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HEAT SOURCE STUDY AND GEOTHERMAL RESERVOIR ASSESSMENT FOR THE ZARQA MA'IN – DAB'A AREA, CENTRAL JORDAN

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ABSTRACT

The dominant structural feature of Jordan is the north-south trending Dead Sea Rift. It is an active part of the African-Syrian Rift, which extends for about 6000 km, from east Africa through the Red Sea, Wadi Araba, Dead Sea, Jordan Valley to south Turkey. The groundwater aquifers of Jordan are divided into three main complexes: A deep sandstone aquifer complex, an Upper Cretaceous aquifer complex and a shallow aquifer complex. The upper and lower aquifers are separated by more or less impermeable marl and marly limestone of Upper Cretaceous age. Geothermal resources in Jordan can be subdivided into two groups: Natural springs in sandstone rock formations, which are the main sources of geothermal energy of Jordan; and geothermal resources that were discovered during oil and groundwater exploration within the deep aquifers in the eastern deserts and along to the eastern margin of the Dead Sea Rift. The Zara – Zarqa Ma'in thermal springs are considered as the major geothermal manifestations in Jordan due to their high temperatures and flow rates.

Many investigations of the geothermal energy potential in Jordan have taken place over the last four decades. Most of these studies were done for, or directed by the Natural Resources Authority (NRA). Thermal waters of Zara – Zarqa Ma'in have been subjected to many studies regarding their chemistry, heat source, therapeutic properties and their potential as a source of energy. A detailed study has been carried out for the three main deep wells in the Zara – Zarqa Ma'in area in this project and a volumetric geothermal assessment has been done by using the Monte Carlo method, for the area which lies between the Zarqa Ma'in fault and the Dab'a fault based on estimating the total heat stored in a volume of both rock matrix and water in the pores.

1. INTRODUCTION AND PREVIOUS STUDIES

1.1 Location of the study area

Jordan is one of the Middle Eastern countries and has an area of about 90,000 km^2 (Figure 1). It is located in the northwestern part of the Arabian Peninsula and consists of three elongated distinctive

