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INVESTIGACIÓN HIDROGEOLÓGICA DEL ACUÍFERO DEL PAINE CONSIDERANDO LAS CONDICIONES DE REFERENCIA DE 1970 Y EL ANÁLISIS A LARGO PLAZO DE 1990 A 2020.

HYDROGEOLOGICAL INVESTIGATION OF THE PAINE AQUIFER CONSIDERING BASELINE CONDITIONS FROM 1970 AND LONG-TERM ANALYSIS FROM 1990 TO 2020.

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RESUMEN

Los recursos hídricos subterráneos son vitales para satisfacer las necesidades de agua dulce en todo el mundo, ya que constituyen la principal fuente de agua potable para casi la mitad de la población mundial, y son especialmente importantes para la agricultura y la industria en las regiones áridas. La cuenca del Paine, situada al sur de Santiago de Chile, se ha visto gravemente afectada por una prolongada mega-sequía, lo que ha influido en la disponibilidad de agua para diversos usos. Sin embargo, no se han realizado estudios hidrogeológicos exhaustivos para comprender el sistema acuífero y establecer una línea base para futuras acciones en la cuenca que permita gestionar mejor los recursos hídricos. Por lo tanto, este estudio investiga las condiciones del acuífero en 1970, consideradas las más cercanas a su estado inalterado. Utiliza datos químicos y del nivel freático para discernir las direcciones del flujo de agua subterránea y la relación entre el río y el acuífero de esa época. Los análisis temporales posteriores, que utilizan las pruebas de Mann-Kendall y la estimación de la pendiente de Theil - Sen sobre los datos del nivel de los pozos de la DGA desde el 1990 hasta el 2020, pretenden verificar estadísticamente la importancia de los descensos del nivel del agua. Los resultados confirman un flujo de aguas subterráneas de este a oeste, corroborado por firmas químicas que vinculan las aguas del Paine con el río Maipo, lo que sugiere una recarga al río desde el acuífero durante esa época. Sin embargo, las tendencias recientes indican un descenso significativo de los niveles de agua desde que comenzó la mega-sequía en 2010, que no concuerda con el aumento de las extracciones de agua subterránea a partir de 2005. Lo anterior pone de manifiesto que es necesario considerar fuentes de agua adicionales, como la infiltración fluvial o el flujo de retorno del regadío, para explicar la variabilidad del nivel del agua, lo que pone de relieve la hidrología de la cuenca. Finalmente, el análisis de las tendencias en los últimos 30 años indica que las condiciones hidrodinámicas han cambiado desde las condiciones iniciales consideradas en el 1970.

Palabras clave: Recursos hídricos subterráneos, mega-sequía, análisis temporal, acuífero de Paine.

ABSTRACT

Groundwater resources are vital for meeting the world's freshwater needs, providing the primary source of drinking water for nearly half the global population, and are particularly important for agriculture and industry in dry regions. The Paine Basin, situated south of Santiago, Chile, has been heavily affected by an extended mega-drought, influencing water availability for various uses. Yet, comprehensive hydrogeological studies to understand the aquifer system and establish a baseline for future actions in the basin to better manage water resources have been lacking. Therefore, this study investigates the aquifer's conditions in 1970, considered closest to its undisturbed state. It uses water table and chemical data to discern groundwater flow directions and the relationship between the river and the aquifer. Subsequent temporal analyses using Mann-Kendall tests and Theil-Sen slope estimation on DGA well-level data aim to statistically verify the significance of water level

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declines. The findings confirm an east-to-west groundwater flow, corroborated by chemical signatures linking the Paine waters to the Maipo River, suggesting river recharge from the aquifer during that era. However, recent trends indicate a significant drop in water levels since the mega-drought began in 2010, not aligning with the increase in groundwater extractions starting in 2005. The above highlights that additional water sources, such as river infiltration or irrigation return flow, need to be considered to explain water level variability, which highlights the hydrology of the basin. Finally, trend analysis over the last 30 years indicates that hydrodynamic conditions have changed since the initial conditions were considered in 1970.

Keywords: Groundwater resources, Mega-drought, temporal analysis, Paine aquifer.

