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Hydrodynamics of salt flat basins: The Salar de Atacama example

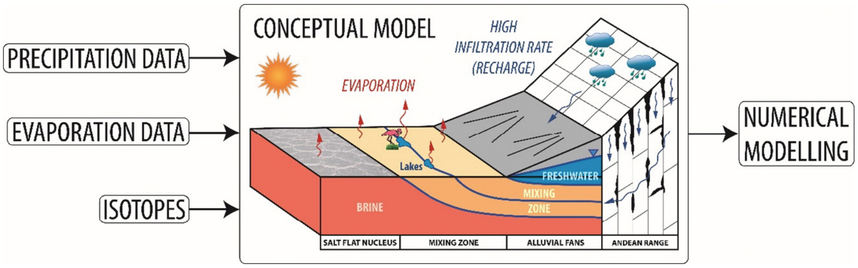
M.A. Marazuela [a,b,c,*], E. Vázquez-Suñé [a], C. Ayora [a], A. García-Gil [d], T. Palma [a,b,c]

[a] *Institute of Environmental Assessment and Water Research (IDAEA), CSIC, Jordi Girona 18, 08034 Barcelona, Spain*
[b] *Department of Civil and Environmental Engineering, Technical University of Catalonia (UPC), Jordi Girona 1-3, 08034 Barcelona, Spain*
[c] *Associated Unit: Hydrogeology Group, UPC-CSIC, Spain*
[d] *Geological and Mining Institute of Spain (IGME), Manuel Lasala 44, 9° B, 50006 Zaragoza, Spain*

HIGHLIGHTS

- A new regional groundwater flow for the Salar de Atacama was proposed.
- The hydrodynamics can be extended to other salt flat systems.
- The regional 3D numerical model served to validate the water balance.
- The conventional infiltration values for the hyperarid zones were not valid.
- Infiltration rates of hyperarid basin that reach 75% are justified.

GRAPHICAL ABSTRACT



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ABSTRACT

The Salar de Atacama is one of the most well-known saline endorheic basins in the world. It accumulates the world main lithium reserves and contains very sensitive ecosystems. The objective of this work is to characterize the hydrodynamics of the Salar de Atacama, and to quantify its complex water balance prior to the intense brine extraction. The methodology and results can be extrapolated to the groundwater flow and recharge of other salt flats. A three-dimensional groundwater flow model using low computational effort was calibrated against hundreds of hydraulic head measurements. The water infiltrated from the mountains ascends as a vertical flux through the saline interface (mixing zone) produced by the density contrast between the recharged freshwater and the evaporated brine of the salt flat nucleus. This water discharges and is largely evaporated from lakes or directly from the shallow water table. On the other hand, the very low hydraulic gradients, coupled with the presence of the mixing zone that operates as barrier, leads the salt flat nucleus to act as a hydrodynamically quasi-isolated area. The computed water table shows the lowest hydraulic head in the salt flat nucleus near the discharge at the mixing zone.

The groundwater balance of the Salar de Atacama in its natural regime was quantified resulting in an inflow/outflow of 14.9 $m^3 \cdot s^{-1}$. This balance considers the basin as an endorheic system. The very low infiltration values that are generally assumed for hyperarid basins are not consistent with the hydrogeology of the Salar de Atacama. Indeed, very high infiltration rates (up to 85% of rainfall) occur because of the high degree of fracturing of rocks and the scarce vegetation. This high infiltration is consistent with the light isotopic composition of the water from the recharge area (Altiplano). Therefore, the existence of additional inflows outside the basin is unlikely.

1. Introduction

Salt flats are saline and endorheic hydrogeological systems that are frequently associated with arid to hyperarid climates, in which the water table is several centimetres or decimetres below the ground

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[*] Corresponding author at: Institute of Environmental Assessment and Water Research (IDAEA), CSIC, Jordi Girona 18, 08034 Barcelona, Spain.
E-mail address: mamarazuela@outlook.com (M.A. Marazuela).

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surface. The largest salt flats in the world are on the Altiplano-Puna plateau of the Central Andean Range, which includes northwestern Argentina, southwestern Bolivia and northeastern Chile (Risacher et al., 2003; Warren, 2010). The salt flats and their brines are a major source of lithium, boron, sodium chloride, iodine, potassium and magnesium (Evans, 1978; Kesler et al., 2012; Munk et al., 2016). Some of these elements are highly valued in the modern economy. For example, lithium is a main constituent in batteries for mobile phones, electric cars (Marom et al., 2011; Tarascon, 2010; Vikström et al., 2013) and even pharmacological treatments (Cipriani et al., 2005).

The Salar de Atacama (SdA) is the third largest salt flat in the world after the Salar de Uyuni (Bolivia) and Salinas Grandes (Argentina). Its brine contains a lithium concentration (~5000 ppm) that is much higher than that of the other salt flats, and makes the SdA the main lithium reserve in the world. In addition, it is located in the most arid area of the Earth and houses exceptional ecosystems, such as the Reserva Nacional de los Flamencos (Ramsar site). These ecosystems are threatened because of the mining exploitation of the brine that has been occurring since the 1980s. In contrast, the brine pumping carried out has allowed to dispose of the best monitoring network in the world, which makes the SdA a reference for the scientific community.

The origin of the SdA dates to the Oligocene-Miocene boundary, synchronous with the increase in volcanic activity and Altiplano uplift (Arriagada et al., 2006). The uplift of the plateau marked the paleoclimatology history as a consequence of the strong topographic gradient reached, giving rise to a more humid plateau and a hyperarid salt flat (Rech et al., 2006). From this ancient time until the mid-1980s, the hydrodynamics of the system were controlled by the different climatic cycles. However, from the 1980s onward, the pumping of the brine for commercial purposes has altered its natural dynamics. Most of the studies that have been carried out in the SdA have analysed the current anthropogenic regime of the system (Salas et al., 2010), in which the water table of the salt flat has been drawn down. However, studies of the natural regime of the system, prior to exploitation, are lacking. Only the water table contour map of the eastern alluvial fans performed by HARZA (1978) is available. Unfortunately, this work does not take density differences into account.

