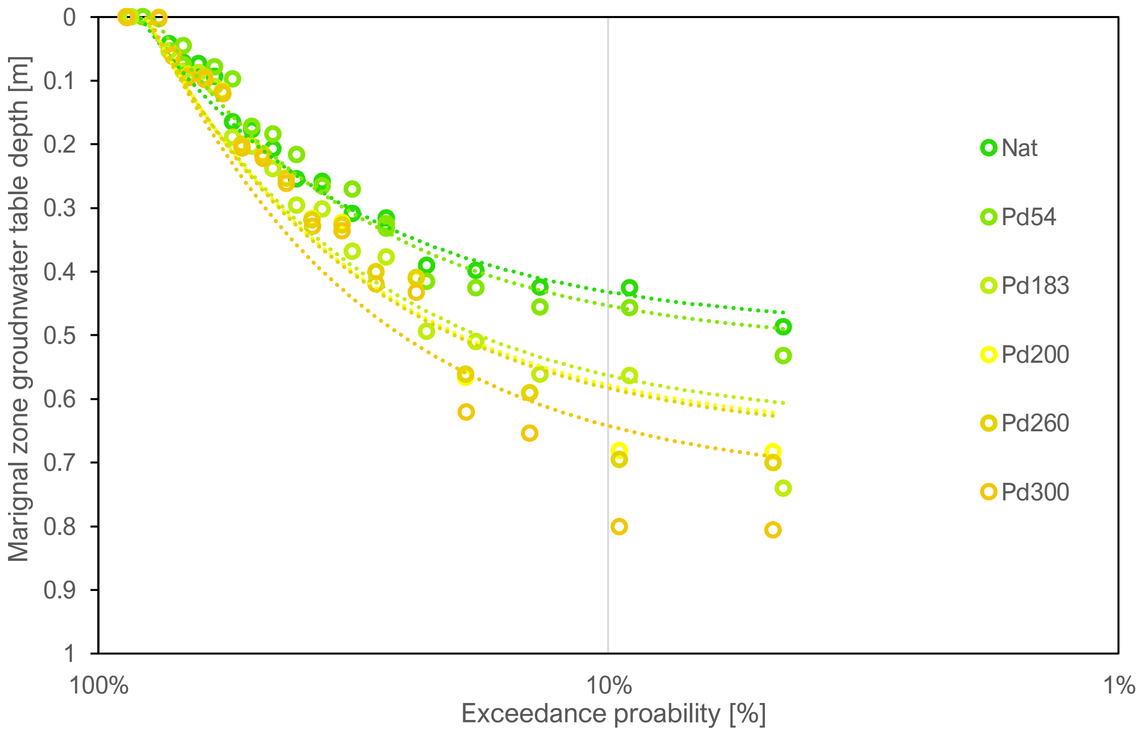

Figure 5.2 Exceedance probability of the GTD of the marginal zone for different pumping rates

The GTD begins to deviate with lower exceedances. This shows that during dry years, changing the pumping rate has more of an impact on the GTD than in wet years. The high pumping rates of 400, 500 and 1000 l/s are not included in the exceedance probability since the sample size is too small due to the environmental flow being zero. The inclusion of these high pumping rates (>300 l/s) skewed the results with a greater proportion of shallower GTD values at a higher exceedance.

5.3 Aquifer governance

For the evaluation of groundwater sustainability, it is important to understand if the governance is equitable and inclusive. To determine this, the legal situation, involvement of stakeholders and current management is analysed.

5.3.1 Legal situation

The current national regulation for Chile's water resources is the Water Code (1981). This framework recognises water as a public good and through capital incentives, uncontrolled groundwater pumping occurs in the SdA (Bauer, 2004). Similarly, brine is seen as a commodity and regulated as a mineral resource. In this manner, the Chilian government has ownership and allows mining companies to manage their own operations (Morse, 2020). This means mining companies have a large say on how groundwater is managed and used. For this reason, World Bank (2013) proposed that the government should reshape the current water laws to reduce the mishandling of water resources. From a social and environmental perspective, the current water right allocation system could be seen as inequitable whereby entities with more money gain more groundwater rights. Valdés-Pineda et al., (2014) describes the governance as not capable of allocating or prioritising different groundwater uses. The Direccion General de Aguas (DGA) authorises rights to groundwater pumping (table 5.2). The groundwater rights show that the mining companies have 30 times more access to groundwater than the indigenous communities (Babidge & Bolados, 2018).

Table 5.2 Water rights of the Atacama basin ***(Babidge & Bolados, 2018)***

Company or Indigenous Community	Quantity [l/s]
Minera Escondida Limitada	1473.4
Minera Utah de Chile Inc	304.0
Compañía Minera Zaldívar Limitada	625.3
Sociedad Quimica y Minera de Chile SQM	4.0
SQM Salar S.A	309.0

Sociedad Chilena de Litio Ltda	8.5
Rockwood Litio Ltda	15.0
Total	2739.2
Comunidad Atacameña de Camar	26.6
Comunidad Atacameña de Peine	65.6
Total	92.2

This uneven distribution of water rights implies that the current groundwater management has significant equity issues. Although, these rights might not necessarily need to be equally distributed since the societal needs of groundwater use differ. For example, if stakeholders' interests are harmonised where they affect each other as little as possible without harming the environment, then the distribution of these water rights could be justified. However, conflicting interests do exist, with indigenous leaders claiming that pumping impinges their traditional rights to the area (Babidge, 2016). As for the environment, the drop of the GTD by 1m from 2000 to 2020 shows minimal environmental impact on the alluvial fans and the same applies for the marginal zone. This goes against findings from various news outlets that report mining companies are harming the environment. This could be true, but the cause is more likely to be brine pumping in the Salar rather than freshwater pumping. Since the environment is unaffected in the alluvial fans, the conflicting interests of stakeholders characterises the ineffectiveness of state law.