INTRODUCTION

Groundwater is an important source of freshwater in supporting human activities and maintaining essential ecosystems (Gleeson et al, 2012). Groundwater resources provide almost half the world's drinking water and support industries such as energy, mining, and manufacturing. Globally, nearly half of the drinking water supply is sourced from groundwater. In arid zones, one of the primary uses of groundwater is for agriculture (Stromberg et al, 1996; Cheng et al, 2016). Due to limited surface water availability, groundwater is heavily relied upon for irrigation purposes.

The importance of groundwater resources is evident through the extensive research conducted by the Chilean Water Authority (DGA) to estimate the quantity of groundwater reserves. The DGA has dedicated significant efforts to studying the availability and sustainability of groundwater in several strategic basins in Chile, reflecting the recognition of its important role in water supply. However, it is worth noting that while there has been a considerable focus on quantifying groundwater reserves, there is a need for further research on water quality to ensure the sustainable management of this vital resource. Water quality is relevant for various activities and the maintenance of ecological systems (Faye et al, 2019). Natural and human-made threats, such as urbanization and agriculture, can significantly affect the natural water cycle, impacting the quantity and quality of groundwater (Evans et al, 2015).

Groundwater quality deterioration is a significant concern in several basins in Chile, including the Paine basin. This deterioration affects various scales, from localized point sources of contamination to diffuse contamination affecting large areas of the aquifer system (Cherry et al., 2022). Urbanization is a significant driver of environmental change, having implications for freshwater use, wastewater management, and groundwater development, protection, and management in urban and irrigated environments.
The Paine area, along with the wider Maipo basin, has been severely affected by an extensive drought, often referred to as a mega-drought, which has led to a significant decline in water table levels (Garreaud et al., 2020). This phenomenon, coupled with the challenges of water management practices in Chile, has exacerbated the scarcity of water resources (Herrera et al., 2023).

Comprehensive hydrogeological studies are imperative to address these issues effectively. Such studies would delineate the hydrodynamics of groundwater within the area, including the determination of flow directions during periods with minimal human disturbance, assessment of water table declines, and analysis of the water's chemical composition.

A thorough understanding of groundwater flow patterns in their natural state is essential for determining the baseline condition of the aquifer (Phillips, 2003). This serves as a reference point for measuring the impact of human activities on water cycle dynamics, contamination levels, and resource depletion (Basilio Hazas et al., 2022). A comprehensive initial assessment of the aquifer under near-natural conditions is critical for evaluating its resilience and planning effective responses to the challenges posed by increased extraction rates and climate variability (Monsley, 2015). Such an understanding is vital for

safeguarding the aquifer against future environmental and anthropogenic stresses.
The objective of the manuscript is to investigate groundwater flow patterns during periods with minimal human influence, using water chemistry data as indicators to trace the movement and characteristics of the groundwater in the Paine aquifer system. Furthermore, it examines trends in water table levels within monitoring wells to assess the sustainability of the groundwater supply. It specifically tries to establish whether there has been a reduction in the aquifer's water volume and, if so, to measure the rate of this reduction.

MATERIALS AND METHODS

STUDY AREA.

The Paine Aquifer, located to the south of Santiago city, is a sedimentary basin primarily filled with alluvial deposits from the Maipo River system (Figure 1). This basin contains a significant industrial complex primarily supplied by groundwater resources. Agriculture also relies on these resources to compensate for irrigation deficits, particularly in the northern part, where it depends almost exclusively on groundwater catchments. Furthermore, a substantial portion of the drinking water supply for the entire area is sourced from these groundwater resources.

The climatic characterization of the basin was carried out with the CR2MET gridded data, available at https://www.cr2.cl/datos-productos-grillados. The mean annual temperature is approximately 15 °C, while the mean annual precipitation obtained from this gridded dataset is 468 mm/year. Figure 2 illustrates the averaged mean values of temperature and precipitation in the Paine basin, Chile. The data indicates higher precipitation levels in winter, with June experiencing the most rainfall at 97 mm on average. Conversely, the summer months show elevated temperatures, with January seeing average highs of 21°C. The region's temperature ranges highlight distinct seasonal patterns, with the warmest and driest conditions typically occurring in summer, transitioning to cooler and wetter weather over winter.

