Evaluating of the hydrothermal groundwater flow of El Hamma shallow geothermal aquifer (South-eastern of Tunisia)

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Abstract

The area of El Hamma, southeast of Tunisia, is characterized by warm groundwater. The aquifer in the city of El Hamma is considered the main source of water to meet the needs of agricultural, industrial, domestic, and traditional baths. Nowadays, groundwater flow in the aquifer system and the thermal origin have been not well explained. The objective of this study is to develop a conceptual model of the geothermal groundwater flow path based on the temperature distribution in the aquifer in the study area.

The groundwater temperature data was collected from 130 wells and implemented into a database. The sampled wells depth range between 25 and 80 m below ground level at temperatures between 18 and 65 degrees Celsius. The temperature remains constant throughout the year, regardless of the external climatic conditions. The variographic analysis and ordinary kriging techniques were used to map the spatial distribution of temperature in the study area.

The conceptual model, hydrodynamic, geological, and thermal data confirm a vertical communication between the deep continental intercalary aquifer and the shallow Senonian aquifer through a system of vertical faults, the most important of which are the F1 fault in the west of the region, the F2 near Wadi El Hamma and the F7 towards the east.

Introduction

Geothermal groundwater can be considered water of abnormally high temperature. This water is a renewable geological resource. They have been used since Roman times for therapeutic purposes (Bassani et al., 2012). Currently they are used worldwide for energy production, industrial processes, district heating and balneology (Lund and Boyd, 2016) and also in geocultural (Agoubi, 2021). Their sustainable exploitation is crucial to ensure their long-term use, future maintenance and environmental protection (Rybach and Mongillo, 2006; Axelsson, 2010; Limberger et al., 2018).

Due to the natural, social, and economic importance of this thermal resource, several studies have been carried out such as those of Crooijmans et al. 2016; Willems et al. 2017; Agoubi, 2021; Torisan et al. 2021. Some other authors, e.g., Williams et al. 2011 and Agoubi, 2018 focus on geothermal water flow and heat flux in geothermal aquifer systems. Previous studies investigated the geochemical properties of thermal waters (Gherardi et al., 2000; Mayer et al., 2015) and other more recent studies were based on the coupling of water flows and heat transfer (e.g., Magri et al., 2012; Baiocchi et al., 2013; Scheck Wenderoth et al., 2014; Brehme et al., 2016) for modeling the geothermal system.

Other researchers such as Bravo et al. 2002; Stonestrom and Constantz 2003; Becker et al. 2004; El -Fiky 2009; Saar 2011, Majumder et al. 2013, Kurylyk et al. 2017, Irvine et al. 2017, Salem et al 2018, Dong et al. 2018, Ren et al. 2018, Li et al. 2019 used water temperature as natural tracers to identify and model water flow in porous and or fractured media. Pola et al. 2020 interpreted a conceptual and numerical model of a geothermal temperature system in the Southern Basin of Italy to know groundwater flow and heat transport using three-dimensional coupled numerical simulations. Torresan et al, 2021 used numerical modeling to assess geothermal resource regeneration for the Euganean geothermal system (NE Italy).

In Tunisia, the thermal potential is very important. More than 80 geothermal events flow from north to south of Tunisia, including 50 geothermal springs identified with the necessary chemical composition for use in thermal treatments that respond to different treatments.

In particular, the system shallow geothermal aquifer of El Hamma (south-eastern Tunisia) which testifies to a positive thermal anomaly, in which there are many wells or thermal boreholes with very high total flows classified as medium to low enthalpy geothermal resources. The water temperature is between 18 and 66°C. The regional context of the basin is non-volcanic and surface heat flux is normal.

Hydrogeological and hydrogeochemical studies of thermal groundwater in El Hamma region have been the subject of numerous reports and articles (e.g., Ben Baccar, 1985; Abidi, 2004; Sahli et al. 2013; Ben Alaya et al. 2013; Agoubi et al. 2015; Agoubi 2018, 2021).

However, most of these previous studies only reported hydrochemical or isotopic data focusing on the interaction between water and rocks. There is little study focused on water heat distribution in the aquifer to understand the groundwater flow in El Hamma geothermal aquifer system and the origin of the thermal anomaly.

In this context, the purpose of this article is to study groundwater flow based on the development of a more conceptual model of temperature distribution in the geothermal aquifer of El Hamma area. This model will integrate all data and knowledge from the most diverse fields such as geology, geophysics, hydrogeology, hydrodynamic parameters, and temperature variations.

Study Areas

This study was carried out in the region of El Hamma, in the south-east of Tunisia (Fig. 1), known as a geothermal zone, characterized by a semi-arid climate, with an average annual rainfall of 150 mm and an annual temperature of around 21.5°C, it sometimes exceeds 40°C in July and August. In recent decades, this region has recognized an imbalance of its ecosystems expressed by a qualitative and quantitative deterioration of groundwater manifested by a rapid decrease in the depth of groundwater due to excessive withdrawals to meet agricultural, industrial, and domestic needs (Agoubi et al. 2015).

The geology of the region is very complex. The Upper Cretaceous period is represented, from the old to the new, by the Cenomanian, the Turonian and the Senonian. The Senonian formation is made up of marls and gypsum topped with limestone and dolomite of varying thicknesses. Finally, the Mio -Pliocene was represented by gypsum marls, red marls, clays, conglomerates, gravels, and sands.

Structurally, it is characterized by the complexity resulting from the tectonic movements that have affected the region. It is organized in Horst and Grabens. The rocks beneath the area have been extensively faulted to form a feature known as the Damier of El Hamma.

From a tectonic point of view, El Hamma region is characterized by the presence of highly developed fault networks. These networks are oriented northwest-southeast (north 140–160) and the most important of them are the F4 and F6 faults (Ben Baccar 1985; Mamou, 1990; Bouaziz, 1995). These faults have already caused the collapse of the eastern massif, bringing into contact the high permeability sandstone levels of the Lower Cretaceous in the west with the low permeability levels of the Upper Cretaceous in the east. This “hydraulic sill” is also called “El Hamma sill” (Rouatbi 1967; ERESS 1972; Mamou 1990; OSS 2003; Abidi 2004).

From a hydrogeological point of view, the thermal aquifer system of El Hamma is a multilayer system containing a succession of permeable, semi-permeable and impermeable levels (Abidi 2004, Agoubi et al 2015, Agoubi 2021). The groundwater is found in two main aquifers in the region. The first aquifer hosted in the shallow Senonian limestone (less than 100 meters) has an average water temperature ranging from 23 to 65°C. The second aquifer is deeper (between 700 and 1500 meters) and hosted in Lower Cretaceous sediments, known as the Continental Intercalary (CI). Its temperature varies between 60 and 80°C. This aquifer is the most extensive aquifer system in southern Tunisia (OSS 2003).

Materials And Method

The approach adopted in the context of this work is presented in the flowchart in Fig. 2. It is articulated in several phases. First, a bibliographical research based on geological, hydrogeological, geophysical studies and the lithological data of the drillings were exploited to determine the geometry of the aquifers in the region. Subsequently, measurements on the ground were carried out: measurements of the depth of the water level and its temperature. based on all these data, a database was created.

For the analysis and interpretation of the data collected, several computer programs were used: mapping software based on the technique of geostatic to minimize the uncertainty of interpolation in a non-sampled place, of drawing, of statistics. After all, the geothermal groundwater flow processes of El Hamma area will be carried out. This ultimately leads to the design of a thermal hydrodynamic model of the thermal aquifer.