The state legally recognises some indigenous territory and water rights, however, fail to recognise the way these rights are exercised by the indigenous communities (Babidge, 2016). The Indigenous Law (1993) introduced regulation to respect, protect and promote indigenous rights. In recent years, the National Corporation for Indigenous Development Corporation (CONADI) strengthened the rights of the indigenous communities by signing an agreement to re-establish groundwater rights. However, these rights only apply to the water that is used for agricultural activity and daily life and does not extend for livestock used in the indigenous territories (Babidge, 2015). One reason for this could be that the rights to extract groundwater were granted to mining companies before the implementation of newer measures protecting environmental and indigenous values. The use of groundwater is important for both activities, but the economic vitality is favoured towards the mining companies. This implies that the instrumental values towards groundwater favours mining preferences over the indigenous communities. To deal with these types of trade-offs between different societal objectives, it is important for all stakeholders to be involved in the decision-making process of groundwater governance.

5.3.2 Involvement in governance

In 2009, the government introduced the International Labour Organisations Convention C169 (2009). This convention ensures that states must oblige by consulting indigenous communities about any potential impacts on their recognised lands. Therefore, for future expansion in groundwater pumping, mining companies must first inform the indigenous communities of their intentions. Babidge (2018) claim that the Peine community has resisted against further groundwater licences. This implies that the C169 could have been successful at encouraging inclusivity in groundwater governance. DGA has also encouraged stakeholder involvement by hosting public meetings to inform indigenous community leaders of the hydrogeological nature of the basin (Babidge, 2018). This sharing of knowledge helps facilitate collaboration and decreases the likelihood of conflict between stakeholders. However, conflict between the indigenous communities and mining companies has been rife in recent years. The Peine and Camar communities appealed against SQM's new environmental monitoring plan since they argue that the plan did not address all issues and thus would not be effective in mitigating negative effects (BHRRC, 2020). Public protests organised by the Council of the Atacama People regarding the potential environmental impacts from mining companies has also occurred. Despite the unrest, SQM continue to promote joint work with communities whilst offering to finance projects to help communities fight the COVID-19 pandemic (Sherwood, 2021). So far SQM have reached cooperation agreements with 3 out of the 18 communities suggesting that negotiations are taking place but with limited consensus. Neither Chilean law nor mining companies' compensation can adequately protect the indigenous communities' intangible values towards groundwater. Groundwater provides benefits for the locals in terms of well-being, meaning and a sense of belonging. The indigenous communities view groundwater as something that is sacred and cannot be traded. There is a spiritual force associated with groundwater that is emphasised through their water rituals (Babidge & Bolados, 2018). The recognition of this intangible value is not represented in the groundwater management of the basin.

5.3.3 Current groundwater management

Groundwater management in Chile is currently transitioning from a use-based to a river basin management system (Retamal et al., 2013). The use-based management reflects the Water Code (1981) whereby users with water rights are responsible for groundwater management. The DGA is responsible for collecting and maintaining hydrological data. Donoso (2014) claim that in accordance with the Water Code (1981), the DGA has a limited role in state interference of groundwater management and instead management powers lie with the mining companies who have water rights. However, Chile’s environmental regulator, the Superintendency of the Environment (SMA) has accountability for upholding environmental standards.

SQM have an environmental monitoring plan that follows the obligations set by the SMA but no comprehensive river basin management plan (RBMP) exists for the Atacama basin. In the monitoring plan, SQM monitors the GTD from 219 monitoring wells (SMA, 2018). Alongside this, a contingency plan is implemented if a monitoring well drops below a certain threshold. Management of this kind is needed since extreme groundwater drawdown in the alluvial fans could reduce the environmental flow towards the marginal zone and has the potential to enhance hydrological drought. This in turn impacts the groundwater dependent ecosystems which requires groundwater for the lagoons, streams, and wetlands. Endangered flamingos rely on the lagoons of the marginal zone. With a reduced groundwater input, the lagoons can reduce in size. From 2017 to 2018, there was a reduction in reproduction at several nesting sites, falling below the average (Gajardo & Redón, 2019). If pumping were to exceed the maximum permitted rate of 260 l/s, the lagoon size becomes more prone to reduction. The pumping rates in the low and high regime indicates minimum deviation from the natural GTD. If the GTD decreases further, phase 1 of the contingency plan is activated and triggers an increased frequency of monitoring whilst phase 2 reduces pumping rates. Phase 2 could have been one explanation as to why the GTD in 2008 (fig 4.5) recovered quickly. Monitoring of sharp increases in pumping rate is important to track since this can cause short-term drawdown values that surpass long-term drawdown averages. This shows that the groundwater management has some form of resilience if disaster were to occur. However, restrictions are needed to enforce these actions.

