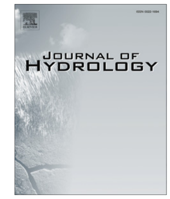
Journal of Hydrology 520 (2015) 342–355

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol



Transient simulations of large-scale hydrogeological processes causing temperature and salinity anomalies in the Tiberias Basin

Fabien Magri [a,b,*], Nimrod Inbar [c], Christian Siebert [d], Eliahu Rosenthal [c], Joseph Guttman [e], Peter Möller [a]

[a] *GFZ German Research Centre for Geosciences, Section 5.3 – Hydrogeology, Potsdam, Germany*
[b] *Freie Universität Berlin, Hydrogeology, Germany*
[c] *Tel Aviv University, The Department of Geophysics and Planetary Sciences, Tel Aviv, Israel*
[d] *Helmholtz Centre for Environmental Research – UFZ, Halle, Germany*
[e] *Mekorot Co. Ltd., Tel Aviv, Israel*

ARTICLE INFO

Article history:
Received 19 September 2014
Received in revised form 19 November 2014
Accepted 20 November 2014
Available online 27 November 2014
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Stephen Worthington, Associate Editor

Keywords:
Numerical modeling
Lake Tiberias
Convection
Brine
Fault
Heat anomaly

SUMMARY

Hot and salty waters occur in the surroundings of the Lake Tiberias. Transient numerical simulations of thermally-driven flow without salinity effects show that mixed convection can explain the upsurge of thermal waters through permeable faults and the high temperature gradient in the Lower Yarmouk Gorge (LYG). It turns out that by including salinity effects, the flow patterns differ from those of a purely thermal regime because heavy brines dampen upward buoyant flow and convective cells. Accordingly, the fault permeability had to be increased to restore a good fit with the measured temperatures. This further supports the hypothesis that the high temperature gradient in the LYG is likely due to fractures or faults in that area. The thermohaline simulations also suggest that the derivatives of relic seawater brines are the major source of salinity. Deep brines leaching salt diapirs cannot reach the surface. However, the presence of local shallower salt bodies below the lake can potentially contribute to the salinity of the western spring and well waters, though in very small amount. This is in agreement with geochemical data according to which the major source of the brines of the Tiberias Basin represents seawater evaporation brines. Besides being of importance for understanding the hydrogeological processes that salinize Lake Tiberias, the presented simulations provide a real-case example illustrating large-scale fluid patterns due to only one source of buoyancy (heat) and those that are additionally coupled to salinity.

1. Introduction

Groundwater flow, heat and brine transport processes in large-scale systems are naturally coupled and mutually dependent. Physically, the coupling is mainly through the Darcy law, in which the buoyancy forces and dynamic viscosity depend on pressure, temperature and solute concentration (e.g. Ingebritsen and Sanford, 1999). The consequence of this coupling is that different system behaviors arise (Chen et al., 1990). On the basis of a linear stability analysis, Lapwood (1948) shows that, for a porous medium heated from below, free convection is triggered when the value of the Rayleigh number of the medium is higher than a critical number $Ra^{critical}$. Depending on the physical properties of the fluid and geological units, different free convective regimes develop in the form of thermal plumes or fingers (e.g. Nield, 1968). In basin systems, free convection is often related to the upsurge of hot springs. For example, Severini and Huntley (1983) shows that convection with a normal geothermal gradient is capable of producing warm springs in northwestern Virginia. When dissolved solutes are also involved, mass transport within the system is associated with the protrusion of the thermal plumes. In saline environments, this coupled flow is called thermohaline convection. Real study cases are the salt domes of the Gulf of Mexico, where upward brine flow along salt flanks occurs as the result of thermohaline convection (Evans et al., 1991). In the coastal aquifers of western Turkey, free convection in the faults induces seawater intrusion (Magri et al., 2012). Depending on the relative importance of both sources of buoyancy (i.e. heat and salt), solute can be either stabilizing and dampen thermal convection (Diersch and Kolditz, 2002) or enhance gravity-driven flow, as in the case of sinking brine from shallow salt structures (Sarkar et al., 1995; Magri et al., 2009).

When thermohaline convection interacts with the regional flow imposed by the topography of the basin, the resulting flow is referred to as mixed convection. Mixed convection is invoked as

* Corresponding author at: GFZ German Research Centre for Geosciences, Section 5.3 – Hydrogeology, Potsdam, Germany, Freie Universität Berlin, Hydrogeology, Germany.

E-mail address: fabienma@gfz-potsdam.de (F. Magri).

http://dx.doi.org/10.1016/j.jhydrol.2014.11.055
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the main process of ore formation in the McArthur Basin, Australia (Garven et al., 2001). The hydraulic conductivity of the units exerts the major control on groundwater flow, and therefore strongly impacts coupled processes. In this regard, permeable faults provide preferential pathways for mixed convection and discharge of the regional flow. Permeable faults can even allow convection within surrounding units that have a small Rayleigh number (McKibbin, 1986).

Here a numerical example illustrating the features of large-scale groundwater flow coupled to heat and brine transport in a faulted system is presented. The Tiberias Basin (Fig. 1), in the Jordan Rift Valley serves as study case.

The Jordan Rift Valley is a series of rhomb-shaped pull-apart basins, one of which hosts Lake Tiberias, also known as Lake Kinneret or Sea of Galilee (Fig. 1). Brines are found in springs and boreholes at the shoreline of the Lake, as well as seepages from the lake's floor (Fig. 1). The springs can be classified in clusters according to their location and the local geological settings, as well as to their chemical properties (Table 1). The lake is a major fresh water reservoir for the whole area. Therefore, understanding the driving mechanisms endangering the lake is a crucial aspect to manage this important freshwater resource.