Sampling And Database

A groundwater sampling campaign from the geothermal aquifer, covering the entire study area, took place in September 2021. A total of 130 water points from the superficial aquifer were monitored and sampled. Before each withdrawal, water is pumped from the well for 15 to 20 minutes to get rid of the groundwater stored in the well and to ensure that a steady state is obtained. Sampling from the hydrothermal field has always been accompanied by in-situ physicochemical measurements. Geographic coordinates (latitude, longitude, altitude) were measured using Garmin GPS. The parameters measured in the field are the water temperature, the depth of the borehole, the level of the water body and the pumping rate. The location of different sampled points is shown in Fig. 3.

Groundwater Flow And Heat Transfer

Darcy's law provides the basic theory of groundwater flow in porous environments. In geothermal regions, groundwater flows with a change in temperature along the paths’ flow. Here we need to combine the groundwater flow equation and heat transfer equation to understand and explore geothermal resources.

Considering the effects of temperature only on the density and viscosity of the fluid, we can write the two-dimensional flow Eq. (1) (Wang et al. 2021) as follows:

$$S_S\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(\frac{\rho_{w(T)}\, g k_H}{\mu(T)}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial z}\left(\frac{\rho_{w(T)}\, g k_V}{\mu(T)}\frac{\partial h}{\partial z}\right)$$

1

Where k_H and k_V are respectively the horizontal and vertical permeability, ρ_w and μ are respectively the density and viscosity of water; Ss is the specific storage defined as (2)

$$S_S = \frac{1}{\rho_W(T)}\frac{\partial\left[\phi\rho_W(T)\right]}{\partial h}$$

2

Groundwater temperature is a valuable marker of flow (Anderson 2005). The use of temperature as a tracer of groundwater flow has been the subject of several studies (Constantz 1998; Townley and Trefry 2000; Becker et al. 2004; Hatch et al. 2010; Luijendijk et al., 2020, Salem et al. 2020, Agoubi 2021). Becker et al. (2004) indicates that the use of temperature to estimate groundwater flow is important for describing groundwater flow and can be useful for calibrating numerical models of groundwater flow.

To study the spatial variation of the temperature of underground hydrothermal waters and to understand the thermal anomalies present in the study area, a geostatistical analysis based on the experimental Variogram of temperature and the ordinary Kriging technique was carried out.

Result And Discussion

Descriptive statistics

The basic statistics of the groundwater parameters of El Hamma geothermal reservoir are presented in Table 1. The standard deviation values are lower than the average values for all elements. Knowing that the standard deviation makes it possible to measure the dispersion of values around the average, in this specific case the values of the standard deviation are lower; This indicates that the values of the variables are scattered. Thus, it highlights a certain heterogeneity of the water extracted from the aquifer in the study area.

Table 1
Descriptive Statistics

	Average	Standard. Deviation	Variance	Skewness	Kurtosis	Minimum	Maximum
TEMPERATURE	41.515	13.773	189,700	0.016	-1.181	18.617	65.496
PZ	55.101	10.802	116.686	-0.503	0.047	25.924	76.529
ELEV	67.621	8.416	70.825	0.861	0.913	51.019	98,000

Piezometric Of The Shallow Geothermal Aquifer Of El Hamma

The shallow aquifer of El Hamma knew in the last decades an increase of exploitation. This evolution varies according to a straight line of the form $y = 0.4368 x – 863.01$ (Fig. 4) Which generates an increase of 4.368 Mm^3 between 2002 and 2021.

On an annual scale, the piezometric level of the shallow aquifer of El Hamma has recorded a continuous decline, due to the incessant increase in exploitation and limited recharge. The value of the average annual drop in this water table is generally between – 0.4 m/year and – 3 m/year during dry years.

Current piezometric of the shallow aquifer.

The piezometric level analysis of the shallow geothermal aquifer of El Hamma is based on the database of the 130 monitored water points where the piezometric level could be measured. In the study area, the piezometric level varies from 25.9 to 76.5 m with a low asymmetry coefficient of the order of -0.503, which suggests that the piezometric data follow a normal distribution. The kurtosis coefficient (Kurtosis is 0.047) which indicates a homogeneous series of piezometric data.

In order to represent the spatial distribution of the piezometry of the shallow geothermal aquifer from field measurements, the geostatic technique was used to reduce the interpolation uncertainty at an unsampled location. this technique is based on variographic analysis (Agoubi et al. 2015)

The variographic analysis of the piezometric levels of the hydrothermal waters of the region of El Hamma was developed by the Surfer software. The most appropriate model in this area is the power model (Fig. 5 and Table 2). This model was validated by cross-validation between the observed and expected values by the piezometric level model, illustrated in Fig. 6. There is a very good match between the data observed and estimated by the model, which confirms the choice of a power model is well suited to modeling the spatial variation of the piezometric level of the hydrothermal aquifer. The RMSE is also used to test the performance of the model. This parameter is often used to compare the performance of interpolation methods. The value of the RMSE is 2.928.

Table 2
Variographic parameters for the piezometric leve

Model	Variogram component				Anisotropy		Cross-validation
	Lag size	Portal Sill	Tidy	Power	Ratio	Angle	RMSE
Power	524.4458467	0.01243	1	1.173	1.272	35.43	2.9287

The piezometric map of El Hamma aquifer (Fig. 7) created for 2021 shows two overall directions of flow, the first in the direction southeast northwest of Jebal Ragouba towards the depression of Sebkhat El Hamma. The second direction is from Mount Aziza west to Wadi El Hamma and the Sebkha depression, and also from Jebal Ragouba to the plain of Jeffara to the east. These results confirm the results of previous studies, especially Abidi 2004 and Agoubi 2018.

Thermal Modeling

Coupled hydrodynamic/thermal numerical modeling has been used by several authors such as: Le Fanic (2005); Thiebaud (2008); Sonney et al. (2012); TOTH et al. (2017) and C. Wang et al. (2021) on one hand to understand the functioning of thermal systems and on the other hand for the numerical validation of hypotheses of circulation of deep and superficial geothermal groundwater. A hydrodynamic/thermal model is applied to the geothermal aquifer systems of El Hamma based on the spatial temperature distribution of groundwater.

The temperature of the hydrothermal waters of the shallow aquifer are quite heterogeneous and they vary between 18.5 to 65.5°C, with an average of 41.5°C,

The variographic analysis shows that the temperature is modeled by a power model (Fig. 8 and Table 3). In order to assess the performance of the model, cross-validation is used. This model is validated by a significant correlation between the estimated values and those measured (Fig. 8). The average square error is 5.9, which suggests the quality of prediction. We notice a very good match between the observed and estimated data which confirms the choice of this model is suitable for modeling the spatial variability of groundwater temperature by the Kriging technique.

Table 3
Variographic model parameters of groundwater temperatur

Model	Variogram component				Anisotropy		Cross-validation
	Lag size	Portal Sill	Range	Power	Ratio	Angle	RMSE
Power	531.2005231	2.426	1	0.4896	1.583	2.587	5.908

The spatial distribution map of shallow groundwater temperature in the study area (Fig. 9) shows a very heterogeneous distribution. In general, temperature values decrease with groundwater flow directions. It decreases from 60°C from Jebel Aziza (southwest) next to the F1 fault to 15°C in the Sebkhet El Hamma depression in the northeast and also decreases from 65°C in the middle of the Jebal basin Ragouba in the south (fault F5) towards the north of the study area (18°C). Similarly, at Chanchou, the eastern part of the study area, the temperature decreases by 63.5°C from the axis of the F7 fault towards the plain of Jeffara where the temperature is 20°C.

