Subsurface thermal regime to delineate the paleo-groundwater flow system in an arid area, Al Kufra, Libya

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Abstract The purpose of this study was to understand the groundwater flow system in Al Kufra basin, Libya, as a case study of arid areas using subsurface temperature. The temperature-depth profiles and water levels were measured in eight boreholes in the area. Well 6 is considered a recharge type profile with low geothermal gradient (0.0068 °C/m) and an estimated paleo-temperature around 19.5 °C. The other profiles are of discharge type with higher geothermal gradient (0.0133 to 0.0166 °C/m). The constructed horizontal 2D distribution maps of the hydraulic heads and the subsurface temperature measurements reveal that the main recharge area is located to the south with low temperature while the main discharge area is located to the north with higher temperature. Vertical 2D distribution maps show that location of well 4 has low hydraulic heads and higher temperature indicating that the fault defined in the area may have affected the groundwater flow system. The estimated groundwater flux ranges from 0.001 to 0.1 mm/day for the recharge area and from 0.3 to 0.7 mm/day in average in the discharge area.

1. Introduction

Around 30% of the earth surface area is dry or semi-dry where potential evapotranspiration surpasses precipitation (McKnight and Hess, 2000). In dry and semi-arid areas, the measure of water recharge of an aquifer is much more important to the maintainable utilization of water than it is in humid districts. In spite of this, no much said about the amounts of water that are required to economically recharge aquifers in such locales. In North Africa and the Arabian Peninsula, where fossil water is mined and not recharged, the rate of utilization of water for farming watering system is high and leads to the aquifers draining. By definition, in those areas, potential evapotranspiration ordinarily exceeds normal rates of precipitation (Kinzelbach et al., 2002).

The aquifer recharge is irregular and the capacity to estimate and analyze the groundwater flow system is extremely restricted. These elements are exacerbated by variations in...
Figure 1  (a) Location map of the study area and Kufra Basin with its confining basement highs (modified from Luning et al., 1999). (b) North–south cross section of Al Kufra Basin (after Roohi, 1996; Al Faitouri, 2013).
topography, vegetation spread, soil sorts and hydrology components that make the recharge processes extremely hard to screen and measure (Kinzelbach et al., 2002). Natural isotopic and hydrochemical tracers have been utilized to assess recharge, discharge and flow rates for arid-area groundwater and were adopted after advancement of high-exactness mass spectrometric and radiometric measuring methods (Aggarwal et al., 2005). In this exploration study, the author has utilized subsurface temperature measurements as a natural tracer procedure to quantify the vertical flux of the studied paleo-groundwater in Al Kufra zone, Libya.

Throughout the past five decades, it has been perceived that subsurface temperature can serve as a characteristic tracer of groundwater stream (e.g., Suzuki, 1960; Stallman, 1963; Bredehoef and Papadopulos, 1965; Stallman, 1965). Therefore, anomalies caused by groundwater stream to depict groundwater recharge and discharge regions have become interesting for hydrogeologists to assess recharge/discharge rates freely of head information, and to compel evaluations of hydraulic conductivity. As indicated by van der Kamp (1982), detailed field surveys habitually experience thermal anomalies because of convection, to the degree that in areas of dynamic groundwater flow such anomalies might be the rule not the exception.

Borehole temperature measurements have been utilized to assess the groundwater flow qualities and past climate change (Sakura, 1993; Taniguchi, 1993; Huang et al., 2000; Uchida et al., 1999; Miyakoshi et al., 2003; Salem et al., 2004a,b; Lubis et al., 2008). Salem (2009), Salem and Bayumy (2016) and Salem and Osman (2016) utilized subsurface thermal system to follow the groundwater stream framework in Wadi El-Assiuty, east Wadi El-Natrun, and northwestern Nile Delta areas, (respectively) Egypt, as examples of semi-arid territories. Underground thermal environment is influenced by thermal conduction and convection because of groundwater flow. The geothermal gradient is relatively low in the recharge zone and high in the discharge region (Taniguchi et al. 1999a,b).