Under the natural regime, the water table depth of the SdA was determined by a complex balance between the water inputs and outputs that tended to be zero (Rosen, 1994; Yechieli and Wood, 2002). The main recharge was precipitation (rainfall) that occurred in the mountains of the basin. The evaporation was controlled by the water table depth, which was a few decimetres below ground (Kampf et al., 2005; Kampf and Tyler, 2006; Tyler et al., 2006). The salt deposits accumulated because of the strong evaporation rates that were maintained for several thousands of years (Corenthal et al., 2016; Hardie, 1991; Wood and Sanford, 1990). These complex systems tend to be very sensitive to climatic and anthropogenic changes (Godfrey et al., 2013).

Although progress has been made in the last few decades to understanding the hydrogeology of the SdA, there are still many uncertainties in the water balance, and no water balance has been validated with numerical models. Thus, some authors present divergences about key factors to calculate the flow discharge: water table depth, areas of discharge and evaporation rates. The first study that addressed evaporation in the SdA (Mardones, 1986) quantified the volume of evaporated water as 5.29 $m^3 \cdot s^{-1}$. Assuming that in the basin-scale balance the inputs (recharge) are equal to the outputs (evaporation), this value should correspond to the recharge value. Subsequent works used this value as a reference and, obtained water balances in the range of 5.17–5.58 $m^3 \cdot s^{-1}$ (Dirección General de Aguas, 2013, 2010, 1986; Muñoz-Pardo et al., 2004). Kampf and Tyler (2006) obtained values of evaporation in a range of 1.6–22.7 $m^3 \cdot s^{-1}$, depending on the multiple calculation methods that were applied, which were based on remote sensing and evaporation zoning. Recently, Corenthal et al. (2016) used an approximated value of recharge from Bookhagen and Strecker (2008), applied the recharge model of Houston (2006) and obtained a net recharge of 0.9 $m^3 \cdot s^{-1}$ (26.5 $m^3 \cdot s^{-1}$ of rainfall with 3.5% of infiltration). However, the same authors predicted that evaporation should have been 21.7 $m^3 \cdot s^{-1}$ to explain the amount of accumulated salts, and they proposed as a probable explanation that the estimated recharge deficit is compensated by contributions from the Altiplano outside the SdA basin. However, this approach is not consistent with the scarce presence of vegetation that would facilitate evapotranspiration and with the scarce evidence of surface runoff that would favour evaporation. If the evapotranspiration is very low and surface runoff almost non-existent, the recharge rate to aquifers should be very high. Therefore, there is still great uncertainty regarding the values of recharge and evaporation in the basin of the SdA under the natural regime.

Numerical models constitute a powerful tool to justify and validate the water balance. The steady-state models offer a hydrogeological reference for the system around which the system will naturally oscillate. These models also serve as a basis to incorporate natural oscillations (e.g., cycles of evaporation, precipitation, etc.) and anthropogenic impacts (pumping and artificial recharge) in future transient-state models. However, determining the average water balance under the natural regime is not trivial and requires an analysis of a sufficiently large time interval that includes several dry and humid climatic cycles. In addition, three-dimensional (3D) numerical models represent a much more powerful tool than two-dimensional (2D) models as they allow including recharge and evaporation processes within a geometry that faithfully reproduces the hydrostratigraphy of the basin in its three spatial components. This allows quantifying the total water balance at the basin scale.

The density contrast between the rainwater (freshwater) and the evaporated water (brine) results in a mixing zone (saline interface) that represents the dynamic equilibrium of both miscible fluids and has a strong influence on the groundwater flow (Marazuela et al., 2018) (Fig. 1). To date, only 2D models of the mixing zone have been published in scientific manuscripts (Duffy and Al-Hassan, 1988; Fan et al., 1997; Holzbecher, 2005; Marazuela et al., 2018; Tejeda et al., 2003; Vásquez et al., 2013; Wooding et al., 1997). To the best of our knowledge, 3D numerical models that integrate the complex recharge-evaporation interaction within a salt flat do not exist. Moreover, no detailed studies have been conducted to provide a numerical response on a regional scale to the role that is played by the mixing zone and its lakes in a salt flat system. The principal reason for this lack of specific studies is probably the high computational cost and the absence of methodologies to consider the effects of density variations. In the case of the SdA, regional models have neglected the effects of density on the flow (Anderson et al., 2002; Muñoz-Pardo et al., 2004), despite of the large density contrasts (1 to 1.23 $kg \cdot L^{-1}$). To overcome this problem, Marazuela et al. (2018) proposed a methodology based on the correction of freshwater and mixed water heads by density variations in salt flats. This method allows the reproduction of the vertical flows that occur in the mixing zone at a low computational cost.

The objective of this study is to characterize the hydrogeological behaviour of the SdA and to quantify its complex water balance, prior to brine exploitation, to establish a reference for the salt flats studies. To reach the objective, firstly, the hydrogeological conceptual model of the system is defined and quantified to subsequently proceed to its 3D numerical modelling, which allows to validate the estimated water balance and to determine its uncertainties. The recent methodology proposed by Marazuela et al. (2018) for 3D numerical modelling of salt flats that is based on the 3D mapping of the salt interface is used. This leads to a discussion about the recharge and hydrodynamics of the salt flat basins, and how the SdA basin can serve as a reference for the hydrogeological conceptualization of other salt flat basins and its 3D numerical modelling.