Assessment of groundwater sustainability in the Maipo River Basin (Chile)

Avaliação da sustentabilidade das águas subterrâneas na Bacia do Rio Maipo (Chile)

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ABSTRACT: In Central Chile, precipitation decreases while drinking water and irrigational demand increase. In the Maipo Basin, shortages in surface water are compensated by increased groundwater abstraction for agriculture and drinking water. Also, agricultural land is transformed due to the expansion of Santiago city. Effective groundwater management is required to protect available groundwater resources and ensure equal distribution among users. Therefore, this study aims to analyze the current groundwater management and governance framework at the basin scale. The study assesses the context of groundwater management and the functioning cooperation mechanisms between the stakeholders. Furthermore, the current knowledge gaps and challenges are identified, and approaches to improve water resources management policy are proposed.

A literature and legal context analysis in the context of the Maipo Basin is supplemented by interviews and a survey among stakeholders. Groundwater sustainability indicators are applied to enhance sustainable water planning and management, support data sharing, show groundwater users' current impact, and stimulate stakeholder communication. Lastly, a sustainable yield index is developed and proposed to assess groundwater management and to provide a concrete initial step to sustainable groundwater management in the Maipo Basin, which could be applied in other basins in Chile.

The results show that groundwater is seen and treated differently than surface water, and its management and governance are neglected. Moreover, hydrological boundaries are not always respected because groundwater management is organized by administrative regions which are not always clearly based on hydrogeological boundaries, and groundwater management is decentralized. Some difficulties in allocating resources to monitoring groundwater use were found. The groundwater sustainability indicators show the urgent situation of 'overgranting' of groundwater rights compared to the recharge. The sustainable yield index demonstrates the unsustainable situation of the region, threatening groundwater-dependent ecosystems. Further recommendations are made towards a more robust groundwater management with the well-defined role of the General Directorate of Water (DGA).

Keywords: Chile, Groundwater, Management, Governance, Indicators, Sustainability

RESUMO: No Chile central, a precipitação diminui enquanto as necessidades hídricas aumentam. Na bacia do Maipo, a escassez de recursos hídricos superficiais é equilibrada pelo aumento de captações de água subterrânea, tanto para agricultura como para o abastecimento público. Além disso, os terrenos agrícolas têm vindo a sofrer alterações devido à expansão urbana, nomeadamente da cidade de Santiago do Chile. Urge uma gestão eficaz das águas subterrâneas para proteger os recursos hídricos disponíveis e garantir a sua distribuição equitativa entre os seus utilizadores. Portanto, este estudo pretende analisar o atual quadro de gestão e governança das águas subterrâneas à escala da bacia hidrográfica do Maipo. O estudo avalia a gestão das águas subterrâneas e o funcionamento dos mecanismos de cooperação entre as partes interessadas. Além disso, identificam-se as atuais lacunas e desafios do conhecimento e propõem-se abordagens para melhorar a política de gestão dos recursos hídricos.

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É feita uma análise no contexto da região hidrográfica, suplementada por entrevistas e questionários a partes interessadas. São aplicados indicadores de sustentabilidade para apoiar o planeamento e gestão sustentável, a partilha de dados, mostrar o impacto atual dos utilizadores e estimular a comunicação entre as partes interessadas. Foi desenvolvido e proposto um índice de produção sustentável para avaliar a gestão das águas subterrâneas e fornecer um ponto de partida concreto para a gestão sustentável dos recursos hídricos subterrâneos na bacia do Maipo, e que tem o potencial de ser aplicado noutras bacias hidrográficas no Chile.

Os resultados mostram que as águas subterrâneas são vistas e tratadas de forma diferente das águas superficiais, e a sua gestão e governança foram negligenciadas. Além disso, os limites hidrológicos nem sempre são respeitados e a gestão das águas subterrâneas é descentralizada. A entidade pública responsável pela água carece de capacidade e recursos para fiscalizar e monitorizar o uso das águas subterrâneas. Os indicadores de sustentabilidade aplicados mostram uma situação grave de "sobre-licenciamento" relativamente aos recursos subterrâneos renováveis. O índice de produção sustentável demonstra uma situação insustentável, ameaçando os ecossistemas dependentes das águas subterrâneas. Finalmente, são feitas recomendações para que possa ser feita uma gestão das águas subterrâneas mais robusta em que o papel da Direção Geral de Águas (DGA) é fundamental.

Palavras-chave: Chile, Água Subterrânea, Gestão, Governança, Indicadores, Sustentabilidade.

1. INTRODUCTION

Chile is a country of hydrological extremes, with its long coastline stretching from Patagonia to one of the driest deserts on Earth, the Atacama Desert, and from the sparsely populated high peaks of the Andes to the densely populated Central Valley (McPhee, 2018). This characteristic is also reflected in Chile's water management. It is a challenge to manage Chile's water resources in a suitable manner while simultaneously having one of the driest and wettest places on Earth. Droughts and accelerated land-use change are known to impact semi-arid regions significantly. Droughts increase groundwater use and consequently decrease aquifer storage. Land-use change often alters the spatial patterns of groundwater recharge. It is, therefore, important to mitigate and study these effects with sustainable groundwater management. On the other hand, especially in the arid and semi-arid regions, water has always played an important role in Chile (Donoso *et al.*, 2020).

The water code that shaped Chilean water governance is the Water Code of 1981 (WC81), a product of this pro-market, neoliberal policy. The code mainly concentrates on surface water and does not integrate groundwater into water management. However, the General Directorate of Water (DGA) provides a similar legal framework to both surface water and groundwater. This system offers the right to use groundwater as a private good, similar to the rights of land ownership. In real life, this implies that groundwater was managed the same way as real estate (Rinaudo & Donoso, 2019). Land and water ownership are, therefore, disconnected. Furthermore, the WC81 states that groundwater and surface water are managed separately, which is kept the same in a reform of the WC81 in 2005 (Donoso *et al.*, 2020). Once a user obtains the rights of a (ground)water resource, it is freely tradeable, with the vision that this would allow for the development of an efficient water allocation system (Meza *et al.*, 2012).

Central Chile is becoming more dependent on groundwater resources. It is expected that groundwater resources will become even more critical due to population growth, economic development, urbanization, water contamination and pollution, and the effects of climate change on water use (Donoso *et al.*, 2020). Climate change is expected to decrease precipitation, and the time of the peak of glacier snowmelt will shift. This significantly impacts water supply and reliability because the region strongly depends on melting water from the Andes. The geological and geomorphological settings allow interaction between groundwater and surface water. The distance between the Andean mountains and the river mouth is relatively short, and the valleys and the steep slopes make a context favourable for interaction between the river streams and the aquifers (Meza *et al.*, 2012).