2. Geologic and tectonic settings

The Al Kufra basin is situated in southeastern Libya near the Egyptian border toward the east, Sudan toward the

Figure 2 Structural maps of Al Kufra Basin. In map (a), a sinistral strike-slip system is dominant with a rhombochasm presently in the deep subsurface defined by synthetic strike-slip master faults (Bellini et al., 1991). Map (b) shows the fault systems estimated from the Bouguer gravity anomaly map of the area (Le Heron et al., 2009).
southeast, and Chad toward the south (Fig. 1a). The study region incorporates Al Kufra Oasis and its surroundings where the essential residence occurs. The eastern Sahara of North Africa is at present the biggest driest district on Earth, where the received solar radiation is fit for vanishing more than 200-times the measure of precipitation (Henning and Flohn, 1977). The Al Kufra basin is limited by four basement high structures, the Tibesti Massif (Jebel Nuqay and Jebel Dohone) to the west, the Jebel Uweinat Massif (Jebel Asba) to the east, the Ennedi and Borkou mountains to the south, and the Calancio Curve (Jebel Dalma) to the north (Fig. 1a). The basin filling accomplishes total thickness of 2600 m (AGIP, 1976) and incorporates Paleozoic silt that is uncomfortably overlain by Mesozoic strata.

According to Luning et al. (1999), Al Kufra Basin sedimentary succession (Fig. 1b) can be classified into the following eight noteworthy stratigraphic units from Precambrian to Cretaceous:

1. The infracambrian strata that originate from a rock unit at the northeastern part. These sediments are portrayed as being made out of limestones, metagray wackes, shales, siltstones and conglomerates.
2. Hassaouna and Memouniat formations (Cambrian and Ordovician) that are undifferentiated and overwhelmed by braided fluvial to shallow marine sandy facies with few marine clay intercalations.
3. The Tanezzuft Formation (Lower Silurian) that comprises shales of green, red and light gray colors at outcrop and are intercalated with wavy undulated or hummocky cross stratified light dark to rosy caramel siltstone to fine sandstone beds.
4. The Acacus Formation (Lower/Upper Silurian) that is a deltaic, shallow marine sandstone unit with a diachronous base.
5. The Tadrart Formation (Lower Devonian) that is formed of braided fluvial sandstones deposited after the regional Early Devonian main sea level fall.

Figure 3  Map of the Paleoriver and buried drainage basins in Al Kufra Basin (Ghoneim et al., 2012). The red dots located in Wadi Al Ramlah indicate the location of the used boreholes.
6. The Binem Formation (Middle to Upper Devonian) that is comprised of marine sandstones and interbedded siltstones and silty shales. The unit shows a general sea level ascent after deposition of the fluvial Tadrart sediments.

7. The Zamah Formation (Carboniferous) that is comprised of cross bedded sandstones with silty shale and siltstone intercalations. The sedimentary environment was continental for the most part with a braided fluvial facies passing upward into shallow marine sediments.

8. Continental Mesozoic fine to coarse grained sandstones that are common over the central part of Al Kufra Basin laying unconformably on the Paleozoic sediments and are locally calcareous (e.g., Chieun Limestone).

The focal point of the Al Kufra basin is covered with sand except for few little hills of Cretaceous Nubian Sandstone outcrops that are constrained toward the north, southeast and the southwest of the Al Kufra Oasis. The base of the Paleozoic...
rocks is uncovered just in the southeast and the southwest where it lays uncomfortably on the Precambrian basement.

Using magnetic datasets, Bellini et al. (1991) proposed a model of Al Kufra Basin as a sinistral transtensional basin in view of the identification of a rhombochasm, about 150 km wide and 400 km long in attractive datasets (Fig. 2a). Based on seismic lines, Luning et al. (1999) reported a rift graben with identifiable syn-and post-fracture fill, inside the pre-found subsurface of the basin. Depending on Bouguer gravity anomaly map of Al Kufra basin, Le Heron et al. (2009) estimated five NE–SW striking faults up to 300 km long in the subsurface. These NE–SW faults are separated and intersected by a later generation of NW–SE fault system (Fig. 2b). Le Heron et al. (2009) integrated the sedimentological, structural, petrographical and geophysical data of the area and concluded the followings: (a) mountain construction during the

Figure 6  Horizontal distribution of the hydraulic heads in Al Kufra area at 200 masl (A) and 200 mbsl (B). Arrows show the direction of the groundwater flow.
Pan-African Orogeny produced intensive deformation which was responsible for the formation of NE–SW faults in the area; and (b) the main mountain building event followed by collapse and, possibly, rifting to cause the deep subsurface of the basin and a collapse along NW–SE-striking faults. These faults play an important role on the groundwater flow and thermal systems as will be shown in the next parts.

