Journal of Hydrology 476 (2013) 200–211

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

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

Basal heat-flow and hydrothermal regime at the Golan–Ajloun hydrological basins

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ARTICLE INFO

Article history:
Received 2 April 2012
Accepted 24 October 2012
Available online 2 November 2012
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Souheil M. Ezzedine, Associate Editor

Keywords:
Numerical modeling
Geothermal systems
Heat flow

SUMMARY

A shallow heat anomaly in the form of heated groundwater is detected in the Lower Yarmouk Gorge (LYG), at Northern Israel and Jordan. Results of 2-D numerical simulations of groundwater flow and heat transfer, conducted for the Golan–Ajloun area, indicate that satisfying the thermal field observations requires: (a) existence of an exceptional source of geothermal heat below the Golan Heights (GH); (b) existence of a deep flow path (~3 km), of several MCM/yr of the total 45.5 MCM/yr forced convection flow component, originating at Hermon Ridge and discharging at the LYG outlets. Said flow component serves as fundamental heat convection component, which transports heat from a great depth and vast area, and significantly affects the geothermal pattern. This deep circulation is causing a considerable part of the basin's elevated heat to be transported to the LYG outlets, preventing shallow thermal expression at the GH. Model results indicate that regional mean basal heat flow value of the GH is 100 mW/m^2, and that the shallow thermal anomaly of the LYG is an expression of a deep crust geothermal anomaly.

Additional possible hydrothermal configurations involve an eastern exceptional heat source or alternatively deep convection that is larger by area magnitude (~3600 km^2) and under standard regional basal heat flow (50 mW/m^2).

1. Introduction

The shallow heat anomaly of the Lower Yarmouk Gorge (LYG) in Northern Israel and Jordan makes that area a potential site for production of electricity in the conventional geothermal method. In addition, knowledge concerning the deep (several km down the crust) geothermal state would provide useful sight into deep geodynamics processes, specifically at the recently volcanically-active Harrat-Ash-Shaam Field and in the vicinity of the tectonically-active Dead Sea Transform (DST).

The hot springs at the LYG are separated into two groups, Hammat Gader and Mukhebeh Springs, located about 2 km apart. These springs had a primary (prior to commencement of pumping) large outflow estimated to be approximately 45.5 MCM/yr (Levitte et al., 1978). In the early 1980s, a series of wells that were drilled within the LYG from both sides of the border revealed artesian pressures and high temperatures at a relatively shallow depth (e.g. in the Mezar-1 well a temperature of 79.2 °C was recorded at a depth of 1230 m; Michelson, 1981).

Previous work has included mainly geochemical and hydrological aspects of the springs (e.g. Arad and Bein, 1986; Arad et al., 1986; Bajjali et al., 1997; Eckstein, 1976; El-Naser, 1991; Levitte and Eckstein, 1978; Mazor et al., 1973, 1980; Starinsky et al., 1979), most of which invoked a mixture of a fresh, cold component of shallow origin and more salty, hot groundwater of deep origin. However, the magnitude and temperature of the deep-origin component flow path and the source of heat remained unknown.

In the present study we examine the geothermal state of the Golan–Ajloun region (Fig. 1) using a computational analysis of groundwater flow and heat transfer. In the frame of the present study a 2-D scheme is employed, where the cross section from Hermon Ridge's southeastern slopes to Wadi Zarqa Gorge (North Jordan) which includes the geological section down to the Triassic strata.

We examined the source of the shallow heat anomaly at the LYG with several representative scenarios. Two hypotheses were considered: (1) encountered heat is related to hydrological conditions and significant transportation of heat; (2) encountered heat is of magmatic origin or deep crust conditions ("exceptional source" of geothermal heat).

2. Integral thermal energy balance

The thermal energy released by the LYG springs (E) is:

$$E = \rho_f Q c_f \Delta T \quad (1)$$

where ρ_f is water density (taken as 1000 kg/m^3), Q the discharge of the LYG springs prior to commencement of pumping, 1.44 m^3/s, c_f

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http://dx.doi.org/10.1016/j.jhydrol.2012.10.035