In recent years, SQM have had six serious fines issued against them amounting to $25 million (SMA, 2019). Most notably, SQM failed to monitor the algarrobo tree in the alluvial fans as was stated in their contingency plan. A small number of algarrobo trees are found in the alluvial fans and use groundwater if its within 12m of the surface (Alvarez & Villagra, 2009). The environmental audit conducted by SMA (2013) verified the loss of 13 specimens of the algarrobo which equated to one third of the total population. However, since the drawdown near Camar-2 pump is only 0.4m (fig. 4.4 map C), it remains unlikely that drawdown causes the decline of the algarrobo trees when roots can extend for 12m. An external influence such as climate impacts could be a more likely cause. SQM also over extracted the maximum permitted quantity of brine and modified the agreed variables to measure. This undermines the reputation of SQM and negatively impacts public perception.

5.4 Groundwater sustainability evaluation

In this section, the aquifer performance and governance results are evaluated with reference to Gleeson et al., (2020) definition of groundwater sustainability. Recommendations are also suggested and answers sub-question 3.

5.4.1 Aquifer performance

Gleeson et al., (2020) defines groundwater sustainability as '*maintaining long-term, dynamically stable storage (and flow) of high-quality groundwater using inclusive, equitable and long-term governance and management'*. Firstly, the evaluation of groundwater sustainability must be based on scientific knowledge. The average recharge rate is high compared to the relatively low pumping rate. This demonstrates pumping is feasible providing that it can be balanced by reducing the other outflow components. Consequently, the groundwater of the alluvial fans is renewable with an average renewal time of 13 years. This short time span is well within the human timescale of 100 years and indicates that groundwater can be replenished for the current generations. The change in storage between the low and high regime is 0.16% of the total groundwater stock. As a result, the groundwater reserve can be maintained in the long-term. Short-term groundwater fluctuations are driven by high levels of rainfall. 97% of the total rainfall in the wet years of 2012, 2015 and 2019 fell between January and March. In the last decade, the combination of low pumping rates and plentiful recharge due to the ENSO phenomenon, results in a reduced rate of decline in GTD. There is a gradual declining trend (1m) in the average GTD of the alluvial fans between 2000 to 2020. This drawdown indicates minimal impact on the environment and the indigenous communities. However, sharp increases in pumping can cause unsustainable drawdown values that surpass yearly averages. If left unmonitored, this could undermine the dynamically stable storage of the alluvial fans. Once the pumping rate is stabilised, it takes around 10 years to reach a new steady state. Supply decreased between the mining and natural period although the groundwater balance is not accurate. The exceedance probability indicates negligible deviation in GTD for the marginal zone between pumping rates for wet years. However, an exceedance of 10% showed greater deviation.

5.4.2 Aquifer governance

The governance component that forms groundwater sustainability should represent inclusive, equitable and long-term management. The conflict between the indigenous communities and mining companies can be attributed to inefficient state law. The Water Code (1981) encourages a free market whereby mining companies have control over groundwater at the expense of indigenous communities' traditional rights. New laws that aim to protect the indigenous rights have been effective to a certain extent. This is demonstrated through successful appeals against further pumping expansion and obligatory consulting. However, state law fails to protect groundwater use for livestock and fails to recognise the psychological ways that indigenous communities engage with groundwater. This lack of understanding towards place identity and dependence undermines the groundwater management of the basin. DGA have made efforts to engage with various stakeholders through public meetings. This represents some form of inclusivity but does not mean that all stakeholders are actively part of the decision-making process. These decisions are dictated by the mining companies with the environmental regulator SMA overseeing them. As a result, SMA have fined SQM for breaching various monitoring protocols. The new SQM contingency plan intention was supposed to be a long-term management solution but was blocked by the indigenous communities, signalling that SQM have fallen short of their commitments. The idea that groundwater management encompasses indigenous communities' needs in the long-term, remains to be seen, since no RBMP exists. For this reason, recommendations to improve the current groundwater management and overall sustainability are needed.

5.4.3 Recommendations

Based on the aquifer performance and governance evaluation, recommendations are made.

[1] Development of RBMP –the monitoring of the basin is conducted by DGA and SQM. SQM contingency plan is an isolated plan that fails to recognise the indigenous community needs. DGA have technical reports of the hydrogeological makeup of the basin with no governance aspects. The development of a RBMP could provide an overview of the condition, problems, objectives, and measures related to groundwater sustainability. RMBPs are not isolated plans but represent the interconnectivity of different societal needs towards groundwater. SMA could conduct such a plan, with the basis to include indigenous community needs. Further state changes are needed to move from a use-base management system to facilitate the development of integrated groundwater management.

[2] Promotion of indigenous communities' involvement and ATPs - the local knowledge, experiences and sharing of groundwater information should be integrated into future management plans. The idea of inclusiveness is crucial to set specific long-term common goals, within a community-based framework. In these plans, flexible and adaptive management should be included with the identification of adaptation tipping points (ATPs). ATPs specifies the conditions when a certain policy action will fail (Kwakkel et al., 2015). This type of management is particularly important for consecutive dry years where externalities are more likely to occur. Such an ATP could come directly from the leaders of the indigenous communities, e.g. crops dying or unusually dry soil. SQM can be advised quickly, and a new policy action can be implemented such as a reduction in pumping rates.