The consequences of groundwater overexploitation are already observed. Groundwater levels have declined in aquifers to below sustainable limits (Nascimento *et al.*, 2022), Andean rivers have dried up and baseflow significantly reduced (Donoso *et al.*, 2020), and groundwater-dependent ecosystems are facing severe damage (Duran-Llacer *et al.*, 2022). Furthermore, an increase in water conflicts is observed because of the intensification of groundwater use (Donoso *et al.*, 2020).

In general, there is a lack of available and sufficient information on groundwater dynamics and its interaction with surface water. Significant data gaps are identified on, for instance, well licencing and abstracted volumes. On the other hand, there is no collective groundwater management because of the lack of groundwater user associations in the basins (Donoso *et al.*, 2020).

In Chile, 83% of the current water problems are related to poor water management, while the remaining 17% can be attributed to climate change (Fundación Chile, 2021). Groundwater governance has already been documented for multiple years. However, its evaluation and monitoring are still relatively little investigated. In most regions, the development of groundwater governance has not kept the same pace as the pressures on groundwater resources (Akhmouch & Clavreul, 2017). Currently, there is no research specifically on the assessment and evaluation of groundwater management and governance in Chilean basins. However, previous studies on groundwater management are often included in a study focusing on surface water.

Furthermore, it is important to realize that groundwater-related problems and opportunities are well-known to a small, specific group of experts but not to politicians and policymakers (FAO, 2016). There is a need to present scientific groundwater data in a more coherent approach to the public and policymakers. The UNESCO Groundwater Resources Sustainability Indicators have the potential to serve policy objectives and support the development of groundwater resource management. Furthermore, the indicators simplify, quantify, communicate, order, and allow for the comparison with other zones or regions (Vrba *et al.*, 2006).

Lastly, the academic sector should try to support the transition to sustainable groundwater management and governance. In the Maipo Basin, it could help by identifying sustainable yield and giving directions to policy.

The main objectives of this study are to:

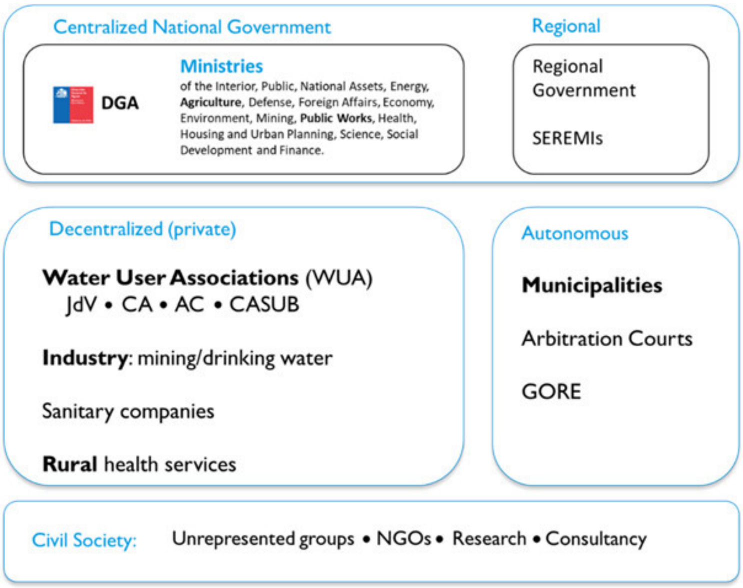
a) Identify the main groundwater-related problems in the Maipo Basin and assess how these problems have developed in the current cultural, historical, and legislative context.
b) Verify the existence and functioning of institutions managing groundwater at the basin scale and how cooperation mechanisms for the groundwater management across water-related users and levels of government from local to basin, regional, national, and upper scales.
c) Verify the existence and level of implementation of Integrated Water Resources Management (IWRM) policies and strategies within groundwater governance.
d) Identify and analyse the current gaps and challenges and the areas needing improvement.
e) Application of groundwater indicators for the improvement of water resource management policy
f) Looking at a sustainable yield index to provide directions and solutions for more precise sustainable groundwater management.

2. GROUNDWATER MANAGEMENT AND GOVERNANCE IN CHILE

The World Bank has identified 42 institutional actors, such as management units, user groups, or water resource stakeholders active in Chile (Peña, 2021). This fact illustrates that the water management sector is quite fragmented. Figure 1 shows the conceptual institutional structure of water governance in Chile. It is characterized by an authority that independently governs the water users and the project developers. The main centralized institutions are the public bodies such as the 'Dirección General de Aguas' (DGA) and the Ministry of Agriculture. The regional government and the regional departments of these centralized bodies have little autonomous power and are there to implement the policy which is made on the national level. The main decentralized and private bodies are the water user associations (WUA).

The literature review on groundwater management and governance in Chile provides valuable background information on its current state and development. It becomes clear that groundwater governance is mainly carried out by decentralized and private institutions, with a centralized government lacking authority on a regional and national level. Furthermore, the large number of different legal stakeholders present makes the integration of groundwater policy and governance even harder. In addition, most institutions focus on surface water without cross-coordination with other sectors and disciplines.

An increased awareness of groundwater role in water policy and legislation could have profound benefits. Groundwater policy requires long-term planning, which is currently lacking in Chilean water legislation. A more prominent place for groundwater would force policymakers to think in longer terms. Also, groundwater planning requires a broader view of the hydrological cycle and will automatically, in a more natural way, cause a shift to an IWRM approach. It is not possible to manage groundwater resources without integrating surface water. However, political will and the budget must be available for this.



AC - Canal associations (Asociaciones de Canales)

CA - Water communities (Comunidades de Agua)

CASUB - Groundwater user community (Comunidad de Aguas Subterráneas)

GORE - Chilean regional governments (Gobiernos regionales de Chile)

JdV - Surveillance boards (Juntas de Vigilancia)

SEREMI - Regional Ministerial Secretariats of Health (Secretarías Regionales Ministeriales de Salud)

Figure 1. Main institutions of Chilean water governance, based on Vergara & Rivera (2018).

3. CHILEAN WATER MARKET AND POLICY

In the analysis of Chilean water market and policy, it has become clear that the Chilean water market on groundwater management are characterized by:

a) A system of water rights holders that secures them the use and possession of water like any other private good;

b) The existence of a water rights market;

c) The role of the State is seen as accompanying;

d) The WUAs, private organizations, are essential for the management of a public good.