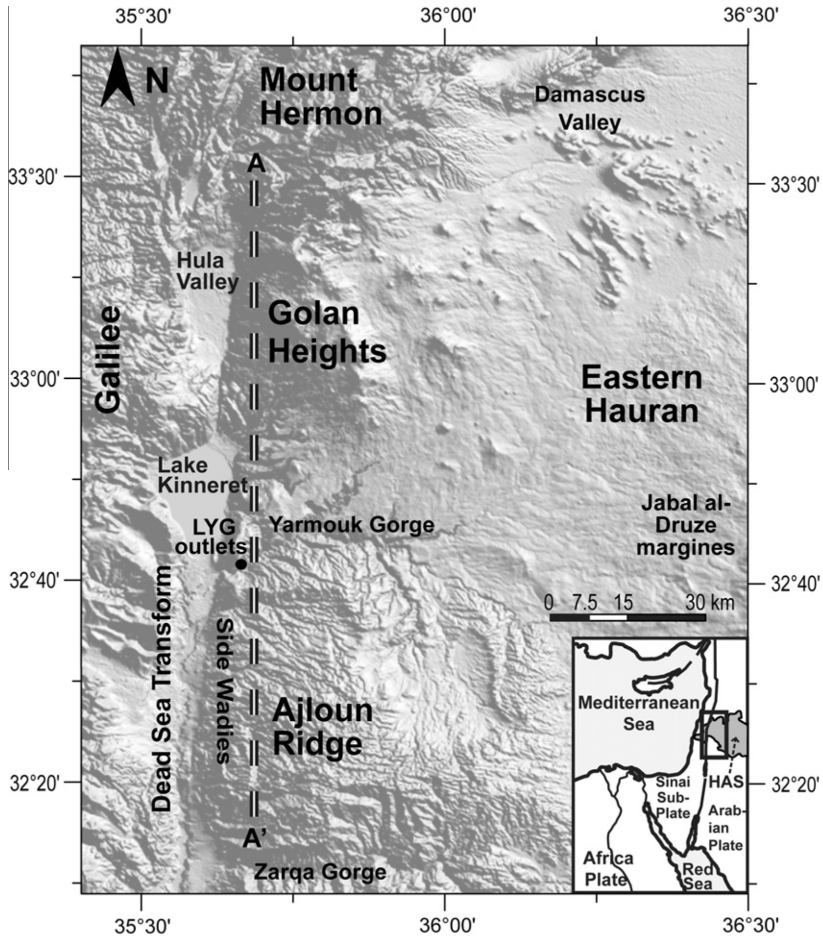

Fig. 1. Map, including cross section – AA′ (shown later in Fig. 2) used for the numerical simulation; HAS – Harrat-Ash-Shaam volcanic field.

Table 1
Discharge temperatures and historical outfluxes of Hammat Gader and Mukhebeh springs; based on: 1 – Bajjali et al. (1997) and 2 – Levitte et al. (1978).

Spring group name	Spring name	Outflow (MCM/yr)		Temperature (°C)
Mukhebeh	Maqla	22.71[2]	~40%[1]	39–43[1]
	Balsam		~60%[1]	33–34[1]
Hammat Gader[2]	Shina	9.43		28
	Balsam	6.14		42
	Bulus			25
	Maqla	4.14		50
	Rieh	3.65		37

specific heat (4200 j/kg °C) and $\Delta T = 37 - 22 = 15$ °C the difference between recharge and volume-averaged discharge temperature (see Table 1). Applying these values yields:

$$E = 1000\ (\text{kg/m}^3) * 1.44\ (\text{m}^3/\text{s}) * 4200\ (\text{J/kg}\ ^\circ\text{C}) * 15\ (^\circ\text{C}) = 90.72 \times 10^6\ (\text{W}) \tag{2}$$

The geothermal Peclet number (Pe) is often used to roughly estimate the magnitude of heat conduction and convection of geothermal systems using characteristic dimensions and physical attributes (Anderson, 2005; Phillips, 2009; van der Kamp and Bachu, 1989). $Pe \gg 1$ indicates that convection is dominant, while $Pe \ll 1$ indicates that conduction is dominant. Pe values of ~1 indicate similar orders of magnitude of heat transfer by both mechanisms. The Pe number is defined as:

$$Pe = \frac{\rho_f c_f q_f z_0^2}{\lambda_e L_0} \tag{3}$$

where λ_e, is the effective thermal conductivity ~3 W/m °C, z_0 a characteristic vertical length (3000 m, Fig. 2), and L_0 a characteristic flow path length from Hermon Slopes to LYG outlets (65,000 m). q_f is the average velocity, that is calculated assuming half of the water discharging at the LYG is of Hermon origin, of 0.72 m^3/s, and dividing it by the product of the basin width (assuming northwestern boundary is Hermon Ridge southwestern margins and northeastern boundary is Damascus Valley) of 30,000 m and the average depth of 3000 m, yielding an average velocity of ~8e−9 m/s. Setting the values in Eq. (3) yields $Pe = 1.6$, which indicates a convective–conductive system.

The maximal hypothetical area where heat can be transferred beneath the GH and the Ajloun Ridge is 2000 km^2 (denoted as A). With $Pe = 1.6$, about half of the basin basal heat flow (J) is being transferred by convection to the LYG outlets and another half is being conducted. The overall heat divided by the area is:

$$2 * E/A = J \tag{4}$$

Setting values, yields:

$$J = 90.72 \times 10^6\ (\text{W}) * 2/2000\ (\text{km}^2) = 91\ (\text{mW/m}^2) \tag{5}$$

The resulting value of 90 mW/m^2 is exceptionally high for this region and is attributed to an exceptional geothermal heat source and/or vast deep groundwater circulation.