[3] Expanded monitoring network with restrictions - more monitoring wells should be located in the alluvial fans since this is the only zone where freshwater is sourced. An expanded network with a daily time step would serve as a better representation of the alluvial fans with reduced spatial sampling error, improving the accuracy of the WTF method. Alongside this, greater accountability is needed towards SQM if the GTD drops below a certain threshold. For this reason, control devices in all pumping wells could be installed and monitored by an independent body. This is particularly important for sharp changes in pumping rates that cause unsustainable drawdowns. If a threshold or certain drawdown rate is exceeded, heavier fines can be issued.

[4] More scientific research towards impact on ecosystems - more research should be conducted to understand the extent to which lithium mining is impacting the ecosystems of the marginal zone since there has been a decline in the endangered flamingos. A numerical model simulating the impact of pumping on the environmental flow would be advantageous. The scope of this research focused on freshwater pumping, although brine pumping most likely has a greater impact. Future scientific research should be independent from mining companies. However, mining companies should be active in conservation activities.

[5] More scientific research towards climate impacts - the majority of scientific research relating to groundwater focuses on mining impacts. Climate change impacts could have been overlooked. The results of this thesis found that recharge fluctuated more in the last decade due to ENSO oscillations, evaporation rates are heavily influenced by climate and can cause significant changes in the GTD, and the decline of the algarrobo trees could also be linked to climate changes. It would be interesting to determine to what extent does climate variability have an impact on groundwater sustainability compared to lithium mining.

6 CONCLUSION

Due to the forecast demand for lithium batteries in the next decades, the pumping of freshwater in the alluvial fans is likely to continue in the future. For a low-carbon future, lithium processing must also strive for sustainability. For this reason, it is important to continually monitor the basin with the objective of meeting groundwater sustainability. In this thesis, the research question was: *how is lithium mining impacting groundwater reserves and what can be done to improve the current groundwater management to achieve groundwater sustainability?* Overall, the aquifer performance of the alluvial fans indicates that freshwater pumping for lithium mining has a small impact on the groundwater reserves. Recharge is superior to pumping with a short renewal time and the decline of the groundwater table in the alluvial fans and marginal zone is small. However, if left unmonitored, sharp increases in pumping can cause an unsustainable response in drawdown. As for aquifer governance, Chile's current water laws fail to protect groundwater use for livestock and fails to recognise the psychological ways that indigenous communities engage with groundwater. The free market allows mining companies to control groundwater and facilitates conflict with the indigenous communities. In response to this conflict, there has been some form of stakeholder involvement through consultations, public meetings, and successful appraisals. However, the blocking of SQMs new contingency plan shows that there is poor consensus and a disregard towards indigenous rights and values. As a result, the aquifer governance of the basin is weak compared to aquifer performance and undermines overall groundwater sustainability. To improve sustainability, the development of a RBMP can more freely and equally represent indigenous community needs in adaptable groundwater management. An increased monitoring network can encourage more scientific research in the region. This research has improved the current knowledge of freshwater hydrodynamics of the alluvial fans. In addition, future groundwater sustainability research should be multidisciplinary in nature and incorporate hydrogeological, administrative, and social aspects to build up a detailed picture of the system.

7 REFERENCES

Abdelhalim, A., Sefelnasr, A., & Ismail, E. (2019). Numerical modeling technique for groundwater management in Samalut city, Minia Governorate, Egypt. *Arabian Journal of Geosciences*, *12*(4), 1–18. https://doi.org/10.1007/s12517-019-4230-6

Albemarle. (2018). *PRIMERA ACTUALIZACIÓN DEL MODELO DE FLUJO DE AGUA SUBTERRÁNEA EN EL SALAR DE ATACAMA SEGÚN RCA 21/2016*. www.sgasa.cl

Alvarez, J. A., & Villagra, P. E. (2009). Prosopis flexuosa DC. (Fabaceae, Mimosoideae). *Tomo*, *35*(1), 49–63.

Babidge, S. (2015). The problem with “transparency”: moral contests and ethical possibilities in mining impact reporting. *Focaal*, *73*(73), 70–83. https://doi.org/10.3167/FCL.2015.730106

Babidge, S. (2016). Contested value and an ethics of resources: Water, mining and indigenous people in the Atacama Desert, Chile. *Australian Journal of Anthropology*, *27*(1), 84–103. https://doi.org/10.1111/taja.12139

Babidge, S. (2018). Sustaining ignorance: the uncertainties of groundwater and its extraction in the Salar de Atacama, northern Chile. *Royal Anthropological Insitute* , *25*, 83–102.