The most striking fact is that the State is seen as accompanying, because of the existence of a strongly privatized water market. However, it has the largest responsibility over some main tasks of groundwater management. In the new water code, this is not different. The DGA even got a larger responsibility and more tasks. WUAs have, in theory, extensive responsibilities and take over functions from the DGA, but regarding groundwater, this is not the case because groundwater user associations do not nearly exist. The principle that the DGA has the power to restrict an aquifer if newly granted water rights harm the existing water rights gives the impression that the economic perspective is more important than, for instance, the ecological value.

Furthermore, groundwater use was not the main objective of the WC81, as groundwater abstraction was minimal at the time of writing (Vergara & Rivera, 2018). However, pressures on groundwater resources have increased. New legislation could not prevent negative effects and it limits sustainable groundwater management. It will be the question whether the new water code, which is in place since the beginning of 2021, addresses groundwater better. The fact that groundwater rights are now granted with a time limit of 30 years is a step in the right direction. However, an aquifer can be depleted in less time. The DGA has the authority to limit the right after five years, which is a good rule, but it seems that the capacity of the DGA is too little to enforce this rule.

4. ANALYSIS OF CURRENT GAPS AND CHALLENGES OF GROUNDWATER GOVERNANCE AND MANAGEMENT OF THE MAIPO BASIN

Furthermore, an analysis of the current State and future challenges of groundwater governance in the Maipo Basin is conducted. The analysis is based on literature analysis, stakeholder interviews, and a survey. The literature analysis is based on recent studies. The interviews and survey assess groundwater governance using a methodology developed by Hamer *et al.* (2020)), which evaluates water governance rationality. Rational groundwater governance tools allow equitable groundwater access and sustainable abstraction. There are five criteria: 1) water system knowledge, 2) water resources usage and monitoring, 3) the legal framework, 4) short and long-term vision, and 5) stakeholder participation and engagement. The methodology can easily be adapted to groundwater governance and provides a clear outline for stakeholder interviews and surveys.

The final assessment using this methodology is shown in Table 1. Water system knowledge on a macro-scale is present. However, on a local scale, there is information missing, and the knowledge gaps are not addressed. Therefore, this criterion is classified as average. Water resource usage and monitoring are classified as low. Illegal abstraction is a significant concern for most respondents, and it is believed that groundwater abstractions are too high while monitoring and inspection are not enforced and are only partly in place. The legal framework is also lacking since most respondents are not confident that the groundwater rights market is equally distributing the water among the groundwater users, and the DGA cannot enforce its legal responsibilities. Also, participants from all the groundwater users are lacking. The short and long-term vision is classified as average to low because some initiatives and ideas address the groundwater-related problem in the long term, such as a nature-based solution. However, there seems to be no consensus on the direction to go, and economic and social interests are leading. Mainly because of this mix of different perspectives, there is no clear vision of the long term. However, awareness of sustainability and ecological values is increasing. The last criterion, stakeholder participation and engagement, are also classified as average to low. There are initiatives to engage stakeholder participation and engagement, like the 'Fondo de Agua'. However, the fragmentation of the stakeholders is considerable, and trust has to be built between them, which takes time. Therefore, in the current State, cooperation is limited.

Table 1. Final assessment of groundwater governance rationality of the Maipo Basin, based on Hamer et al. (2020).

Assessment of rationality of groundwater governance of the Maipo Basin	Score
Water system knowledge and gaps	Average
Water resources usage and monitoring	Low
Legal framework	Low
Short and long-term vision	Average - low
Stakeholder participation and engagement	Average - low

5. STUDY AREA: THE MAIPO BASIN

The Maipo Basin consists almost entirely of one large connected aquifer with multiple important water users (Figure 2), such as agriculture and domestic use, with different interests. FAO (2016) argues that governance of such aquifers is challenging but not impossible. Because of the abundance of stakeholders, creating a formal regulatory regime is a complex task. Together, they should strive towards creating a database with shared and common knowledge to encourage informed groundwater abstraction. Currently, the DGA has most of the information on groundwater. However, it is incomplete and only in large documents, such as the Strategic Plan for Water Management (Plan Estratégico de Gestión Hídrica, PEGH) for the Maipo Basin. Shared responsibility and vision under all groundwater users are important for the sustainability of the groundwater resources, and providing the information is an integral part of this. As the role of the DGA is seen as supplementary, providing information should have a more prominent importance. Ideally, this will lead to more engaged and participative groundwater management.

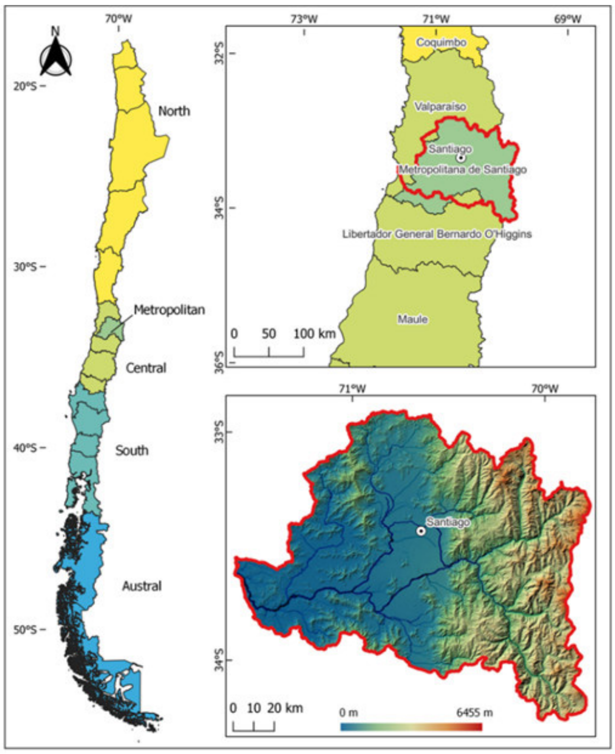


Figure 2. Situation of the study area within Chile.

Human interventions have seriously affected recharge processes, and more understanding is needed. The expansion of urban land at the expense of agriculture has consequences on groundwater recharge rate, drinking water demand, and the increase of groundwater rights. These factors have been poorly studied up until now. This could mainly be explained because groundwater abstraction in the Maipo Basin does not have a long history. Therefore, the absence of high-quality reference studies on natural recharge and the status of aquifers is a severe problem. Agent-based modelling could be a promising tool to consider all stakeholders in hydrogeological and numerical models and to improve IWRM in the basin. This way, better strategies and planning can be conducted (Suárez *et al.*, 2021). Measures must be taken to adapt to the local and national context (FAO, 2016). Figure 3 provides an overview of the aquifer systems and the SHAC units (Hydrogeological Sectors of Common Use that Belong to the Aquifer). In the Maipo River basin, there are seven aquifer systems: Colina, Puangue, Melpilla, Chacabuco, Maipo – Mapocho, Maipo Alto and Cuencas Costeras sur. The first five are often taken as one aquifer.