The graph of water temperature against the X direction of Jebel Aziza at Chanchou (Fig. 10) shows temperature fluctuation with the direction of water flow from the western part to the eastern part of the study area, where the temperature of shallow groundwater increases as we approach the axis of the faults located in the area where the water temperature near the F1 fault is 61 degrees, while in the fault F5, it is 65 degrees. In the areas between the fault the temperature decreases to reach 20 degrees.

The temperature profile according to the water sample along the axis fault F5 (from Jebel Ragouba to Sebkhet El Hamma in Fig. 11) shows a decrease in temperature from the southern part (Jebel Ragouba) where the water temperature reaches about 65°C to the northern part from the study region (20°C). The direction of water cooling is not linear. It shows an equivalent aspect that indicates slow cooling due to the aerodynamic effect (Agoubi 2018).

The high-water temperatures observed in El Hamma’s surficial aquifer is a tracer of groundwater flow (Agoubi 2018, Luijendijk et al., 2020, Salem et al. 2020, Agoubi 2021) indicating a flow hot water from the deep Continental Intercalary aquifer. (Abidi 2004; Agoubi et al. 2015) to the SI superficial aquifer through localized fault networks in the region mainly F1, F2, F5 and F7. Indeed, the water temperature in the CI aquifer is about 78°C.

A synthetic vertical section of west to east direction of the temperature distribution of a geothermal aquifer of El Hamma was carried out (Fig. 12 and Fig. 13). Groundwater temperature increases with depth due to the geothermal gradient which in the study area is 0.45°C/km (Agoubi et al. 2018). However, the horizontal temperature propagation is quite heterogeneous due to the presence of a network of faults which allows the communication of deep aquifer with shallow aquifer.

At Jebel Aziza, located west of the study area, water flows from the deep aquifer (Continental Intercalary), which has a temperature of 80 degrees, vertically through the F1 fault level to until it reaches the surface reservoir, then mixes with the surface water and continues its flow horizontally and its temperature gradually decreases to 25 degrees.

At the planar sites of the F5 and F7 faults, the same phenomenon occurs, where the warm waters of the deep Continental Intercalary aquifer rise vertically towards the superficial aquifer due to the presence of a thermal gradient, this action is controlled by the hydrodynamic parameters of the deep aquifer.

Groundwater flow is controlled by the tectonic events present in the area (F1, F2, F5 and F7) as well as the hydrodynamic parameters of the CI aquifer. The pressure of the CI aquifer is greater than that of the surface aquifer, allowing groundwater to rise vertically into the surface aquifer.

Underground water flow systems

The geothermal flow pattern in the study area has been summarized by several researchers (Mamou 1990, OSS 2003, Abidi 2004, Agoubi et al. 2015 and Agoubi 2018) based on the hydrodynamic parameters, geochemical compositions, and stable isotopes of the aquifer system as follows, the warm waters of the deep continental aquifer rise rapidly through systems faults and then they later converge in a shallow aquifer; An aquifer whose temperature decreases with flow directions. This pattern is confirmed in this study depending on the water temperature distribution.

Conclusion

This article examines shallow geothermal water and flow systems in El Hamma region, by collecting and examining temperature measurement data and water levels in the aquifer in 130 samples. To study the functioning of these aquifer systems and the direction of groundwater flow and communication between the two reservoirs.

The presence of geothermal water here is highly controlled by the geological structure as warm water from the deep CI aquifer occurs vertically through fault systems primarily F1, F5 and F7 and then diversifies laterally into the shallow aquifer.

The geothermal water resources of El Hamma are of great economic importance due to their temperature. These resources require fairly detailed studies and regular monitoring to ensure their sustainability. Consequently, its monitoring and management are necessary to ensure its sustainability and increase its economic interest.

Declarations

Author contribution

All authors contributed equally.

Boulbaba HADDAJI: Sampling, visualization, methodology, software, data processing, text writing.

Belgacem AGOUBI: review and editing, supervision, visualization.

Adel KHARROUBI: data processing, software, writing, reviewing, and editing, supervising.

Data availability

The data used during this study will be made available upon request to the corresponding author, Boulbaba HADDAJI (haddajiboulbaba2018@gmail.com).

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Conflict of interest

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Figures

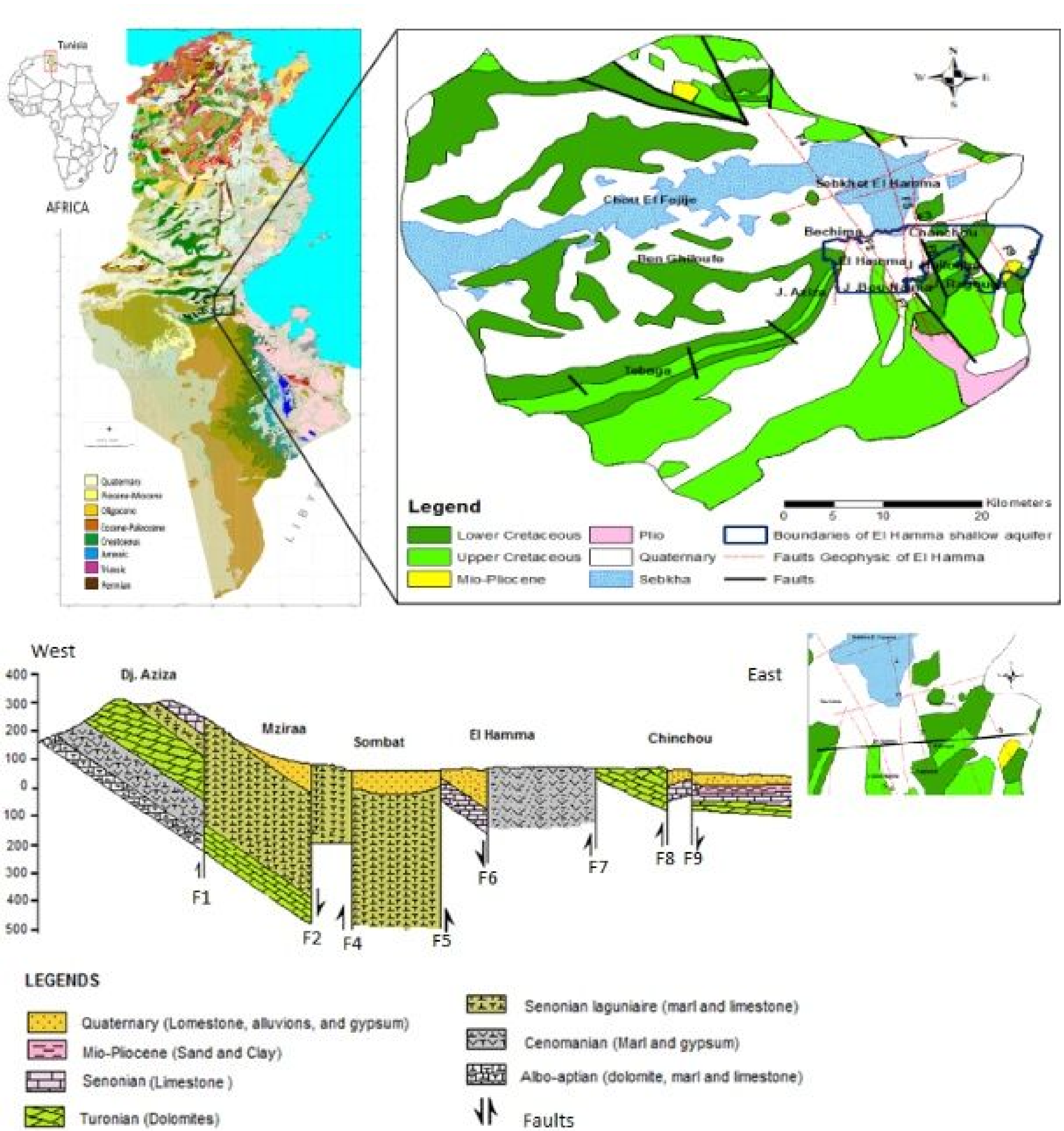


Figure 1

Geographical location and geological maps of the study area.

