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Characterising flow regime and interrelation between surface-water and ground-water in the Fuente de Piedra salt lake basin by means of stable isotopes, hydrogeochemical and hydraulic data

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Summary This research reports the characterisation of ground- and surface-water interaction in the Fuente de Piedra Salt lake basin in southern Spain by a combined approach using hydraulic, hydrogeochemical and stable isotope data. During three sampling campaigns (February 2004, 2005 and October 2005) ground- and surface-water samples were collected for stable isotope studies (^{18}O, D) and for major and minor ion analysis. Hydraulic measurements at multilevel piezometers were carried out at four different locations around the lake edge. Conductivity logs were performed at four piezometers located along a profile at the northern lake border and at two deeper piezometers in the Miocene basin at a greater distance from the lake. To describe processes that control the brine evolution different hydrogeochemical simulations were performed. Hydrogeochemical data show a variety of brines related to thickness variations of lacustrine evaporites around the lake. Salinity profiles in combination with stable isotope and hydraulic data indicate the existence of convection cells and recycled brines. Furthermore restricted

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ground-water inflow into the lake was detected. Dedolomitisation processes were identified by hydrogeochemical simulations and different brine origins were reproduced by inverse modelling approaches.

Introduction

Salt lakes occur in arid to semi-arid environments whenever internally drained basins are formed due to tectonic activity or dissolution processes and the floors of such basins intersect the water-table (Duffy and Al-Hassan, 1988; Yechieli and Wood, 2002). The main requirement for the occurrence of a saline lake is that evaporation exceeds precipitation (Hardie et al., 1978).

Salt lakes give insights in sedimentary history and palaeoclimate. They often provide economically valuable evaporate minerals and they are important for water resources assessments because they may affect the ground-water quality in their vicinity (Yechieli and Wood, 2002).

Topographically, these environments range from essentially planar surfaces like the sabkhas of the Arabian Gulf through closed, shallow basins with seasonal standing water like Fuente de Piedra salt lake or the salt lakes of Western Texas, to well-developed, closed basins containing permanent water bodies such as the Dead sea or Great salt lake (Yechieli and Wood, 2002).

With regard to the hydrogeologic background, a distinction is made between coastal sabkhas and inland sabkhas (playas, saline lakes, salt lakes). These inland saline systems are subdivided according to the elevation of the land surface in relation to the ground-water-table. A discharge playa occurs when the level of the capillary fringe is in coincident with the playa floor, which is the case in the Fuente de Piedra salt lake. Extensive accumulation of evaporates usually occurs in these environments. Discharge playas that are subjected to continuous subsidence at rates that exceed the rate of sediment accumulation may evolve into saline lakes like the Dead Sea which are permanently inundated (Rosen, 1994).

Because evaporation concentrates the salt lake water, the brine, driven by density forces may flow into the fresher ground-water. As long as brine is supplied, cellular flow circulation may occur below the salt lake bottom until it reaches the impermeable substratum. This scenario is known as ''free convective flow'' (Fan et al., 1997). Free convective flow is very slow and could be considered negligible for the calculation of a water budget at a given salt lake environment.

A large number of modelling approaches regarding density driven flow have been performed to characterise the ground-water flow below and in the vicinity of salt lakes and playas. Most of these codes include density driven flow and are applied for prognostic issues focusing on salinisation in different watershed scenarios. Rogers and Dreiss (1995) simulated the basin-wide saline ground-water distribution in Mono basin, California. Other investigations were carried out in the Murray—Darling basin where more than 200 saline water disposal basins are impacting the underlying aquifers and the river Murray (Narayan and Armstrong, 1995; Simmons et al., 2002). Further modelling studies focused on density-dependent ground-water hydrodynamics beneath saline disposal basins and the development of convection cells (Fan et al., 1997; Simmons and Narayan, 1997; Simmons et al., 1999; Wooding et al., 1997a; Wooding et al., 1997b). Using laboratory experiments and numerical modelling, Johannsen et al. (2006) investigated fingering instabilities of brines underlain by freshwater.

Besides these transport modelling studies, a number of field studies were performed to characterise ground-water flow and brine evolution in saline environments using stable isotope data. Among the environmental tracers that have proved useful in many hydrogeological investigations due to their abundance and the simplicity of their analytical determination are stable isotopes of ^{18}O and D (Aketwana and Richardson, 2004; Craig and Gordon, 1965; Gonfiantini, 1986; Vallejos et al., 1997; Zimmermann, 1979). As they constitute a part of the H_2O molecule, they are natural tracers behaving chemically like water. An important factor for studies of closed lakes is isotopic alteration by rapid evaporation. This process leads to a kinetic fractionation of oxygen and causes the water to shift to the right of the meteoric ^{18}O—D water line. Water subjected to rapid evaporation evolves along an evaporative line, with a slope less than eight. The slope depends on local climatic conditions, particularly the humidity in the air (Clark and Fritz, 1999). When surface-water that has been subjected to evaporation infiltrates into the ground-water it can be easily identified by its isotopic fingerprint and provides a helpful means to characterise the flow regime.

Mineral precipitation and brine evolution for a chemically controlled closed system are determined by the chemical divide concept (Hardie and Eugster, 1970). If water evaporates and leads to mineral precipitation, the concentrations remain fixed if the concentration ratios in solution are equal to the stoichiometric ratios in the mineral. However, if the ratios are different, the solute with the highest concentration increases, while all the other constituents of the mineral decrease in concentration as soon as the mineral starts to precipitate. This process may lead to a variety of brine compositions depending on the initial ion ratios. Wood and Sanford (1990) modified this chemical divide concept for the more common open hydrological system. Further important factors that control the hydrogeochemical evolution of brines are dissolution and precipitation processes such as dolomitisation and dedolomitisation (Yechieli and Wood, 2002).

Hydrogeochemical simulations have to account for the activities of the different solutes. For concentrated brines it is generally agreed that the Pitzer equations (Pitzer, 1987) currently provide the most satisfactory method of calculating activities. An example for their application is published by Liu et al. (2004) who performed hydrogeochemical simulations to characterise the geochemical evolution of brines and salt minerals.