According to Ghoneim et al. (2012), a combined remote sensing (optical and radar symbolism) and GIS (hydrologic system depiction) investigation permits mapping of Al Kufra Paleoriver (Fig. 3) and reveals insight into its geomorphic development amid the Neogene. The Al Kufra framework, which is presently the biggest covered area with the windblown sands of the Eastern Sahara, drained a range of around 236,000 km² southern Libya (Ghoneim et al., 2012). This drainage system was likely controlled by tectonic subsidence (Ghoneim et al., 2012). The stream was released over an extensive inland delta to the Al-Jaghbub depression in northern Libya, and through the Sirt Basin to the Mediterranean Sea. Radar imagery helped to identify its buried features including watersheds, areas of conceivable stream catch, profoundly chiseled valleys, and the distal edges of the inland delta. The study region is unique for the groundwater stream framework investigation as there are many boreholes scattered along Wadi Al Ramlah paleo-drainage from the recharge to the discharge areas (Fig. 3).

Al Kufra area is presently one of the five sources of the Great Man-Made River Project of Libya. The task started in 1976 and was propelled in 1984. The Cretaceous sandstone aquifer in Al Kufra Basin is basically unconfined and groundwater stream heads northeastward releasing into the main Nubian artesian basin of Egypt (Al Faitouri, 2013). Vertical recharge over the principle basin is improbable as the precipitation rate is most likely under 3 mm/a. The age of the groundwater at the northern part of Al Kufra basin is in overabundance of 20–22 × 10³ years (Al Faitouri, 2013). Such an unconfined aquifer cannot be in balance with current recharge. It is believed however, that a way to deal with balance may exist in marginal recharge regions.

### 3. Surface air temperature

As indicated by El-Tantawi (2005), the present mean yearly air temperature of Al Kufra range is 23.4 °C. At the time of Nubian Sandstone Aquifer groundwater recharge, the surface air temperatures were lower than the current conditions. Abouelmagd et al. (2014) figured out the noble gas recharge temperatures (NGTs) of the Nubian Sandstone Aquifer in Sinai, utilizing measured concentrations of Ne, Ar, Kr, and Xe. The assessed normal recharge temperature was 19.9 °C.

![Figure 7](image_url) Cross-section of the hydraulic head distribution along the south (well 6)-north (well 1).

![Figure 8](image_url) Temperature-depth profiles of the used boreholes.
Hydraulic heads were measured by water level meter in ten destinations in Al Kufra area (Fig. 4). Potentiometric levels were measured at every site in three or two boreholes with variable depths. The measured hydraulic heads were utilized for assessing the groundwater stream framework in vertical and horizontal directions (Figs. 6 and 7). Temperature-depth profiles were constructed in only seven boreholes (1, 4, 6, 8, 10, 11 and 12, Fig. 5). Temperature was logged after one week of halting the flow of the boring liquid, the temperature dissimilarity due to penetration liquid is negligible (Lee and Han, 2001). Temperature of the water and c₀ρ₀ is the heat capacity of the water and cp is the heat capacity of the aquifer. The simulation is constrained for semi-infinite layers with just vertical conduction and convection, and vertical groundwater flux is thought to be consistent with depth.

5. Results

5.1. Aquifer system

The slope of the ground surface in the study area is to the central part and the northeastern direction (Fig. 4). The Nubian Aquifer in the study area consists of layers of sand separated by layers of clay ranging in age from Permian to Early Cretaceous (Fig. 5). According to Al Faitouri (2013), the aquifer in the study area is comprised of continental fluvial sediments of lenticular beds. Variety in lithology on a level plane and vertically makes the permeability not the same from one spot to other. The aquifer is composed of 700 m sand in the upper part lying above clay layers that separate the deep and shallow aquifers. Transmissivity has been assessed in light of long period pumping tests from 2004 to 2008 and to range from 4.85 \( \times 10^{10} \) to 2.21 \( \times 10^{10} \) \( \text{m}^2/\text{s} \). The storativity has been ascertained to range between 0.0709 to 0.0284 (m/s). The slop is the heat capacity of the aquifer.

To analyze the borehole temperature profiles with heat advection because of groundwater flow, computations of subsurface temperature have been made using different vertical groundwater fluxes. Carslaw and Jaeger (1959) acquired the expository solution for temperature utilizing a one-dimensional heat conduction–advection mathematical statement under the state of a direct increment in surface temperature as

\[
T(z, t) = T_0 + \left( b + T_0 U \right) \frac{z}{2U} - 2e^{z/(2U)} \text{erfc} \left( \left( z + Ut \right) / \sqrt{2z} \right) \]

\[
+ \frac{U(t - z)}{e^{2z/(2Ut)}} \text{erfc} \left( \left( z - Ut \right) / \sqrt{2z} \right) \]

(2)

where \( b \) is the rate of increase in surface air temperature, \( t \) is the time after semi-equilibrium condition (Taniguchi et al., 1999a,b), \( T_0 \) is the paleo-surface temperature (initial temperature), \( T_G \) is the average geothermal gradient, and

\[
U = \frac{\omega c_0 \rho_0}{c_p} \]

(3)

in which \( v \) is the vertical groundwater flux, \( c_0 \rho_0 \) is the heat capacity of the water and \( c_p \) is the heat capacity of the aquifer. The simulation is constrained for semi-infinite layers with just vertical conduction and convection, and vertical groundwater flux is thought to be consistent with depth.