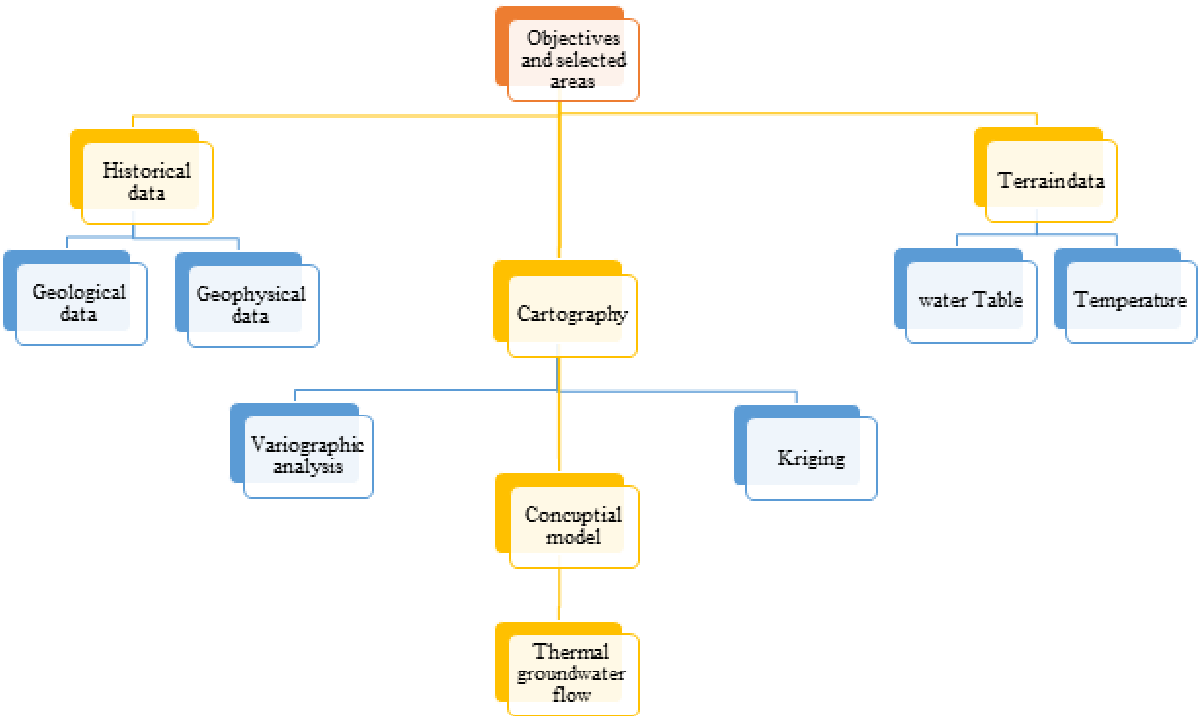


Figure 2

Flowchart of the methodological approach.