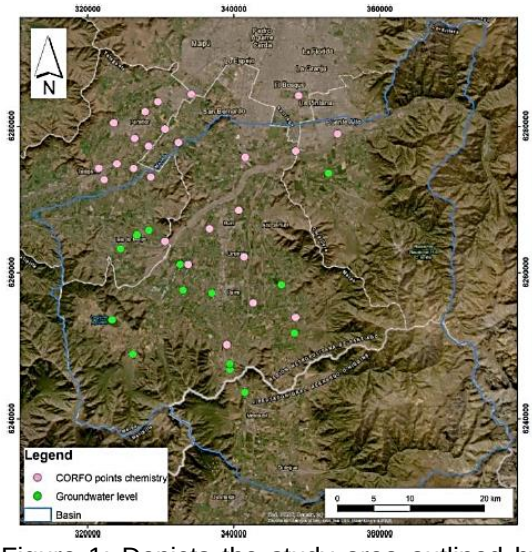

Figure 1: Depicts the study area outlined by the hydrographic basin boundaries. Additionally, it identifies CORFO points where the chemical analysis from the CORFO study (1970) was considered, along with water level data from the DGA monitoring network. Source: Own elaboration with public information.

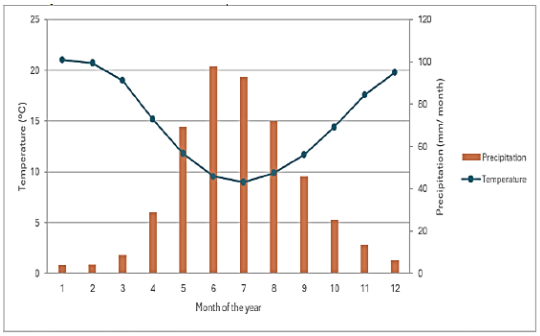

Figure 2: Monthly average temperatures and precipitation in the Paine Basin. Source: Own elaboration with data from CR2MET gridded database.

MATERIALS AND METHODS.

To establish an initial understanding of the groundwater flow and chemical composition in the Paine area, data from the 1970 CORFO study were utilized, reflecting the aquifer's condition with minimal anthropogenic alterations. A piezometric map was created to assess groundwater flow direction, and modified Stiff diagrams were used to graphically represent water sample ionization. Measurements of ion concentrations in water samples are displayed on three horizontal

axes, with anions (Na, Ca, and Mg) on the left and cations (Cl, HCO_3, and SO_4) on the right, all expressed in milliequivalents per liter (meq/L). The width of the horizontal lines on the graph indicates ion concentration, with wider diagrams denoting higher mineralization. The chemical analysis aims to complement the evaluation of flow lines from piezometric maps and is a work in progress to establish the changes in this relationship caused by both shifts in water governance and the megadrought.

Additionally, water table records from the DGA's monitoring network from 1990 to 2020 were used. Mann-Kendall tests were applied to these wells for the periods 1990-2000, 2000-2010, and 2010-2020 to detect changes in water level trends and significant variations across each analyzed period. An analysis incorporating DGA inputs (diffuse rainwater recharge) and extractions was also performed to evaluate seasonal data variations.

RESULTS

NATURAL ACUIFER CONDITIONS.

Figure 3 displays the piezometric map of the Paine area, detailing groundwater levels that generally mirror the topography of the Paine aquifer basin. The prevalent groundwater flow is east to west and southwest, indicating a significant recharge area in the Andes Mountains through mountain front recharge processes, with discharge occurring in the Melipilla area and natural outflow to rivers, as indicated by red arrows. The lower groundwater extraction during this period suggests that the current flow closely approximates the aquifer's natural flow regime.

Figure 4 presents modified Stiff diagrams, illustrating the spatial distribution of the groundwater's chemical composition in Paine. The waters are classified as sodium-calcium-sulfate, with salinity variations depicted by the diagram size. There's a noted similarity in the hydrogeochemical signature between groundwater and river samples, which suggests that the aquifer recharges the river in this area. This is supported by the analysis of the 1970 piezometric map, where the levels are generally higher than the riverbed. The aquifer supplies water to the river in some areas, although this relationship depends largely on annual recharge to the aquifers and water withdrawals near the rivers. The interaction between the river and the aquifer is complex, with the aquifer providing water to the river during wet periods and receiving water from the river during dry periods. This dynamic results from a combination of reduced recharge and increased groundwater extraction due to decreased surface water availability. However, it should be noted that these interpretations are based on data from the 1970s, and subsequent changes in land and water use in the area may have altered this pattern.