Babidge, S., & Bolados, P. (2018). Neoextractivism and Indigenous Water Ritual in Salar de Atacama, Chile. *Latin American Perspectives*, *45*(5), 170–185. https://doi.org/10.1177/0094582X18782673

Bauer, C. J. (2004). Siren song: Chilean water law as a model for international reform. In *Siren Song: Chilean Water Law as a Model for International Reform*. Resources for the Future. https://doi.org/10.4324/9781936331062

BBC. (2019). *The farmers who worry about our phone batteries - BBC News*. https://www.bbc.com/news/business-49355817

Berghuijs, W. R., Hartmann, A., & Woods, R. A. (2016). Streamflow sensitivity to water storage changes across Europe. *Geophysical Research Letters*, *43*(5), 1980–1987. https://doi.org/10.1002/2016GL067927

BHRRC. (2020). *Chile: Court upholds complaint from indigenous communities against SQM over water usage rights linked to lithium mining*. https://www.business-humanrights.org/en/

Bierkens, M. F. P., & Wada, Y. (2019). Non-renewable groundwater use and groundwater depletion: A review. *Environmental Research Letters*, *14*(6). https://doi.org/10.1088/1748-9326/ab1a5f

Bredehoeft, J. (1997). Safe Yield and the Water Budget Myth. *Ground Water*, *35*(6), 929–929. https://doi.org/10.1111/j.1745-6584.1997.tb00162.x

Brunner, P., Li, H. T., Kinzelbach, W., Li, W. P., & Dong, X. G. (2008). Extracting phreatic evaporation from remotely sensed maps of evapotranspiration. *Water Resources Research*, *44*(8), 8428. https://doi.org/10.1029/2007WR006063

Bustos-Gallardo, B., Bridge, G., & Prieto, M. (2021). Harvesting Lithium: water, brine and the industrial dynamics of production in the Salar de Atacama. *Geoforum*, *119*, 177–189. https://doi.org/10.1016/j.geoforum.2021.01.001

Cabello, J. (2021). Lithium brine production, reserves, resources and exploration in Chile: An updated review. *Ore Geology Reviews*, *128*, 103883. https://doi.org/10.1016/j.oregeorev.2020.103883

CORFO. (1977). *Research of hydraulic resources in the Big North*.

de Vries, J. J., & Simmers, I. (2002). Groundwater recharge: An overview of process and challenges. *Hydrogeology Journal*, *10*(1), 5–17. https://doi.org/10.1007/s10040-001-0171-7

Delin, G. N., Healy, R. W., Lorenz, D. L., & Nimmo, J. R. (2007). Comparison of local- to regional-scale estimates of ground-water recharge in Minnesota, USA. *Journal of Hydrology*, *334*(1–2), 231–249. https://doi.org/10.1016/j.jhydrol.2006.10.010

Deutsche Welle. (2020). *Lithium extraction for e-mobility robs Chilean communities of water | Environment| All topics from climate change to conservation | DW | 23.01.2020*. https://www.dw.com/en/lithium-extraction-for-e-mobility-robs-chilean-communities-of-water/a-51844854

Devlin, J. F., & Sophocleous, M. (2005). The persistence of the water budget myth and its relationship to sustainability. *Hydrogeology Journal*, *13*(4), 549–554. https://doi.org/10.1007/s10040-004-0354-0

DGA. (1999). *EVALUACION DE LA DISPONIBILIDAD DE RECURSOS HIDRICOS PARA CONSTITUIR DERECHOS DE APROVECHAMIENTO EN LAS SUBCUENCAS AFLUENTES AL SALAR DE ATACAMA. II REGION*.

DGA. (2010). *Resource availability assessment update resources to build exploitation rights in the tributary sub-basins to the Salar de Atacama*.

DGA. (2013). *ANÁ ÁLISIS Di GOBIERN MINISTE DIRECCI DIVISIÓ IN S DE L SALA R visión de Sant NFORME T*.

Donoso, G. (2014). Integrated water management in Chile. In *Integrated Water Resources Management in the 21st Century: Revisiting the paradigm*. CRC Press. https://doi.org/10.1201/b16591-16

Elshall, A. S., Arik, A. D., El-Kadi, A. I., Pierce, S., Ye, M., Burnett, K. M., Wada, C. A., Bremer, L. L., & Chun, G. (2020). Groundwater sustainability: A review of the interactions between science and policy. *Environmental Research Letters*, *15*(9). https://doi.org/10.1088/1748-9326/ab8e8c

Flexer, V., Baspineiro, C. F., & Galli, C. I. (2018). Lithium recovery from brines: A vital raw material for green energies with a potential environmental impact in its mining and processing. *Science of the Total Environment*, *639*, 1188–1204. https://doi.org/10.1016/j.scitotenv.2018.05.223

Gajardo, G., & Redón, S. (2019). Andean hypersaline lakes in the Atacama Desert , northern Chile : Between lithium exploitation and unique biodiversity conservation . *Conservation Science and Practice*, *1*(9), e94. https://doi.org/10.1111/csp2.94

Garcés, I., & Alvarez, G. (2020). Water mining and extractivism of the Salar de Atacama, Chile. *WIT Transactions on Ecology and the Environment*, *245*, 189–199. https://doi.org/10.2495/EID200181

Gehman, C. L., Harry, D. L., Sanford, W. E., Stednick, J. D., & Beckman, N. A. (2009). Estimating specific yield and storage change in an unconfined aquifer using temporal gravity surveys. *Water Resources Research*, *46*(4). https://doi.org/10.1029/2007WR006096

Gleeson, T., Cuthbert, M., Ferguson, G., & Perrone, D. (2020). Global Groundwater Sustainability, Resources, and Systems in the Anthropocene. *Annual Review of Earth and Planetary Sciences*, *48*, 431–463. https://doi.org/10.1146/annurev-earth-071719-055251