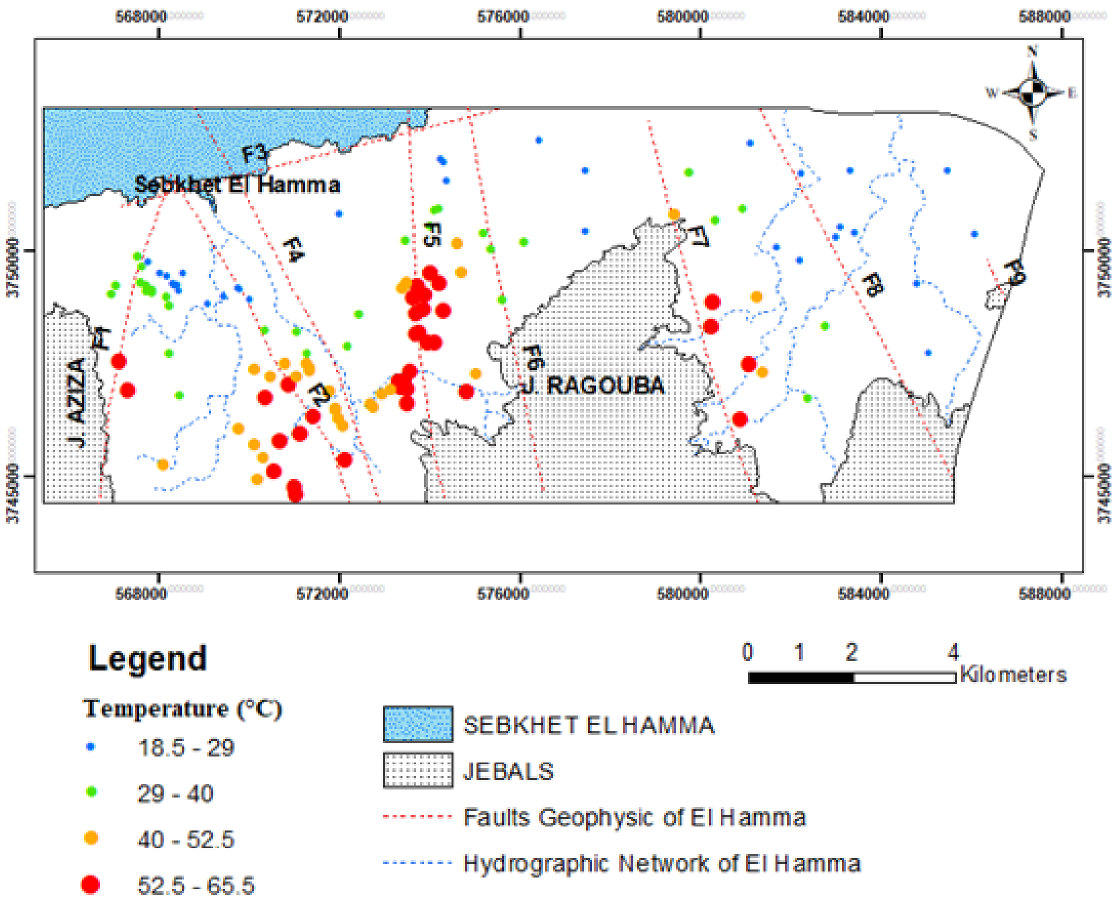


Figure 3

Location of sampled water points

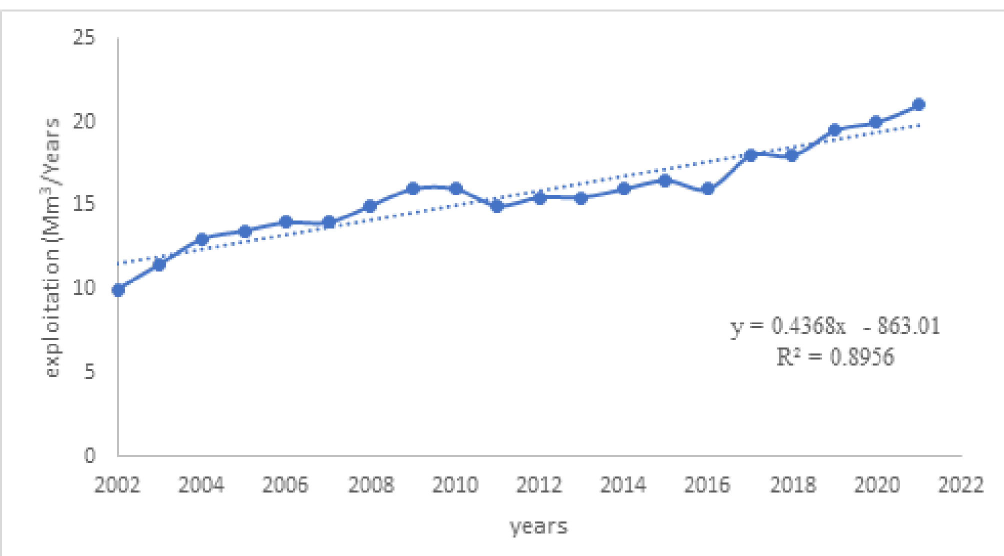


Figure 4

Evolution of the exploitation of the shallow aquifer of El Hamma between 2002 and 2021.

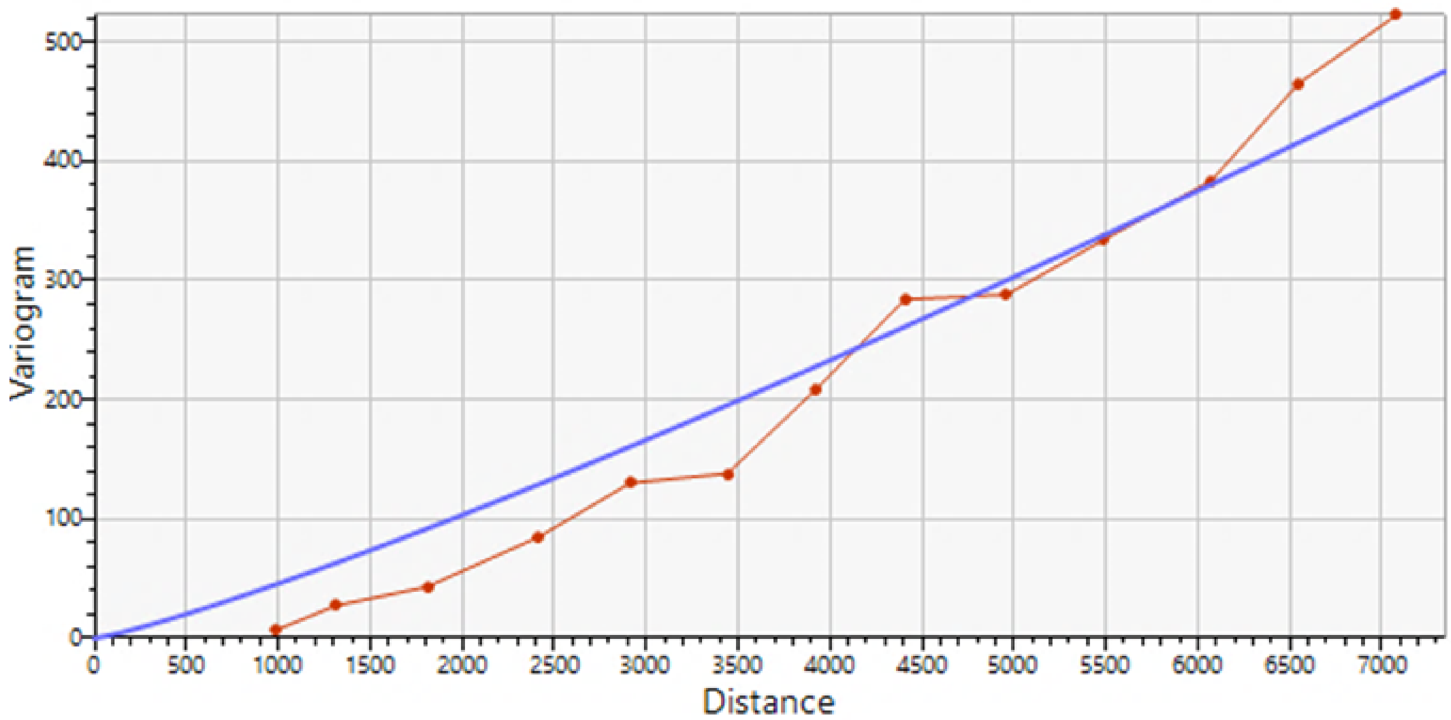
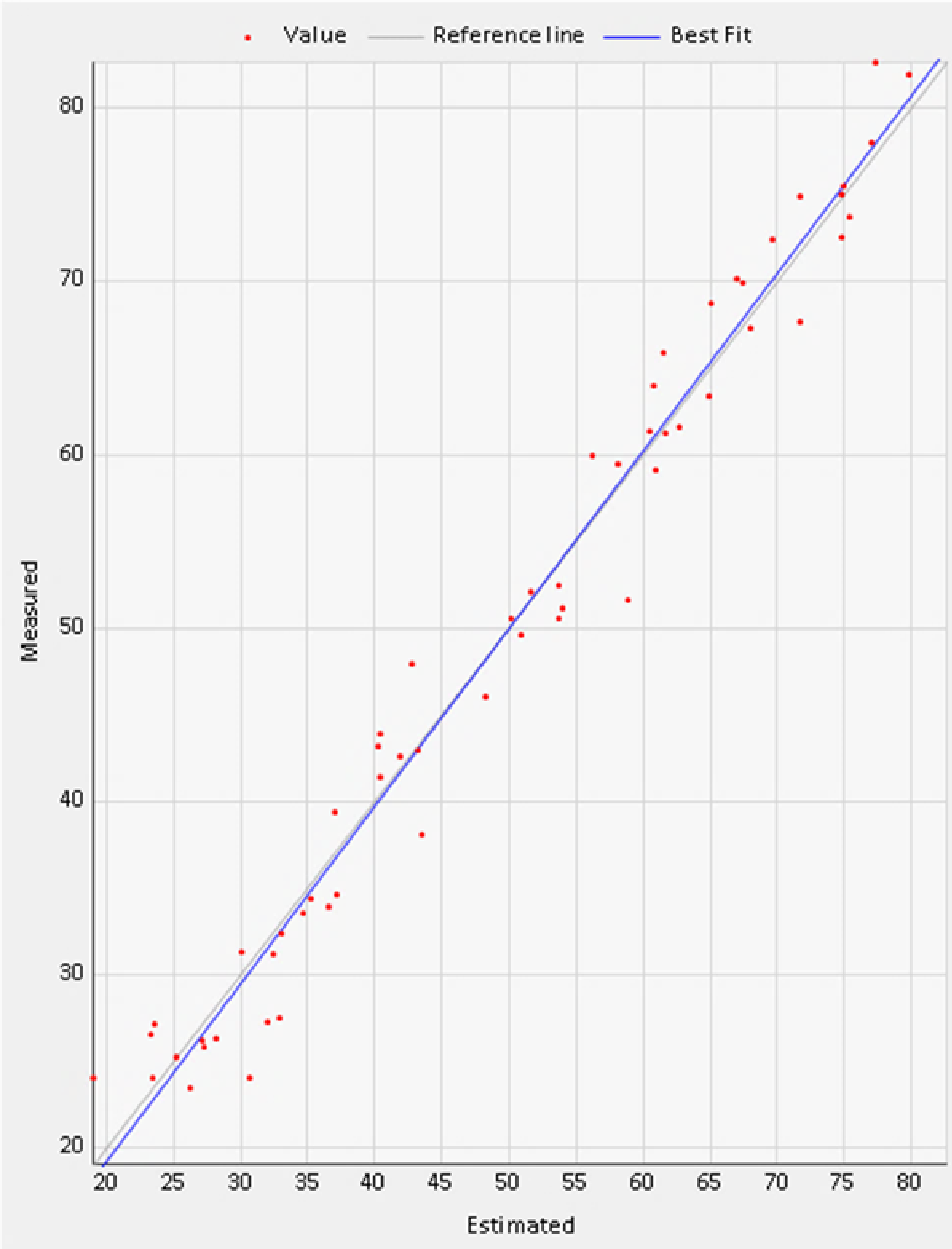