Increased salinity from waters originating in the Santiago basin compared to those from Paine and higher sulfate levels in the Talagante area are evident. However, more precise methodologies are needed to determine water quality, which is an ongoing study conclusively. The distinctly less saline sample from the southern area suggests potential water inflow from the southern basin into the Paine basin, which needs further verification. During this period of reduced anthropogenic impact, the Angostura River is likely receiving more recharge from the Paine basin than from other basins, deduced from its hydrogeochemical type, with the overall signature of the basin.

Stiff diagrams confirm the groundwater flow direction from east to west, as inferred from piezometric data. Notably, the chemical composition of groundwaters in the Talagante area (Figure 4) is similar, likely due to the discharge of groundwater originating from the urban area of Santiago.

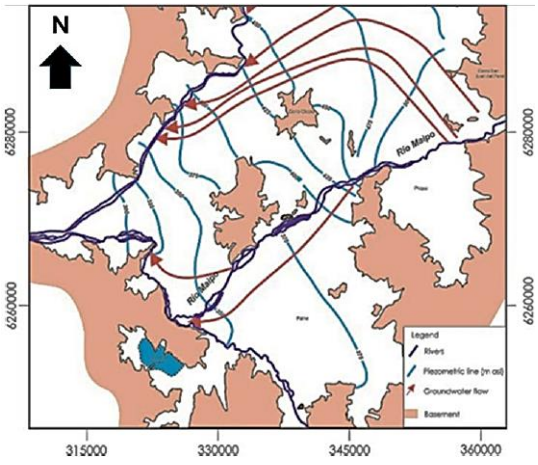

Figure 3: 1970 Piezometric Map displaying flow lines in red. Source: modified from CORFO (1970).

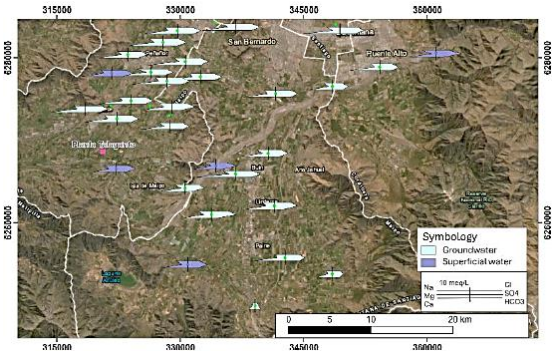

Figure 4: Modified Stiff diagrams based on chemical data from groundwater and river studies by CORFO (1970). Source: Own elaboration with data from CORFO, (1970).

WATER TABLE DEPTH TIME SERIES ANALYSIS.

Water table levels in the Paine Aquifer have progressively declined, with the onset of the mega-drought in 2010 marking a period of high reduction. Well logs from the Paine Aquifer demonstrate a historic low in water levels, with a decrease of 5 to 20 meters over the last decade, significantly outpacing the 2-meter drop recorded from 2000 to 2010. Figure 5 features data from five monitoring wells in the basin's central area. Dirección General de Aguas data corroborates a marked decline in water levels post-2010, statistically significant as per the seasonal Mann-Kendall test results, indicating a shift in groundwater characteristics since the mega-drought began, exacerbated by increased extraction due to scarce surface water.

This trend becomes evident when plotting the median values of water table levels from the DGA's well records on an annual basis (Figure 6), where no significant trends are observed before 2010. However, post-2010, coinciding with the onset of the mega-drought, there is a notable decline in water levels. This pattern is unique to this basin; other central Chilean basins began experiencing declines in water levels before 2010 (Jódar et al, in review).