GlobalData. (2020). *Global lithium demand to more than double by 2024 on EV growth: GlobalData | S&P Global Platts*. https://www.spglobal.com/platts/en/market-insights/latest-news/metals/100720-global-lithium-demand-to-more-than-double-by-2024-on-ev-growth-globaldata

Grageda, M., Gonzalez, A., Quispe, A., & Ushak, S. (2020). Analysis of a process for producing battery grade lithium hydroxide by membrane electrodialysis. *Membranes*, *10*(9), 1–21. https://doi.org/10.3390/membranes10090198

Guzmán, J. I., Faúndez, P., Jara, J. J., & Retamal, C. (2021). *ROLE OF LITHIUM MINING ON THE WATER STRESS OF THE SALAR DE ATACAMA BASIN*.

Haileslassie, A., Ludi, E., Roe, M., & Button, C. (2020). *Water Values: Discourses and Perspective*. 1–10. https://doi.org/10.1007/978-3-319-70061-8_140-1

Healy, R. W., & Cook, P. G. (2002). Using groundwater levels to estimate recharge. *Hydrogeology Journal*, *10*(1), 91–109. https://doi.org/10.1007/s10040-001-0178-0

Hiscock, K. M., Rivett, M. O., & Davison, R. M. (2002). Sustainable groundwater development. *Geological Society Special Publication*, *193*(1), 1–14. https://doi.org/10.1144/GSL.SP.2002.193.01.01

Houston, J. (2006). Variability of precipitation in the Atacama Desert: Its causes and hydrological impact. *International Journal of Climatology*, *26*(15), 2181–2198. https://doi.org/10.1002/joc.1359

Huet, M., Chesnaux, R., Boucher, M. A., & Poirier, C. (2016). Comparing various approaches for assessing groundwater recharge at a regional scale in the Canadian Shield. *Hydrological Sciences Journal*, *61*(12), 2267–2283. https://doi.org/10.1080/02626667.2015.1106544

IDAEA-CSIC. (2017). *CUARTA ACTUALIZACIÓN DEL MODELO HIDROGEOLÓGICO DEL SALAR DE ATACAMA*.

Indigenous Law. (1993). *Law 19.253 | Indigenous Justice*. https://justiciaindigena.wordpress.com/law-19-253/

INN. (2018). *Low Cost, High Margins: Lithium Brine Extraction | INN*. https://investingnews.com/innspired/lithium-brine-extraction-electric-vehicle-market/

Jafari, H., Raeisi, E., Hoehn, E., & Zare, M. (2012). Hydrochemical characteristics of irrigation return flow in semi-arid regions of Iran. *Hydrological Sciences Journal*, *57*(1), 173–185. https://doi.org/10.1080/02626667.2011.636365

Jerez, B., Garcés, I., & Torres, R. (2021). Lithium extractivism and water injustices in the Salar de Atacama, Chile: The colonial shadow of green electromobility. *Political Geography*, *87*, 102382. https://doi.org/10.1016/j.polgeo.2021.102382

Koïta, M., Yonli, H. F., Soro, D. D., Dara, A. E., & Vouillamoz, J. M. (2018). Groundwater storage change estimation using combination of hydrogeophysical and groundwater table fluctuation methods in hard rock aquifers. *Resources*, *7*(1). https://doi.org/10.3390/resources7010005

Kwakkel, J. H., Haasnoot, M., & Walker, W. E. (2015). Developing dynamic adaptive policy pathways: a computer-assisted approach for developing adaptive strategies for a deeply uncertain world. *Climatic Change*, *132*(3), 373–386. https://doi.org/10.1007/s10584-014-1210-4

Labour Organisations Convention C169. (2009). *Convention C169 - Indigenous and Tribal Peoples Convention, 1989 (No. 169)*. https://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO::P12100_ILO_CODE:C169

Labrecque, G., Chesnaux, R., & Boucher, M. A. (2020). Water-table fluctuation method for assessing aquifer recharge: application to Canadian aquifers and comparison with other methods. *Hydrogeology Journal*, *28*(2), 521–533. https://doi.org/10.1007/s10040-019-02073-1

Latham, E., Kilbey, B., & Entaiba, A. (2019). *Lithium supply is set to triple by 2025. Will it be enough | S&P Global*. https://www.spglobal.com/en/research-insights/articles/lithium-supply-is-set-to-triple-by-2025-will-it-be-enough

Liu, W., & Agusdinata, D. B. (2020). Interdependencies of lithium mining and communities sustainability in Salar de Atacama, Chile. *Journal of Cleaner Production*, *260*. https://doi.org/10.1016/j.jclepro.2020.120838

Liu, W., Agusdinata, D. B., & Myint, S. W. (2019). Spatiotemporal patterns of lithium mining and environmental degradation in the Atacama Salt Flat, Chile. *International Journal of Applied Earth Observation and Geoinformation*, *80*, 145–156. https://doi.org/10.1016/j.jag.2019.04.016

Marazuela, M. A., Vázquez-Suñé, E., Ayora, C., & García-Gil, A. (2020). Towards more sustainable brine extraction in salt flats: Learning from the Salar de Atacama. *Science of the Total Environment*, *703*, 135605. https://doi.org/10.1016/j.scitotenv.2019.135605