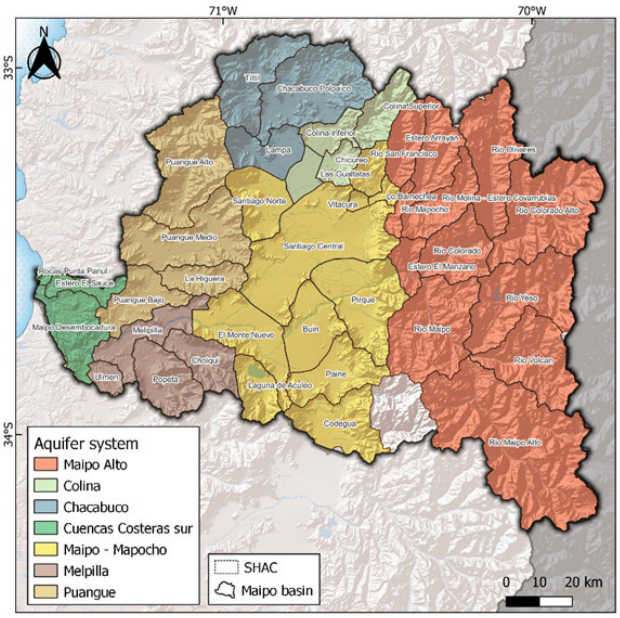


Figure 3. Aquifer systems of the Maipo River Basin and the corresponding SHAC units (DGA, n.d.; División de Estudios y Planificación, 2017).

According to DGA (2022), there are 11 SHAC units under prohibition and 13 under restriction. This means that all the active, used aquifers are under some sort of limitation for granting new water rights. The location of the SHACs under restriction or prohibition are shown in Figure 4.

6. GROUNDWATER POTENTIAL INDEX

To protect groundwater resources it is important to have a high-resolution map. This map is currently lacking in the Maipo basin. However, it possible to construct a high-resolution map of the occurrence of groundwater resources in the Maipo basin. The method used is the Groundwater Potential Index (GWPI). The term 'groundwater potential' is described in Rahmati *et al.* (2015) as: 'the possibility of groundwater occurrence in an area'. Thus, this is the possibility that there are groundwater resources. However it does not mean that it is there in reality per se. Artificial influences such as groundwater abstraction, managed aquifer recharge, or land-use change are not taken into account.

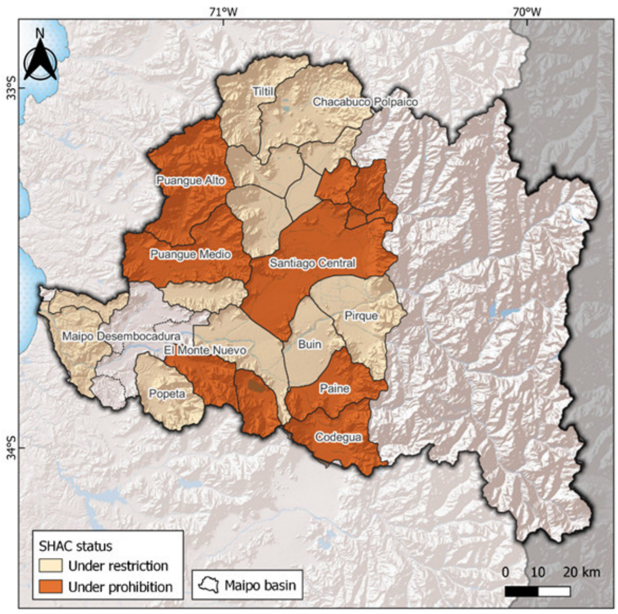


Figure 4. Areas under restriction and prohibition for the Maipo River basin, based on DGA (2022).

The GWPI zones were elaborated based on the methodology presented in Figure 4 (van der Hulst, 2022), and the result is presented in Figure 5. The method was based on the Analytical Hierarchy Process (AHP) method, which uses weights and criteria to different thematic layers. The thematic layers, the factors influencing groundwater, are chosen based on data availability and previous studies. The index should include climatic, hydrologic, and hydrogeological data. This study considered eight thematic layers: geomorphology, land-use, geology, lineament density, drainage density, slope, soil type, and precipitation.

High groundwater potential index is observed in the Central Valley. In the Andean mountain range, the potential is predominantly low. Furthermore, there is a considerable area in the coastal mountain range where the groundwater potential is very poor because of the combination of steep slopes, little precipitation, and the occurrence of intrusive rocks. A poor potential for groundwater characterizes the majority of the basin. Some areas in the Andean mountain range have a high or very high groundwater potential, mainly because the precipitation is higher here than in the rest of the basin. Also, river valleys with a flat surface and sedimentary rocks create more suitable conditions for groundwater occurrence.

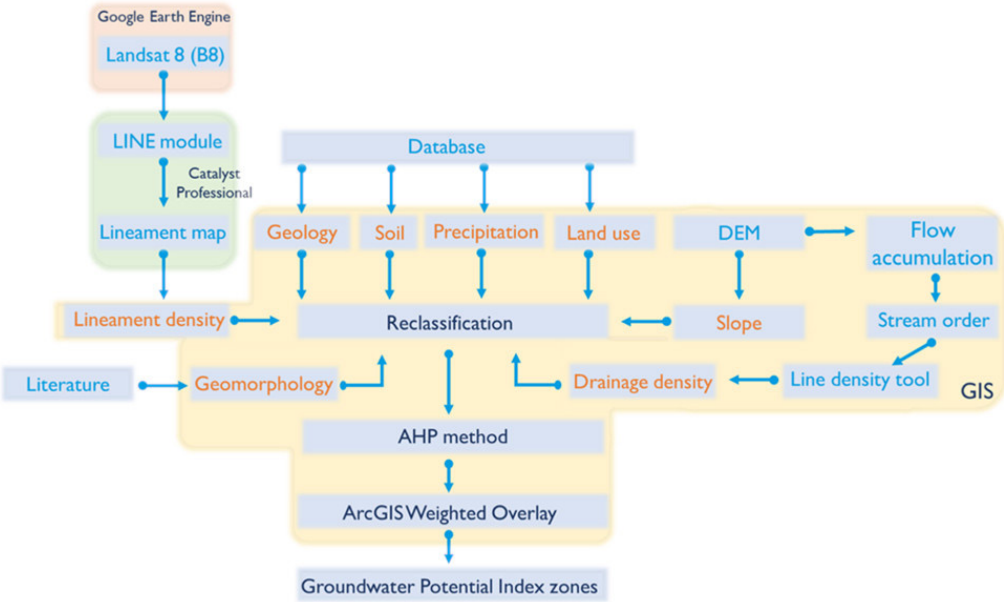


Figure 5. Methodology used to obtain a Groundwater Potential Index map (van der Hulst, 2022). The colour represent the used software: yellow: GIS, green: Catalyst Professional, and red: Google Earth Engine.