4. Measurements and analysis

Hydraulic heads were measured by water level meter in ten destinations in Al Kufra area (Fig. 4). Potentiometric levels were measured at every site in three or two boreholes with variable depths. The measured hydraulic heads were utilized for assessing the groundwater stream framework in vertical and horizontal directions (Figs. 6 and 7). Temperature-depth profiles were constructed in only seven boreholes (1, 4, 6, 8, 10, 11 and 12, Fig. 5). Temperature was logged after one week from mud circulation stop utilizing a digital thermistor thermometer with determination of 0.01 °C. The geothermal gradient was calculated using the following equation (Bullard, 1965):

\[
\text{Geothermal gradient (°C/m)} = \frac{\text{bottom hole formation temperature (°C)}}{\text{mean annual surface temperature (°C)}} - \text{depth(meter)}
\]

(1)

\[
\text{Temperature (°C) and depth (m).}
\]

\[
\text{Geothermal gradient (°C/m)} = \frac{\text{bottom hole formation temperature (°C)}}{\text{mean annual surface temperature (°C)}} - \text{depth(meter)}
\]

(1)

Figure 9 Vertical two dimensional subsurface temperature distributions along the main flow system from south (well 6) to north (well 1). Temperature units are in (°C).

(17.5–22 °C). This is similar to the normal NGT (20 °C) reported for the Nubian groundwater from the Western Desert of Egypt (Patterson, 2003). It is also in match with the reported findings from fossil groundwater aquifers in North Africa (Guendouz et al., 1998). Through a recharge period that took place 45 to 23 * 10³ year before present, the NGTs for the Mainland Intercalaire Aquifer inside the Northwestern Sahara Aquifer Framework (in Algeria, Tunisia, and Libya) are evaluated to be 2–3 °C lower than the present mean yearly air temperature (Guendouz et al., 1998). As indicated by Al Faitouri (2013), Al Kufra aquifer tests demonstrate that the recharge of the aquifer is thought to be consistent with depth. Vertical conduction and convection, and vertical groundwater flux is thought to be consistent with depth.
the following: (a) the general groundwater flow takes a direction from the south, east and west to the central part and then to the northern direction; and (b) compared to the topographic map (Fig. 4), the shallow groundwater flow system is topographically controlled where a local discharge area is recognized in the low lands. The vertical groundwater flow system along the main flow direction from south to north is presented in Fig. 7. The hydraulic heads decrease from south to north along the main groundwater flow system in the area. Abnormal low hydraulic head zone in the location of well 2 is followed by higher piezometric levels in the area of well 4. Such phenomenon could be related to a probable fault effect (Bense et al., 2008).

5.2. Temperature data analysis

Field temperature data were recorded and are presented in Fig. 8. According to Domenico and Palciauskas (1973) classification of the temperature profiles, well 6 is a recharge type profile while wells 1, 4, 8, 10, 11 and 12 represent discharge type profiles. Although wells 10 and 11 are located in topographically high areas (Fig. 4) with higher hydraulic heads (Fig. 6), they show high temperature values. This could be related to fault effect (Fig. 2) where the deep hot groundwater raises upward along the fault zones. Profile 6 shows surface warming in the upper part. The Paleo-surface temperature estimated from the extension of profile 6 is around 19.9 °C which is similar to the estimation of Abouelmagd et al. (2014), Al Faitouri (2013), Patterson (2003) and Guendouz et al. (1998). According to the geothermal gradient of the measured profiles, three profile groups are recognized. The first group has low gradient (0.0068 °C/m) and characterizes the recharge area where profile 6 is located. The second group of profiles is of discharge type and has an intermediate gradient (0.0154,
0.0138 and 0.0133 °C/m of profiles 1, 8 and 12, respectively). The third group has higher geothermal gradient (average 0.0166 °C/m for profiles 4, 10 and 11) compared to the other two groups. Such higher geothermal gradient of the third group could be related to the fault effect. Faults force the deeper hot groundwater to flow upward producing higher geothermal gradient.