Figure 5

Variable analysis of the piezometric level of the shallow geothermal aquifer of El Hamma. Experimental and fitted variogram (experimental variogram in red, fitted model in blue)



Kriging - Cross Validation

Figure 6

Cross-validation between observed values and model estimates

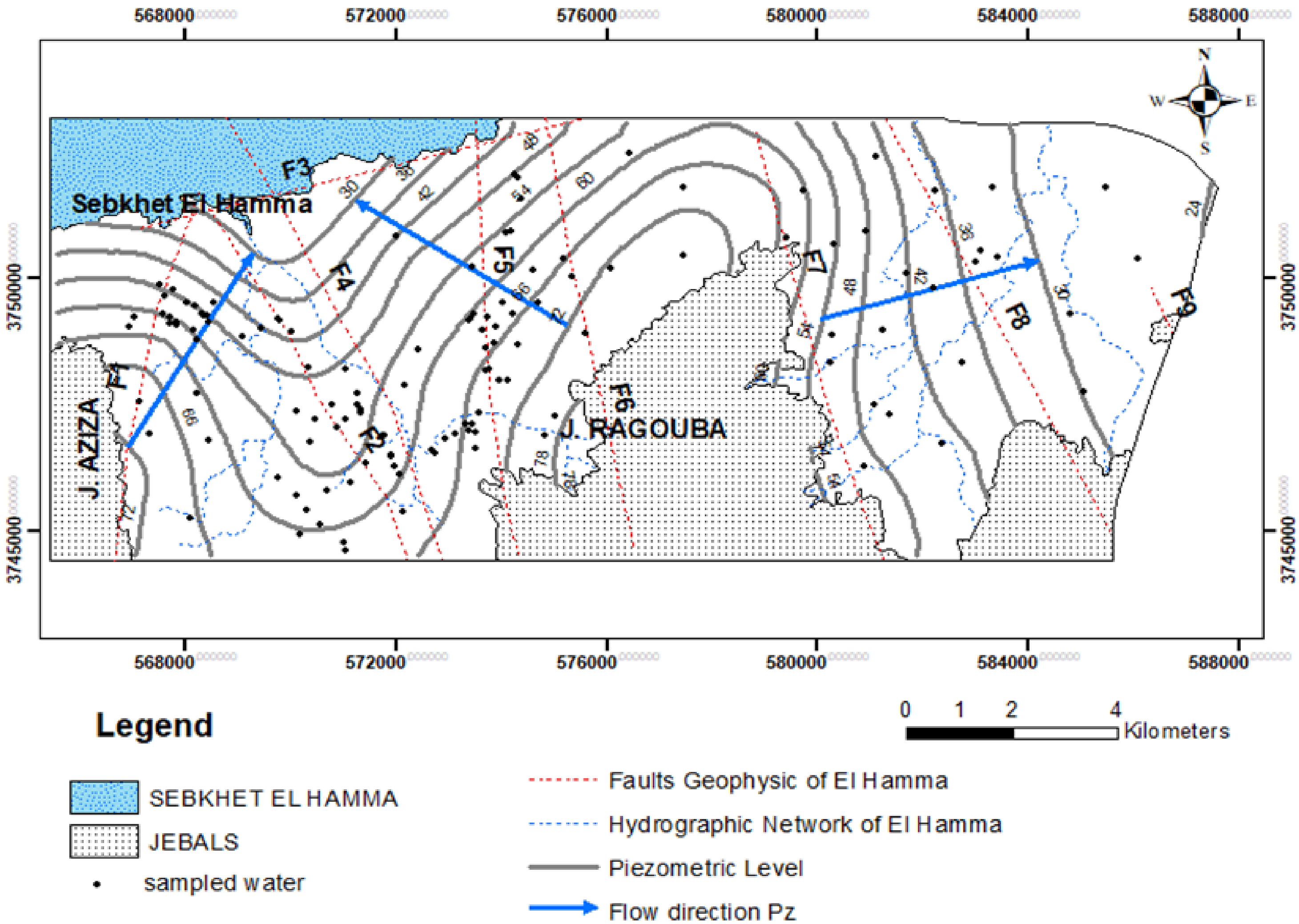


Figure 7

Piezometric map of El Hamma geothermal aquifer

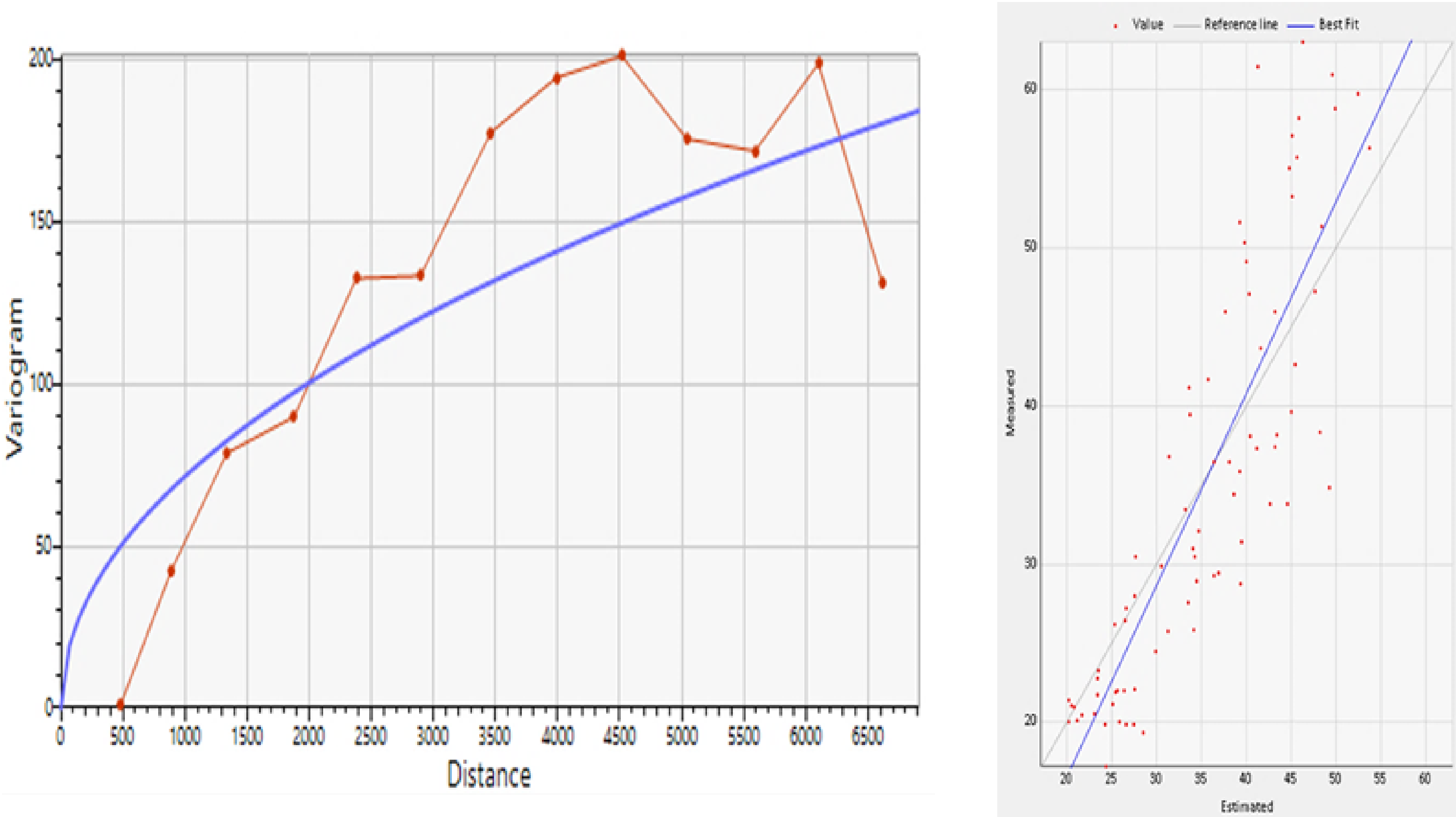