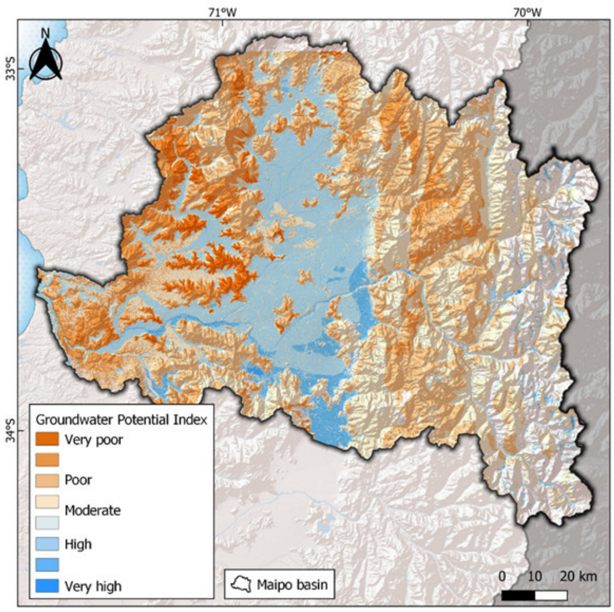


Figure 6. Groundwater Potential Index (GWPI).

7. GROUNDWATER SUSTAINABILITY INDICATORS

7.2 Selected groundwater sustainability indicators

Groundwater sustainability indicators help show patterns and raise concerns simply and attractively. There is not a large variety of groundwater sustainability indicators, though. However, the UNESCO Groundwater Sustainability Indicators form a solid base to explore groundwater dependence, availability, and quality on an aquifer scale.

Table 2 shows the selected groundwater sustainability indicators. The indicators are selected based on observations and measurements of groundwater data about water quality and quantity that describe social, economic, and environmental aspects. Moreover, to avoid the selection of the indicators based on data availability, the indicators are chosen before data selection (Vrba *et al.*, 2006). Because different SHACs manage the aquifer, the scale of the indicators is per SHAC. However, because the data on agricultural dependency and surface water rights were only available on a sub-basin scale, these indicators could not be presented per SHAC. This results from selecting the indicators first and subsequently gathering the required data. Calculating an indicator on a basin scale would not fit this study because the objective is to show variability within the basin itself. However, this was needed for the drinking water indicator because the data on drinking water use was only available for the whole Maipo basin. Furthermore, the indicators have been modified to the Chilean context, for instance, the indicator on groundwater rights compared to recharge.

The indicators provide a more understandable perspective on groundwater use in the Maipo Basin. Especially since the Maipo Basin is large and multiple complex processes play a role. These indicators show that the Central Valley is approximately 30% dependent on groundwater for agricultural use. Drinking water production is less dependent on groundwater. However, it puts extra pressure on the system, especially in the aquifer around the Santiago metropole.

Table 2. Selected groundwater sustainability indicators with the corresponding scale and data sources.

Category	Indicator		Scale	Data source(s)
Groundwater Dependence	1	Groundwater volume per capita	SHAC	DGA (2021), INE (2017)
	2	Agricultural dependency on groundwater	Sub-basin	DGA (2021a)
	3	Groundwater as a percentage of total use of drinking water	SHAC and basin	DGA (2021a)
	4	Total granted water rights of groundwater (all uses) as a percentage of total ground and surface water rights granted	Sub-basin	DGA (2021a)
Groundwater Availability	5	Total groundwater rights as a percentage of groundwater recharge	SHAC	Nascimento & Barreiras (2021), (DGA, 2021a)
	6	Total groundwater abstraction as a percentage of groundwater recharge	SHAC	Nascimento & Barreiras (2021), (DGA, 2021b)
	7	Total granted groundwater rights as a percentage of groundwater volume	SHAC	DGA (2021a)
	8	Groundwater level decline	SHAC	DGA (2021a)
Groundwater Quality	9	The total area with high vulnerability as a percentage of the total area of the SHAC	SHAC	Nascimento & Barreiras (2021)

7.2 Groundwater Dependence

Indicator 1, groundwater volume (m3/year) per capita per SHAC (Figure 7), indicates that the SHACs Melpilla and Puangue Medio have relatively the largest groundwater volume per capita available. Furthermore, the southern region has, in general, more groundwater available per capita. These areas are regions with a low population density and large groundwater volumes.

The map of indicator 3 (Figure 7), a drinking water indicator, shows the rural and urban groundwater Drinking Water Demand (DWD) as a share of the total DWD and per SHAC; and the share of rural and urban groundwater DWD. Groundwater plays a small part in the total DWD in most SHACs. However, only the Santiago Central sector has a total groundwater DWD which is 16% of the total DWD. Thus, this shows that drinking water production is not as dependent on groundwater as agriculture. Regarding the share of urban and rural groundwater DWD, in most SHACs, the urban groundwater DWD succeeds the rural groundwater DWD. In general, the further away from Santiago, the higher the share of rural groundwater DWD.

7.3 Groundwater Availability

The result for indicator 5, shown in Figure 7, demonstrates the ratio between the granted groundwater rights and the recharge. In several SHACs, the ratio is higher than one, which means that the amount of granted groundwater rights is higher than the recharge. It can be observed that the ratio in the northern and central parts of the Central Valley is slightly higher than in the south. A possible explanation could be the lower recharge in the North could be due to less precipitation, or higher granted groundwater rights. A few regions have less granted groundwater rights than recharge. Only in the Maipo Alto sub-basin and near the outlet are SHACs with a ratio of less than one.

The ratio between the monitored abstraction (DGA, 2021) and the recharge (Nascimento & Barreiras, 2021), indicator 6 (Figure 7), shows the same pattern as in the previous indicator. The highest ratios are observed in the northern and central parts of the Central Valley. However, the ratio is significantly lower in absolute terms. The areas with more agriculture show lower ratios than those with the granted groundwater rights. That might indicate that there is an over-abstraction in many parts of the basin. Mainly in the SHAC Colina Sur and Vitacura, there is serious over-exploitation. In regions with high irrigation, there is a smaller difference between the recharge and monitored abstraction. However, there is still overexploitation in large parts.