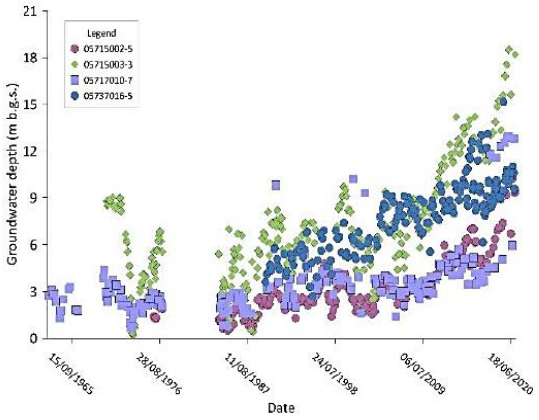

Figure 5: Time-drawdown graph for 4 observations wells in Paine basin. Source: Own elaboration with data from DGA network.

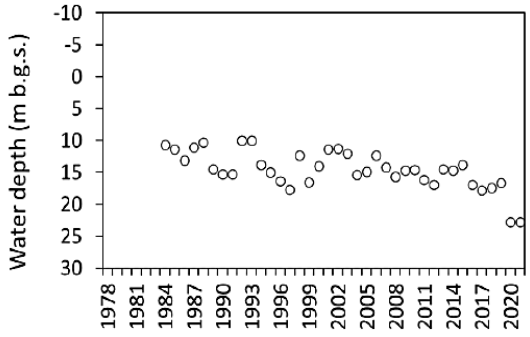

Figure 6: Median values of groundwater depth from the DGA monitoring network's well data, plotted annually. Source: Own elaboration.

Upon closer analysis of the Paine aquifer well data using seasonal Mann-Kendall tests and Theil-Sen slope estimation, distinct patterns emerge. From 1990 to 2000 and continuing through to 2010, the data reveal little fluctuation in groundwater levels, suggesting a period of relative stability in the aquifer. However, the following decade (2010-2020) presents a sharp contrast, with many wells showing an increased slope according to Theil-Sen estimates (Figure 7). This upswing aligns with the more pronounced groundwater depletion highlighted in Figures 5 and 6. The reasons for these changes are twofold: a significant decrease in precipitation due to the prolonged megadrought affecting the region and an escalation in aquifer water extraction activities. This intensified drawdown reflects the increased demand for water 6 amidst scarce rainfall, which has led to a critical strain on the aquifer's reserves.

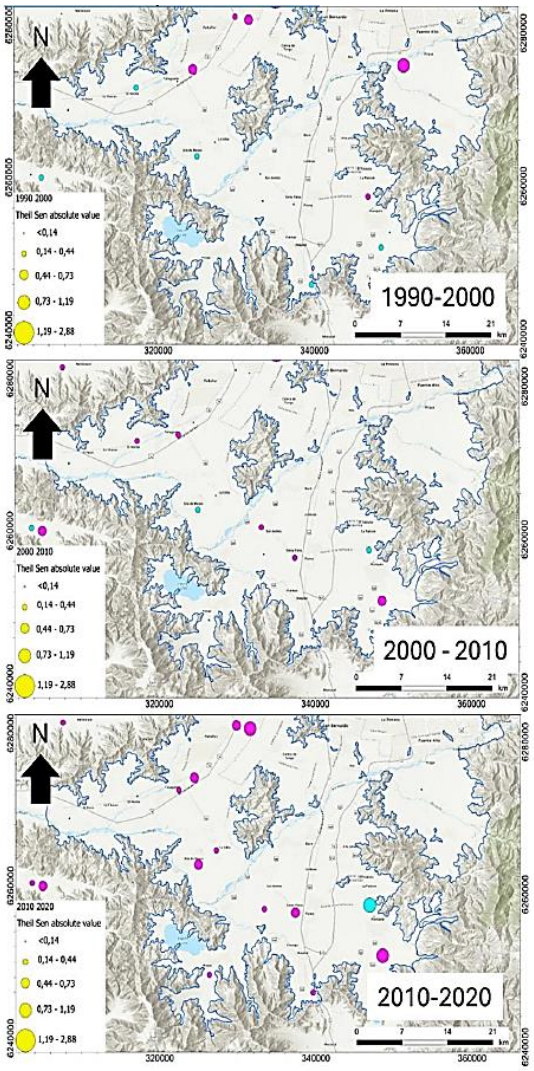

Figure 7: Displays Mann-Kendall analysis and Theil-Sen slope trends for wells in the Paine basin across three periods: 1990-2000, 2000-2010, and 2010-2020. Purple indicates a negative trend, while light blue denotes a positive trend. Source: Own elaboration.