Figure 8

Variable temperature analysis of El Hamma's shallow geothermal aquifer. 1.Experimental and adjusted variogram. 2. Cross-validation between observed values and model estimates.

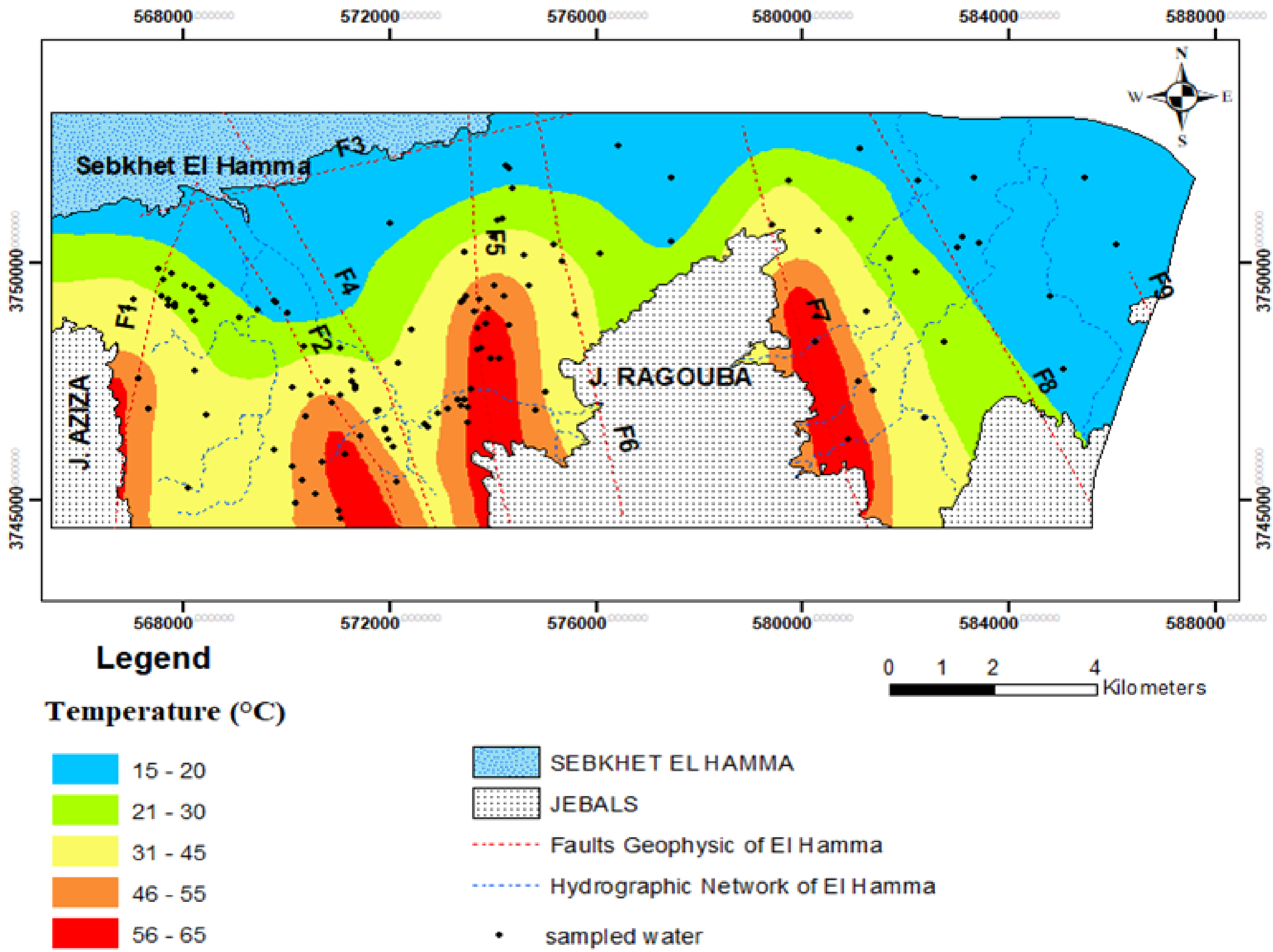


Figure 9

Spatial temperature distribution map of shallow groundwater.

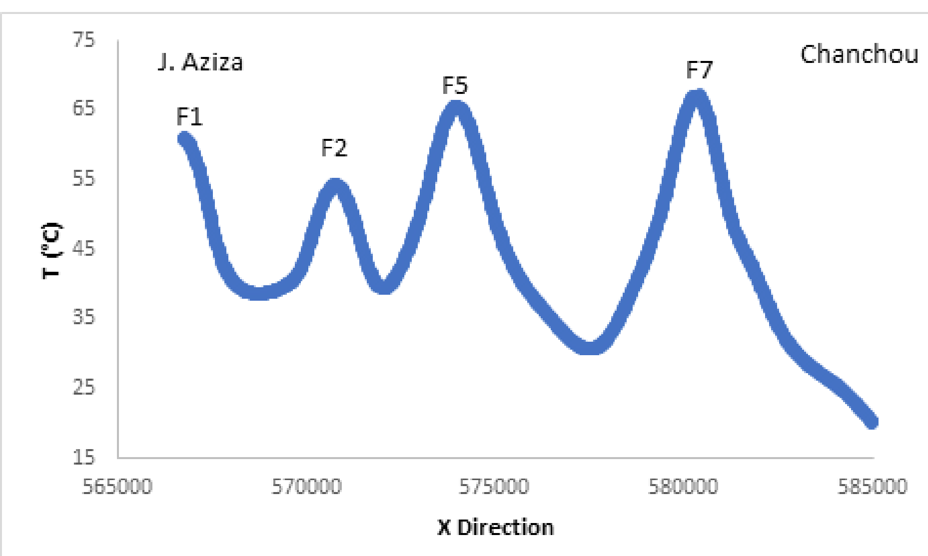


Figure 10

Temperature profile West East (J. Ragouba – Sebkhet El Hamma)