Marazuela, M. A., Vázquez-Suñé, E., Ayora, C., García-Gil, A., & Palma, T. (2019a). Hydrodynamics of salt flat basins: The Salar de Atacama example. *Science of the Total Environment*, *651*, 668–683. https://doi.org/10.1016/j.scitotenv.2018.09.190

Marazuela, M. A., Vázquez-Suñé, E., Ayora, C., García-Gil, A., & Palma, T. (2019b). The effect of brine pumping on the natural hydrodynamics of the Salar de Atacama: The damping capacity of salt flats. *Science of the Total Environment*, *654*, 1118–1131. https://doi.org/10.1016/j.scitotenv.2018.11.196

Marazuela, M. A., Vázquez-Suñé, E., Custodio, E., Palma, T., García-Gil, A., & Ayora, C. (2018). 3D mapping, hydrodynamics and modelling of the freshwater-brine mixing zone in salt flats similar to the Salar de Atacama (Chile). *Journal of Hydrology*, *561*, 223–235. https://doi.org/10.1016/j.jhydrol.2018.04.010

Mardones L. (1986). *Geological and Hydrogeological Characteristics of the Salar de Atacama*.

Maréchal, J. C., Dewandel, B., Ahmed, S., Galeazzi, L., & Zaidi, F. K. (2006). Combined estimation of specific yield and natural recharge in a semi-arid groundwater basin with irrigated agriculture. *Journal of Hydrology*, *329*(1–2), 281–293. https://doi.org/10.1016/j.jhydrol.2006.02.022

Mongabay. (2020). *Chile renews contract with lithium company criticized for damaging wetland*. https://news.mongabay.com/2018/12/chile-renews-contract-with-lithium-company-criticized-for-damaging-wetland/

Morse, I. (2020). *Water or Mineral? In Chile, a Debate Over Lithium Brine*. https://undark.org/2020/12/21/chile-debate-over-lithium-brine/

OCMAL. (2018). *Impacto socioambiental de la extracción de litio en las cuencas de los salares altoandinos del cono sur*.

Philip, J. (1957). EVAPORATION, AND MOISTURE AND HEAT FIELDS IN THE SOIL. *Journal of the Atmospheric Sciences*, *14*(4), 354–366. https://journals-ametsoc-org.proxy.library.uu.nl/view/journals/atsc/14/4/1520-0469_1957_014_0354_eamahf_2_0_co_2.xml

Rahimi-Feyzabad, F., Yazdanpanah, M., Gholamrezai, S., & Ahmadvand, M. (2021). Institutional constraints to groundwater resource management in arid and semi-arid regions: a Straussian grounded theory study. *Hydrogeology Journal*, *29*(3), 925–947. https://doi.org/10.1007/s10040-020-02283-y

Ramsar. (2010). *Sistema Hidrológico de Soncor del Salar de Atacama | Ramsar Sites Information Service*. https://rsis.ramsar.org/ris/876

Retamal, R., Andreoli, A., Arumí, J. L., & Rojas, J. (2013). Gobernanza del Agua y Cambio Climático: Fortalezas y Debilidades del Actual Sistema de Gestión del Agua an Chile. Análisis Interno. *Interciencia*, *38*(1). https://www.researchgate.net/publication/242347141

Rezaei, A., & Mohammadi, Z. (2017). Annual safe groundwater yield in a semiarid basin using combination of water balance equation and water table fluctuation. *Journal of African Earth Sciences*, *134*, 241–248. https://doi.org/10.1016/j.jafrearsci.2017.06.029

Rudestam, K., Brown, A., & Langridge, R. (2018). Exploring “Deep Roots”: Politics of Place and Groundwater Management Practices in the Pajaro Valley, California. *Society and Natural Resources*, *31*(3), 291–305. https://doi.org/10.1080/08941920.2017.1413693

Sherwood, D. (2021). *La lucha del gigante del litio SQM por ganarse a las comunidades indígenas chilenas | Reuters*. https://www.reuters.com/article/mineria-chile-sqm-idLTAKBN29K1DX

SMA. (2013). *INFORME DE FISCALIZACIÓN AMBIENTAL INSPECCIÓN AMBIENTAL SQM SALAR*. www.sma.gob.cl

SMA. (2018). *INFORME DE FISCALIZACIÓN AMBIENTAL*.

SMA. (2019). *SMA approves Compliance Program that imposes demands on SQM Salar SA valued at USD 25 million | Superintendency of the Environment*. https://portal.sma.gob.cl/index.php/2019/01/07/sma-aprueba-programa-de-cumplimiento-que-impone-exigencias-a-sqm-salar-s-a-avaluadas-en-usd-25-millones/

SQM. (2018). *Seal Agreement News | SQM*. https://www.sqm.com/en/

SQM. (2021). *SQM monitor online*. https://www.sqmsenlinea.com/env-systems?type=followup

Staff, R. (2020). *Electric cars to account for 79% of lithium demand by 2030: Chile | Reuters*. https://www.reuters.com/article/us-chile-lithium-idUSKBN25M2PG

USGS. (2008). *Calculating Flow-Duration and Low-Flow Frequency Statistics at Streamflow-Gaging Stations Report 2008-5126*.