DISCUSSIONS

It has been deduced that groundwater flow in the central Chilean basins, including Paine, predominantly moves from east to west, facilitated by orographic lift, a common feature where aquifer recharge primarily occurs from the high-altitude zones of the mountain range. Although not a central aim of this manuscript, using the altitude-recharge relationship established by Jódar et al. (under review), it's possible to estimate recharge values from rainfall alone. From 1979 to 2009, the average recharge in the basin was 122 mm/year, which plummeted to 45 mm/year during the megadrought, reflecting a reduction of over 60%. Data on water rights from the DGA were analyzed to compare groundwater extractions with direct rain recharge (Figure 8), revealing increased extractions prior to 2010, aligning with findings by Taucare et al. (2023) and Jódar et al. (under review).

However, it's suggested that the rise in groundwater extractions may not have directly impacted the aquifer, due to the Maipo River's recharge potentially exceeding that from rainfall. Therefore, the notable decline in water levels since 2010 can be attributed to the compounded effects of diminished rainfall from the megadrought and increased water extractions. The reduced rainfall likely led to lower Maipo River flow and, consequently, decreased aquifer recharge, exacerbated by the rising groundwater extraction, thereby extending the water transit time before reaching the aquifer.

The inferred relationship between the river and aquifer in 1970, as depicted by modified Stiff diagrams, may have been impacted by declining water table levels and reduced rainfall. This dynamic change is not unique to Paine, but it is likely observable in other central Chilean basins (Muñoz et al., 2020). Some basins, like Chacabuco-Polpaico, have even experienced complete drying of surface water courses.

Therefore, future hydrological balance studies should evaluate additional water sources, including river recharge and irrigation return flows, since rainfall alone cannot explain the fluctuations in water table levels. Despite water level declines in other central Chilean basins, Paine's water level has been less severely impacted, possibly due to inflow from the Maipo River. Furthermore, minimal declines have been noted in the Talagante area, even with increased extractions, attributed to groundwater flow from the Santiago basin. Assessing water level declines requires understanding the aquifer's natural state and all variables impacting its water balance. A chemical anomaly reported in 1970 to the south of the Paine basin may suggest groundwater recharge from the southern basin, which was not dominant at the time due to the chemical similarity between the river and groundwater inputs from the Maipo.

However, this hypothesis requires further verification through updated chemical sampling.

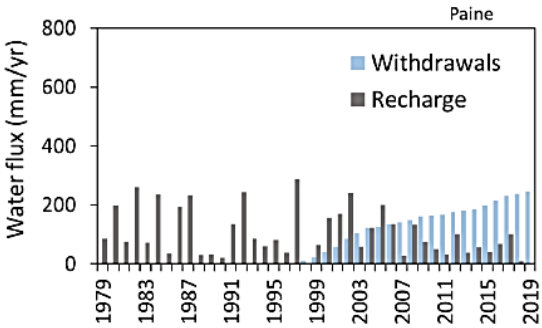

Figure 8: Water flows of the Paine basin, considering recharge exclusively from rainfall and water extractions, for analyzing changes in the aquifer's hydrodynamics within the basin. Source: Own elaboration.

CONCLUSIONS

The research conducted on the Paine aquifer provides an understanding of the natural groundwater conditions and anthropogenic impacts over two periods, 1970, which are the most natural conditions, and 1990 - 2020. The evidence points to a traditionally east-west groundwater flow, largely influenced by the Andean Mountain front recharge processes. However, there has been a significant deviation from this natural state since the onset of the megadrought in 2010. The lower extraction rates from the 1970 period offer an insight into the aquifer's more natural conditions, while recent data (1990 – 2020) point towards a stressed system with declining water levels.

The temporal analysis, incorporating a series of groundwater level observations and statistical tests, underscores a critical transition in the Paine aquifer's hydrodynamics, with a marked reduction in recharge rates and increased extraction volume. This finding highlights the need for a holistic approach to future water management and research, considering the interplay of natural phenomena like megadrought and human activities such as land and water use changes. To accurately assess the current state and forecast future conditions of the Paine aquifer, it is important that ongoing and future studies integrate advanced methodologies, including hydrological modeling, to encompass the multifaceted influences on the aquifer system.

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