Vertical 2D cross-sections were constructed (Fig. 9) along the main groundwater flow direction from south to north to explain the subsurface temperature distribution in relation to the groundwater flow system and to show the expected fault effect. The recharge area to the south is characterized by colder temperature (well 6) compared to the discharge area to north (well 1). Comparing with Fig. 7, Well 4 might be affected by fault structure leading to formation of local warm temperature zone due to local groundwater discharge. No temperature data are available for well 2 for complete comparison between Figs. 9 and 7. Fig. 10(A, B and C, respectively) represents the horizontal two-dimensional subsurface temperature distributions at 300 m, 0.0 m and −100 m from sea level. Comparing temperature distributions of these levels indicates that temperature values increase downward. According to the shape of isothermal lines (Fig. 10) and the groundwater flow system (Fig. 6), there are two types of recharge areas. The first is located to the south where the isothermal lines have lower temperature values (location of well 6). The second area is noticed toward the southeastern and western directions where wells 11 and 10 are located, respectively. The latter recharge areas are characterized by hot water and higher geothermal gradient which might be related to the fault effect. Area of well 1 is considered the main discharge area with an intermediate geothermal gradient and higher temperature values.

6. Modeling

Eq. (2) was used to calculate the vertical groundwater flux by setting $T_0$ (paleo-temperature) to 19.5 °C as estimated from profile 6 (Fig. 8). Depending on the previously calculated geothermal gradient, $T_G$ average value equals 0.0142 °C/m and thermal diffusivity ($\alpha$) is $6 \times 10^{-7}$ m²/s. The change from the paleo-humid climate to the recent arid climate is supposed to have spanned 1000 year ($\tau$), then the used value of $b$ is 0.004 °C/year. Temperature depth profiles are computed using Eq. (2) for different values of $U$ (Taniguchi et al., 1989) in the first sand layer of the aquifer which has an average thickness of 700 m.

Figs. 11 and 12 show the calculated temperature profiles for the study area. Positive values of $U$ means downward groundwater flow (recharge) and negative values means the upward groundwater flow (discharge). Profiles 6 (Fig. 11) shows low recharge flux with $U$ ranging from 0.001 to 0.1 m/year in its deeper part (>250 m) and nearly static in its shallower part (<250 m). The discharge profiles (1, 4, 8, 10, 11 and 12, Fig. 12) have $U$ values ranging from −0.3 to −0.5 m/year in its deeper zone but they have a little higher flux in their shallower zones (−0.5 to −0.7 m/day). These results reveal that, the current recharge is too low but the groundwater still moves downward and discharging upward at the peak of the paleodrainage (Al Ramlah) basin and along the fault zones.

7. Discussion and conclusions

Al Kufra is a typical example of an arid area with paleo-recharged groundwater. The subsurface temperature was checked as groundwater flow tracer in such area. Constructed temperature–depth profiles are classified into three types depending on the shape of the profile and the geothermal gradient. Recharge type (well 6) is located at the southern part of Al Ramlah paleo-drainage basin. The geothermal gradient of this profile as a recharge type is low (0.0068 °C/m) and its extension indicates a paleo-recharge temperature of 19.5 °C. On the other hand, wells of the second group are located in the main discharge areas in the central and northern parts, including wells 1, 8 and 12 with geothermal gradient of 0.0154, 0.0138 and 0.0133 °C/m, respectively. Although the third group of wells has the higher geothermal gradient compared to the other two groups (0.0166 °C/m in average for profiles 10 and 11) they are located in the recharge area to the southeastern and western parts of the area. This phenomenon could be related to fault effect. The observed vertical and horizontal systems of the groundwater flow and the subsurface thermal regime are integrated. Generally, the groundwater recharged where the isotherms are cold (well 6) and discharged where isotherms get warm (well 1). The groundwater flows upward due to fault effect as clearly shown in wells 4, 10 and 11. The cold groundwater recharged in the southern part and the warm water is flowing from the southeastern and western parts and mixes together in the central part of the study.
area and then flowing to the northern part where the main discharge area of Al Ramlah paleo-drainage basin is located.

The modeled 1D temperature profiles were compared to the observed ones. It is estimated that, the recharge flow in the recharge area (well 6) in the southern part of Wadi Al Ramlah is nearly nil in the shallow zone (< 250 m deep) and ranges from 0.001 to 0.1 in the deeper zone (250 m deep). The discharge flow in the central and northern parts of the area where profiles 1, 4, 8, 10, 11 and 12 are located ranges from −0.3 to −0.5 m/year in its deeper zone but they have a little higher flux in their shallower zones (−0.5 to −0.7 m/day). It is estimated that, the current recharge is too low but still the groundwater flowing downward and discharging upward at the peak of the paleo-drainage basin and along the fault zones. It can be concluded that subsurface thermal regime is a good tool to trace the groundwater flow system not only in the humid areas but also in the arid areas even when the groundwater is a fossil water.

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