The ratio between the georeferenced granted groundwater rights and the volume (indicator 7) (Figure 7) indicates that the granted groundwater rights are, for most SHACs lower than the volume. However, in Maipo Desembocadura and Colina Inferior, the granted groundwater rights greatly exceed the SHAC's volume. Five other SHACs have ratios higher or around 1. Despite the uncertainties about whether granted groundwater rights are used in reality, this indicator does provide a view on the 'overgranting' of groundwater rights in the SHACs and where the groundwater pressure is high.

The groundwater level decline is the most direct indicator to see what are the real effects of this overexploitation (indicator 8). Figure 7 shows the average groundwater depletion (m) per SHAC. Three different regions can be distinguished: 1) in the SHACs near the outlet of the Maipo basin there is an increased water level; 2) in the Southern and Central parts of the Central Valley, in which the groundwater level decreased, however, not drastically, with the maximum around 5m; and 3) in the Northern part of the Central Valley the water depth dropped severely. In the SHAC Chacabuco Polpaico, for instants, has dropped 38.6 m. In the other sectors, the drop in water level stays between 5 and 30 m.

Groundwater quality

The selected indicator to characterize the groundwater quality for the Maipo Basin was the Total area with high vulnerability as a percentage of the total area of the SHAC (indicator 9) (Figure 8). The data source is based on Nascimento & Barreiras (2021). It indicates that the highest vulnerability is observed mainly in the South of the Central Valley. The maximum percentage is calculated for the SHAC Buin, where 62% of the total area presents high vulnerability. Furthermore, the vulnerability is also high in Colina Sur, El Monte Nuevo, Paine, La Higuera, Puangue Bajo, and Melpilla. This high vulnerability is a result of a combination of variables (soil type, precipitation, run-off, groundwater levels, recharge, slope, landuse, etc, explained in Nascimento & Barreiras, 2021) that determine agricultural lands one of the main factors for the contamination of aquifers (Nascimento & Barreiras (2021)). This result is not observed in the Central Santiago SHAC and the other highly populated areas, where there is little recharge and no agriculture. Furthermore, the values of vulnerability in the Maipo Alto region are low, partly explained by the lower recharge in that area, as well as the little human impact.

7.5 Discussion on the groundwater sustainability indicators

According to these sustainability indicators, the status of groundwater in the Maipo Basin are classified as under stress. According to the data sources and calculations, monitored abstraction is already larger than estimated recharge in many regions. In addition, the results might indicate that there is 'overgranting' in some areas. Nevertheless, because monitoring network is not completely extensive and representative, some results might be limited to the data quality. The granted groundwater rights exceed the recharge in many regions. Looking at groundwater depletion (Figure 7), this decrease seems to be quite important in some areas, especially in areas with greater concentration of abstractions, nearby or within urban areas.

In addition, overexploitation, as seen in the 'overgranting' of groundwater rights compared to the recharge in the Maipo Desembocadura, could cause additional conditions for saline intrusion. If the groundwater level decreases near the coast, more seawater could flow inland. However, this depends on whether the SHAC is compensated by increased groundwater flow from other areas, like the Central Valley.

8. SUSTAINABLE GROUNDWATER MANAGEMENT

8.1 Background

Groundwater management in the Maipo Basin needs to shift to sustainable groundwater management. The first step is integrating the term sustainable yield into the current management approach. This study aimed at improving the current sustainable use criteria applied by DGA, and is based on the analysis made by van der Hulst (2022):

1) Presently, and according to DGA (2021a), the sustainable volume of the aquifer is equal to the volume corresponding to the granted permanent groundwater rights. Therefore, it does not detail the difference between granted groundwater rights and recharge in most regions, and the granted groundwater rights are the maximum groundwater abstraction. In addition, the system of groundwater rights can only work when actual groundwater abstraction is monitored, which does not happen. The situation gets quickly unsustainable when the volume of the granted groundwater rights is larger than the calculated sustainable volume. Therefore, a more efficient characterization of groundwater use is required to estimate a sustainable yield of the aquifer systems.
2) Hydrological data is processed at the administrative level. This procedure might lead to difficulties in managing an aquifer system if several administrative entities are involved and containing partly one of more aquifers within the same administrative boundary. So, it is considered that the processing of hydrological data should be made at the aquifer system level.
3) There is too little awareness of the environmental consequence of groundwater level decline. The surface water discharge indicator results show that the minimum ecological flow is endangered in nearly most SHACs, which can severely impact Groundwater-Dependent Ecosystems (GDEs) in the Maipo Basin.