Previous numerical simulations based on a W–E cross-section crossing the lake (Gvirtzman et al., 1997a,b) show that topography-driven flow from the Galilee and convection below the Golan coexist (i.e. mixed convection) and can explain different spring behaviors as well as the anomalous geothermal gradient of the area. Similarly, Roded et al. (2013) study the high heat flow below the Lower Yarmouk Gorge (LYG) along a N–S profile at the eastern side of the lake. However, those studies account neither for the salinity effects of relic brines in the units nor for the effects imposed by the presence of a salt dome. Furthermore, in

Table 1
Range of temperatures, Total Dissolved Solids (TDS) and flow rates for the major cluster of springs (Cs), wells (w) and boreholes (b) as located in Fig. 1. The values are adapted from selected publications (superscript number) and do not provide a strict minimum–maximum interval.

Location "Cs": cluster of springs, "w": well, "b": borehole	Abbreviation	TDS (g L^{-1}) range	Temperature (°C) range
Tabgha (Cs)	Ta	2.25–5.23[1,2]	19–29[1]
Fuliya (Cs)	Fu	2.06–2.72[1,7,2]	27–30[4,7]
Tiberias Hot Spring	Ti	28.94[1]	64[4,3]
Mukhebeh (Cs)	Mu	0.5[9]	33–43[9,8]
Hammat Gader (Cs)	HG	0.64–1.22[1,9]	28–50[1,7,5]
Gofra (Cs)	Go	5.07[7]	32[7]
Hitin 3 (w)	H3	0.48–0.517[6,7]	25.8[7]
Kinneret 10 (b)	K10b	24.7–31.7[7]	46–52[7]
Ha'on (w)	Ha	14–22.5[1,7]	24–35[1,7,3]
Zemah-1 (b)	Z	220	–

[5] Rimmer (2003)
[8] Levitte and Eckstein (1978)
[1] Möller et al. (2012)
[2] Abbo et al. (2003)
[3] Rimmer (2003)
[4] Gvirtzman et al. (1997a,b)
[5] Water Authority of Israel (2012)
[6] Bergelson et al. (1998)
[7] Bergelson et al. (1999)
[8] Levitte and Eckstein (1978)
[9] Baijjali et al. (1997).

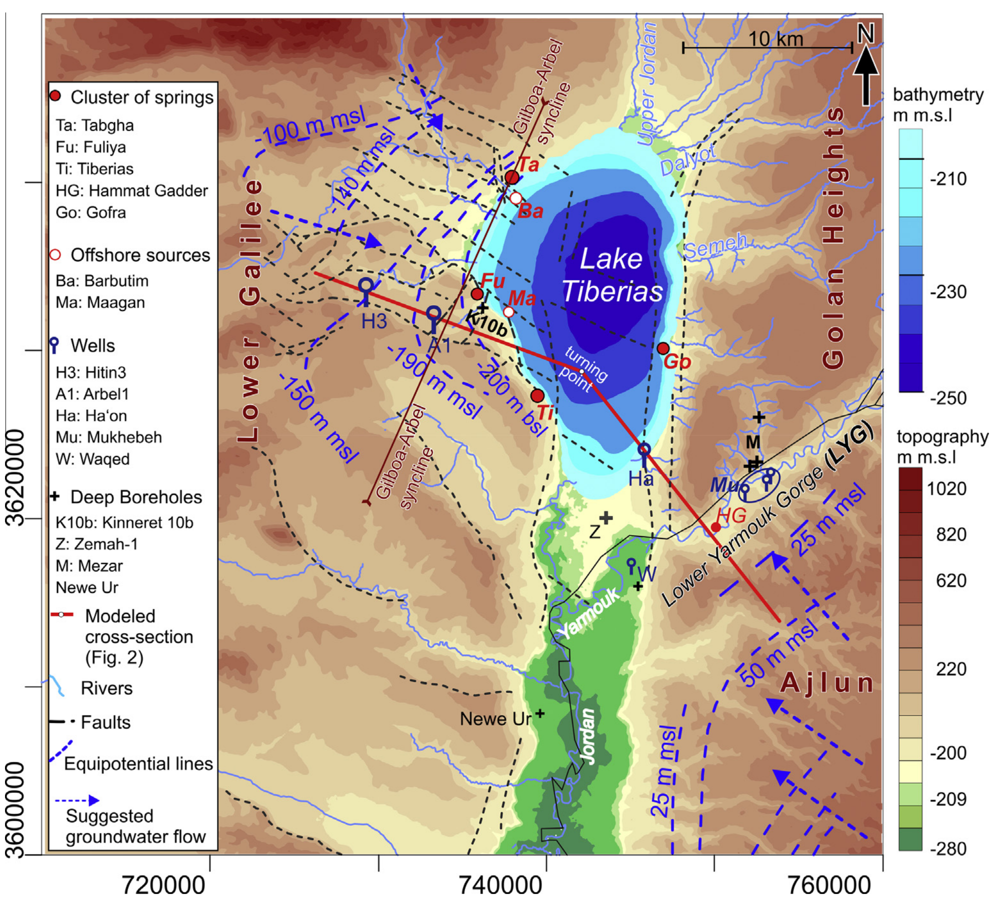

Fig. 1. The Tiberias Basin (TB). Study area including: location of the modeled cross section (Fig. 2), topography and lake bathymetry (SRTM data, Reuter et al., 2007), major faults (Hurwitz et al., 2000a,b; Reznikov et al., 2004), clusters of springs, wells, deep boreholes, equipotential lines mean sea level (Water Authority of Israel, 2012; BGR, 2001) and suggested groundwater flow directions (Bergelson et al., 1998). LYG: Lower Yarmouk Gorge.