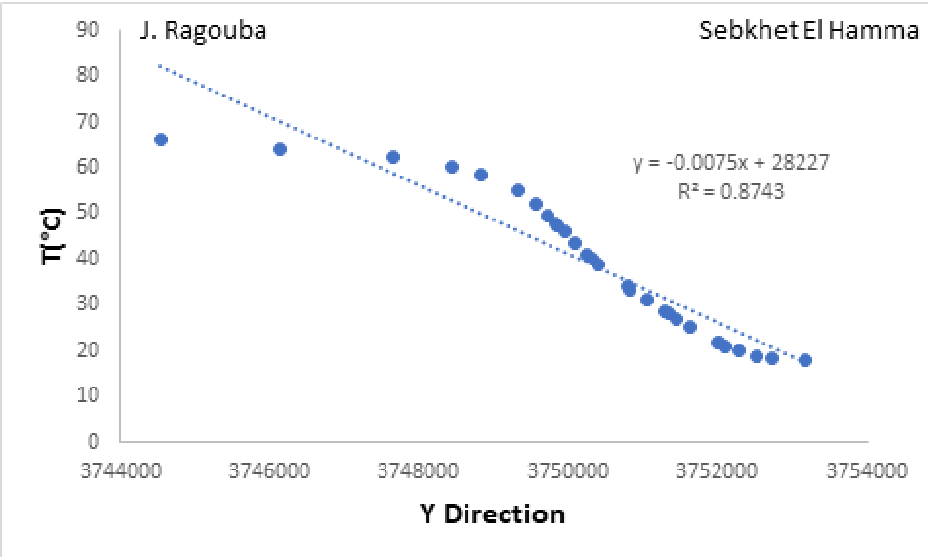


Figure 11

Temperature profile along the axis of the F5 fault (from South to North)

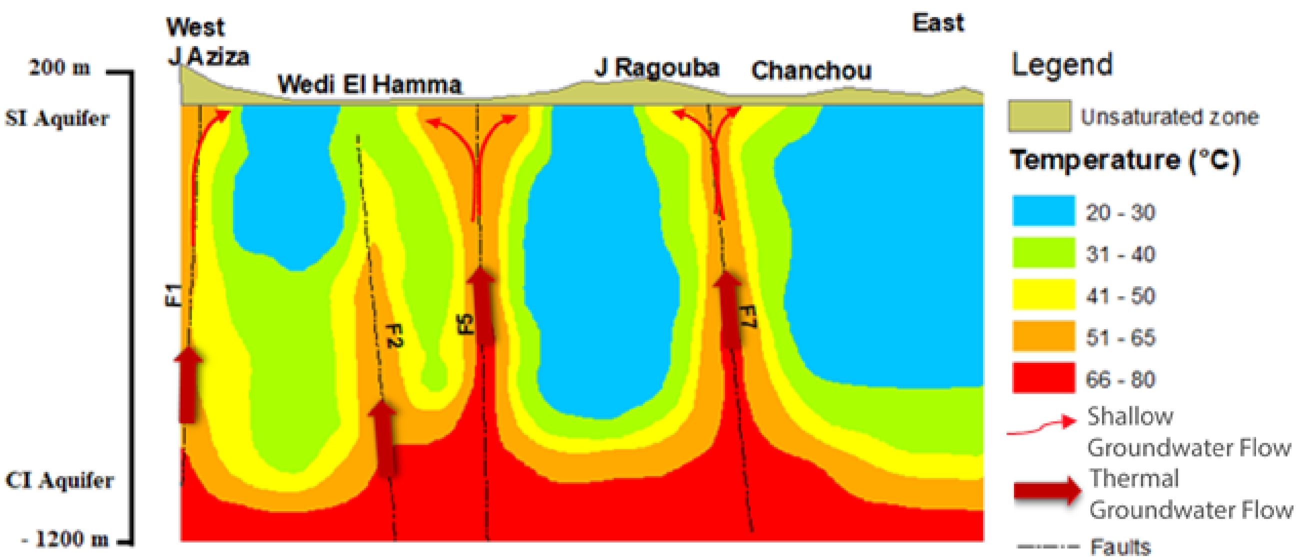


Figure 12

Vertical section of temperature distribution

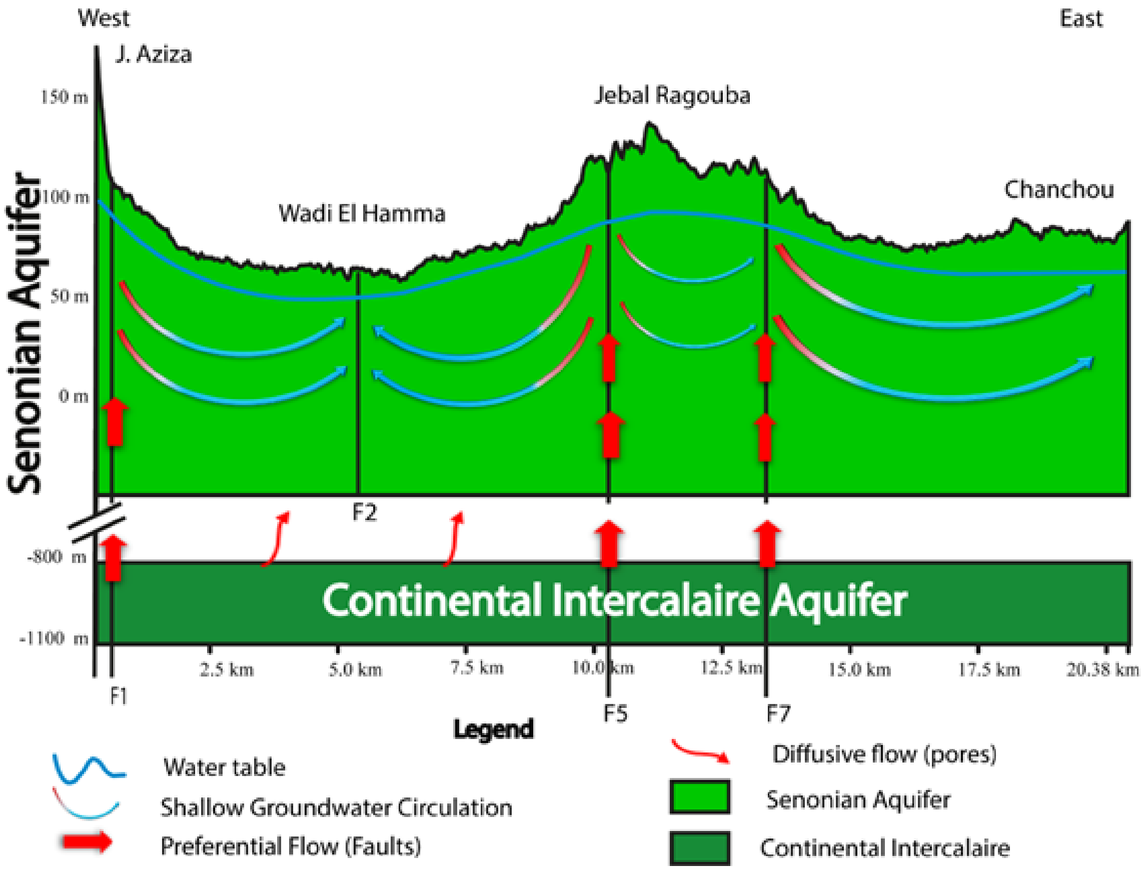


Figure 13

Conceptual hydrodynamic / thermal model of vertical and horizontal flow of geothermal waters