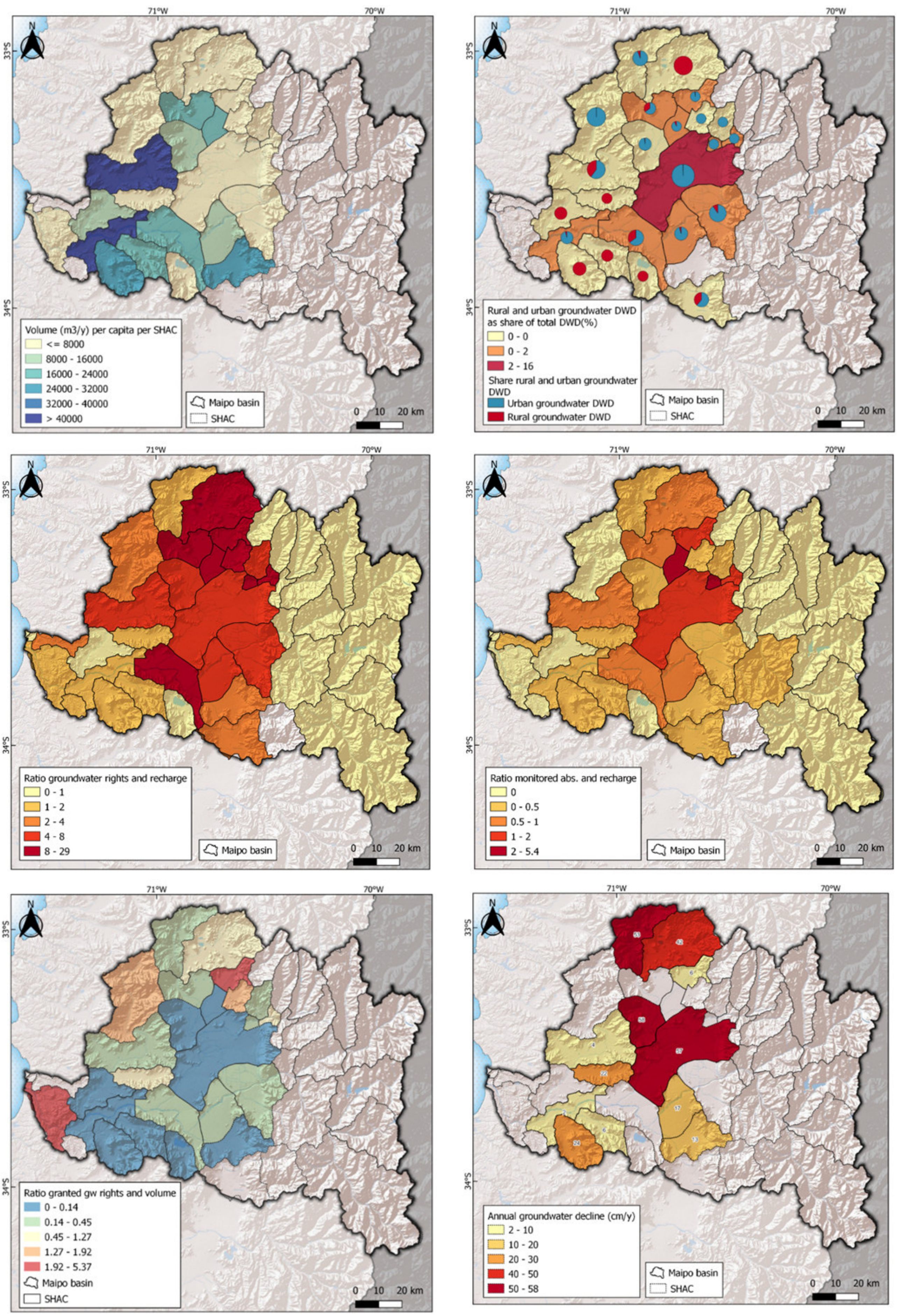


Figure 7. Results of groundwater sustainability indicators. Indicators 1, 4 regarding Groundwater Dependence, and indicators 5, 6, 7, 8 regarding Groundwater availability (consult Table 2) (van der Hulst, 2022).

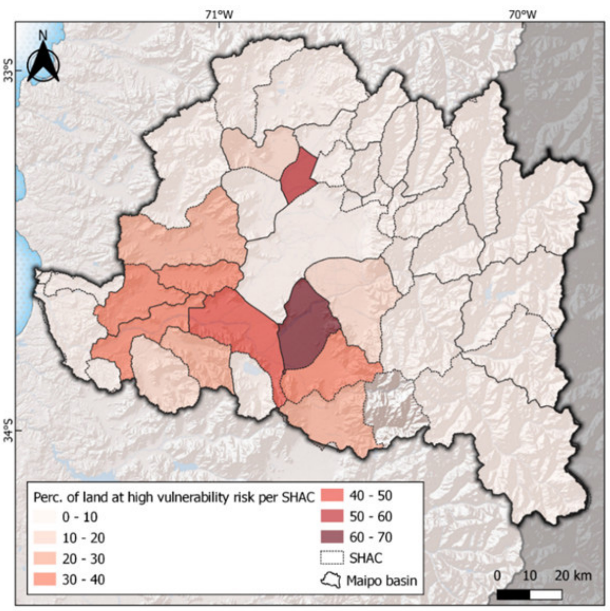


Figure 8. Percentage of total land with high vulnerability, per SHAC.

8.2 Sustainable yield index

Therefore, considering the previous background terms, a sustainable yield index is proposed to identify these areas and classify them. It is calculated using the GWPI, the Groundwater-Dependent-Ecosystems zones (GDEZ), the ratio of monitored abstraction and recharge, and the ratio of groundwater rights and recharge. These four parameters encompass groundwater's hydrological and environmental value (GWPI and GDEZ), which should be protected and are vulnerable to over-abstraction, and the socioeconomic pressures on the system (groundwater abstraction and groundwater rights).

The workflow to calculate this index is shown in Figure 9. The index scale is per SHAC because information on granted groundwater rights and abstraction is only available on this level. Therefore, the GWPI and GDEZ are averaged per SHAC.

The four different thematic layers are considered to be equally important. To give importance to the different classes of the layers, the layers are reclassified into five different classes, with a range from very low importance (1) to very high importance (5). The reclassification table is shown in Table 3. The GWPI and the GDEZ have the same classes as the final result of the calculations. The excluded classes in the GDEZ map are assumed to have the lowest value. The rank for the abstraction and groundwater rights thematic layers are slightly different. A rank of 1 indicates very high pressure on the groundwater system, and a rank of 5 indicates very low pressure. The classes are based on the groundwater sustainability indicators and logical values to compare.

The higher the rank, the higher the value of the natural system and the less pressure on the groundwater system, indicating higher sustainability. However, the lower the rank, the lower the importance of GDEs and groundwater occurrence, meaning a higher pressure on the system. The used limits per category are demonstrated in Table 4. The limits are based on the minimum, 4, and the maximum value, 20, that can be calculated.

The calculated sustainable yield index (SYI) per SHAC (Figure 10) shows that the Central Valley have, in general, lower sustainability than outside. Along the river valley of the Maipo River in the Coastal mountain range, the index is high, just like the edges of the Central Valley at the side of the Coastal mountain range. In the Maipo Alto region, the index is between moderate and very high. The moderate SYI can be explained by limited recharge and GDE zones. A subregion of the Maipo