USGS. (2017). *USGS GWRP: Techniques/Methods -Water-Table Fluctuation (WTF) Method*. https://water.usgs.gov/ogw/gwrp/methods/wtf/estimating_rise.html

Valdés-Pineda, R., Pizarro, R., García-Chevesich, P., Valdés, J. B., Olivares, C., Vera, M., Balocchi, F., Pérez, F., Vallejos, C., Fuentes, R., Abarza, A., & Helwig, B. (2014). Water governance in Chile: Availability, management and climate change. *Journal of Hydrology*, *519*(PC), 2538–2567. https://doi.org/10.1016/j.jhydrol.2014.04.016

Varni, M., Comas, R., Weinzettel, P., & Dietrich, S. (2013). Application de la méthode de fluctuation du niveau piézométrique pour caractériser la recharge des eaux souterraines dans la plaine de la Pampa (Argentine). *Hydrological Sciences Journal*, *58*(7), 1445–1455. https://doi.org/10.1080/02626667.2013.833663

Wang, D. (2012). Evaluating interannual water storage changes at watersheds in Illinois based on long-term soil moisture and groundwater level data. *Water Resources Research*, *48*(3). https://doi.org/10.1029/2011WR010759

Water Code. (1981). *Decree with the force of Law No. 1,122 - Fixed text of the Water Code.* https://www.ecolex.org/es/details/legislation/decreto-con-fuerza-de-ley-no-1122-fija-texto-del-codigo-de-aguas-lex-faoc002992/?type=legislation&q=c%C3%B3digo+de+agua

World Bank. (2013). *Estudio para el mejoramiento del marco institucional para la gestión del agua*.

8 APPENDIX

Table 8.1 Groundwater balance flow components for natural (1975-1997) and mining period (1998-2020) in m^3/s

Year	Lateral recharge	Direct recharge	Evaporation discharge (marginal zone)	Evaporation (alluvial fans)	Pumping	Change in storage
1975	3.52	0.73	0.97	0.00	0.00	3.28
1976	1.34	0.27	0.97	0.00	0.00	0.64
1977	1.96	0.41	0.97	0.00	0.00	1.39
1978	1.28	0.26	0.97	0.00	0.00	0.57
1979	0.64	0.16	0.97	0.00	0.00	-0.17
1980	0.77	0.19	0.97	0.00	0.00	-0.02
1981	3.04	0.81	0.97	0.00	0.00	2.88
1982	0.36	0.09	0.97	0.00	0.00	-0.52
1983	2.40	0.63	0.97	0.00	0.00	2.06
1984	3.93	1.06	0.97	0.00	0.00	4.02
1985	1.16	0.30	0.97	0.00	0.00	0.49
1986	2.06	0.53	0.97	0.00	0.00	1.62
1987	2.12	0.54	0.97	0.00	0.00	1.68
1988	0.17	0.03	0.97	0.00	0.00	-0.77
1989	1.29	0.34	0.97	0.00	0.00	0.66
1990	1.02	0.24	0.97	0.00	0.00	0.29
1991	0.14	0.03	0.97	0.00	0.00	-0.81
1992	0.41	0.09	0.97	0.00	0.00	-0.48
1993	0.78	0.19	0.97	0.00	0.00	-0.01
1994	0.46	0.11	0.97	0.00	0.00	-0.40
1995	0.91	0.24	0.97	0.00	0.00	0.18
1996	0.82	0.17	0.97	0.00	0.00	0.02
1997	1.56	0.47	0.97	0.00	0.00	1.06
Natural average	1.40	0.34	0.97	0.00	0.00	0.77
1998	0.15	0.03	1.14	0.00	0.04	-1.00
1999	0.71	0.21	1.03	0.00	0.04	-0.15
2000	1.93	0.41	1.13	0.00	0.05	1.15
2001	2.97	0.82	1.06	0.00	0.05	2.67
2002	1.82	0.49	0.93	0.00	0.05	1.33
2003	0.86	0.18	0.93	0.00	0.05	0.07
2004	0.67	0.10	0.80	0.00	0.05	-0.08
2005	1.07	0.28	0.98	0.00	0.06	0.31
2006	0.43	0.11	0.85	0.00	0.04	-0.34
2007	0.22	0.06	0.72	0.00	0.05	-0.48
2008	0.65	0.10	1.14	0.00	0.11	-0.50
2009	0.25	0.06	1.14	0.00	0.20	-1.03
2010	0.20	0.03	1.15	0.00	0.18	-1.10
2011	1.65	0.40	1.08	0.00	0.19	0.78

2012	3.45	0.83	1.10	0.00	0.20	2.99
2013	2.29	0.49	1.02	0.00	0.20	1.57
2014	0.10	0.02	0.92	0.00	0.19	-0.98
2015	3.32	0.81	1.09	0.00	0.20	2.84
2016	0.11	0.12	0.86	0.00	0.15	-0.78
2017	3.76	1.24	0.93	0.00	0.20	3.87
2018	0.98	0.27	0.56	0.00	0.13	0.56
2019	3.78	1.50	1.08	0.00	0.13	4.08
2020	0.27	0.25	0.70	0.00	0.06	-0.24
Mining average	1.38	0.38	0.97	0.00	0.11	0.67