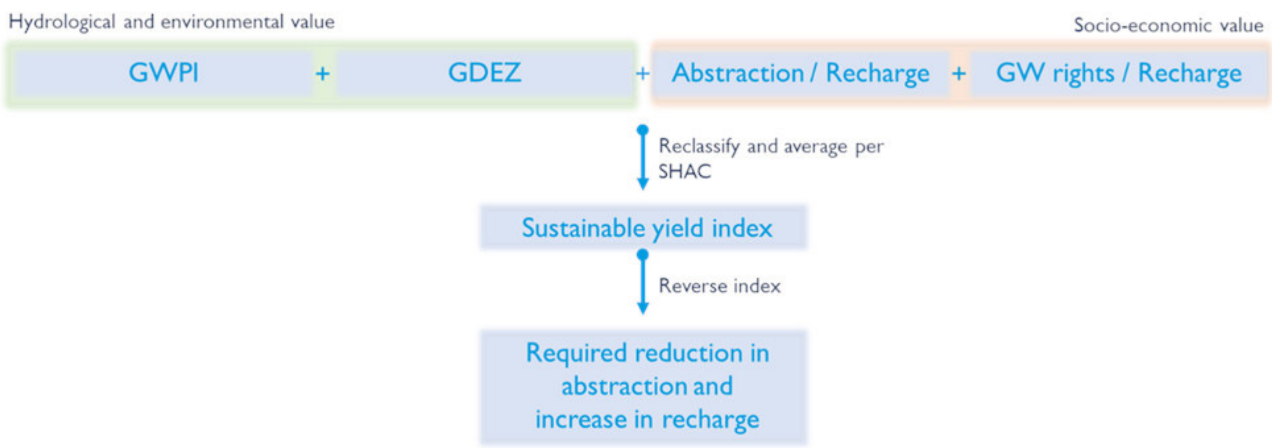


Figure 9. Workflow to obtain sustainable yield index.

Alto region is characterized by very high values of SYI. In these SHACs, there is almost no pressure on the groundwater system. A small number of groundwater rights have been granted, and abstraction is practically zero.

The five SHACs with lower values of SYI are located in the central-north part of the Central Valley. The pressure on the groundwater system is high, with many granted groundwater rights and monitored abstraction over the recharge. Also, the areas are characterized by a small existence of GDEs.

Table 3. Reclassification table for the four different thematic layers used in the GDEZ mapping.

Rank	GWPI	GDEZ	Monitored abstraction/ recharge		Groundwater rights/ recharge	
			Min	Max	Min	Max
5	Very high	Very high		=0.0		<=1
4	High	High	>0.0	<=0.5	>1	<=2
3	Moderate	Moderate	>0.5	<=1.0	>2	<=4
2	Low	Low	>1.0	<=2.0	>4	<=8
1	Very low	Excluded	>2.0	<=5.4	>8	<=29

Table 4. Used categories for sustainable yield index (SYI).

Sustainable yield index category	Min	Max
Very low	=4	< 7
Low	>= 7	< 10
Moderate	>= 10	< 13
High	>= 13	< 16
Very high	>= 16	=20

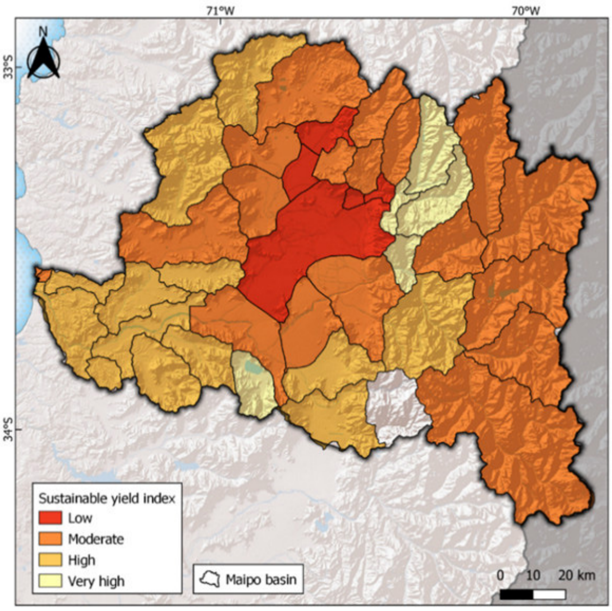


Figure 10. Sustainable yield index per SHAC.

After calculating the sustainable yield index, the index could be reversed to a quantitative estimate of a reduction in abstraction or increase in recharge required to obtain a moderate sustainable yield index for the SHACs that have been identified with low sustainability. The values of the GWPI and the GDEZ will not change because they represent the hydrological and ecological values. Furthermore, the groundwater rights are already granted (fixed), representing groundwater demand. Thus, the ratio of monitored abstraction and recharge is the only thematic layer that can be changed in the short term and could provide a first insight into the necessary change in abstraction or recharge.

For the five SHACs with a low sustainable yield index, the required increase in recharge or reduction in abstraction has been calculated and shown in Table 5. This shows that the SHACs Vitacura and Colina Sur require the largest change in groundwater use. The other SHACs need a smaller change. However, these SHACs are larger in the area and therefore need, in absolute terms, a significant change.

Table 5. Calculated required reduction in abstraction or increase in recharge in mm/year per SHAC with a low sustainability index.

SHAC	Needed reduce abstraction/ increase recharge in mm/year
Colina Inferior	34.9
Santiago Central	29.6
La Barnechea	51.35
Vitacura	329.05
Colina Sur	296.1

It becomes clear that in some regions, there is an unsustainable system (Figure 9). Moreover, using the index reversed, it can calculate the necessary reduction in abstraction or the increase in recharge that is needed in the SHAC. The index can also easily be applied to other basins in Chile since it is adapted to the Chilean data availability and context. It can serve as an effective tool to measure groundwater management.

Policymakers should look for nearby SHACs, where the pressure on the system is lower, aiming essentially at reducing the abstraction in the low sustainable regions. Also, the possibility of nature-based solutions such as MAR could be studied as an alternative or partial solution, even if the execution and implementation is difficult. The required efforts in Colina Sur and Colina inferior seem to be quite difficult or even impracticable. However, the area of the SAHCs is small, meaning relatively small projects can have large positive effects.

9. CONCLUSION

Groundwater plays a vital role in the hydrological cycle and is a unique resource with huge potential in this region. However, it is vulnerable and needs to be protected and managed. It becomes clear that groundwater resources are not sufficiently protected for future generation in the Maipo Basin. A change in mindset among all stakeholders is needed, and responsibility needs to be taken collectively.

As urbanization increases, consequently, the drinking water demand will increase. In combination with climate change and the recent droughts, greater demand and dependency on groundwater exist. This could be seen as a problem. However, it is also an opportunity. As mentioned in FAO (2016), "Groundwater governance will also be influenced by the relative contribution of groundwater to different economic sectors and segments of the population."

A larger dependency on groundwater could therefore imply higher awareness and development of groundwater management and governance. Agriculture is highly dependent on groundwater, mainly in the Central Valley. Santiago's largest water service companies are already highly dependent on groundwater. Chile's politicians and policymakers can no longer ignore groundwater in the Maipo Basin because it is important to the economy and people's livelihood in urban and rural areas. This could be seen as a negative development for groundwater resources. However, it also presents an opportunity to show groundwater's importance and make the resource more visible. Groundwater management and governance could give a long-term vision from a multidisciplinary perspective to the Maipo Basin.

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