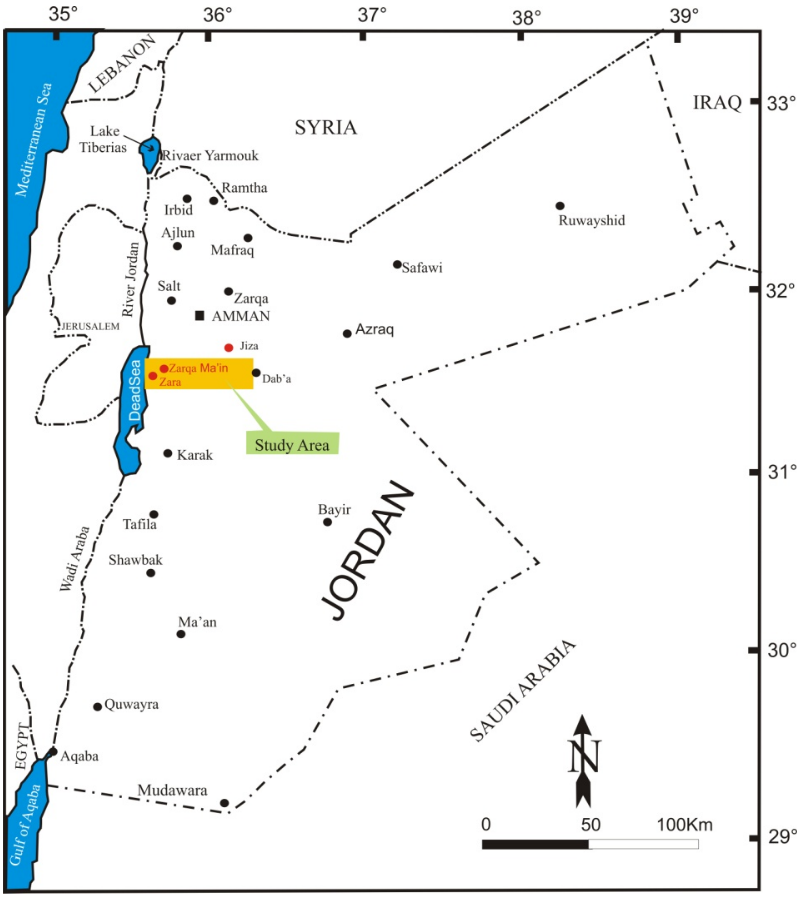


FIGURE 1: Map of Jordan and location of the study area

topographic provinces trending in a general north-south direction. The Rift Floor Province forms the western part of the country. The floor elevation of the Rift rises from sea level at Aqaba on the Red Sea shore to about 240 m above sea level (m a.s.l.) in Wadi Araba, and falls to around 750 m below sea level (b.s.l.) at the bottom of the northern part of the Dead Sea. To the north of the Dead Sea, it rises gradually to about 210 m a.s.l. on the shores of Lake Tiberias (Salameh and Bannayan, 1993). The Highlands Province is located east of the Rift ranging in width from 30 to 50 km. The highlands rise in elevation to more than 1000 m a.s.l. in northern Jordan and to more than 1200 m a.s.l. in the southern part. These elevations drop sharply to the Rift in the west, but gradually towards the Plateau in the east. The Plateau Province is located at the eastern toes of the highlands with a land surface ranging from 1000 m a.s.l. in the south to 700 m a.s.l. in the northeast. The Azraq Basin in the middle forms the deepest part of the plateau with an elevation of 500 m a.s.l.

Jordan lies among the dry and semi dry climatic zones which are characterized by their minimal rainfall and high percentage of evaporation, with a mix of a Mediterranean and dry desert climate. The temperature varies from a few degrees below zero in the winter to around 46°C in the summer season. Annual precipitation ranges from 50 mm in the desert to 600 mm in the northwest highlands. Only nine percent of Jordan's area receives more than 200 mm of rainfall annually. Approximately 92% of the rainfall evaporates, 5.4% recharges the groundwater and the remaining 2.4% becomes surface water.

The geographic area of investigation is Central Jordan, where wells with the highest temperature and the country's main hot springs are located. It extends from Zara hot springs on the eastern shore of the Dead Sea through Zarqa Ma'in thermal springs to Dab'a region in the east and belongs mainly to the Wadi Mujib groundwater catchment which consists of two sub-catchments: Wadi Waleh and Wadi Zarqa Ma'in, with a total area of about 600 km^2. The study area is enclosed between coordinates 200,000–260,000 E and 106,000–116,000 N (PG). The area of possible geothermal interest ranges from the Zarqa Ma'in (63°C) to the Zara (59°C) hot springs at the Dead Sea.

Three of the main topographical units of Jordan are present in the study area: The Rift area in the west, the Highlands in the middle and the Plateau in the east. Therefore, different weather conditions prevail in the area, due to the great differences in elevation (-400 to about 830 m a.s.l.). In the study area intense agricultural activities have developed in recent decades. In the highlands, agriculture is supported by rainfall with major crops of wheat, barley, tobacco, olives and grapes. Vegetables are mainly grown by irrigation in the Zara – Zarqa Ma'in area and in the eastern parts of the study area.

1.2 Geothermal resources

Geothermal resources in Jordan can be subdivided into two groups (Sawarieh, 2005):

1) Natural springs in sandstone rock formations, which form the main sources of geothermal energy in Jordan. Other geothermal resources such as fumaroles, boiling springs and mud pools are not found.
2) Geothermal resources that were discovered during oil and groundwater exploration within the deep aquifers in the eastern deserts and along the eastern margin of the Dead Sea Rift; the main resources of this group are the Shuneh and Mukheibeh well fields.

Most thermal springs are distributed along the eastern escarpment of the Dead Sea Rift that extends from Mukheibeh thermal field in the north to Afra and Burbeitta thermal fields in the south (Figure 2). Most of the springs have temperatures below 45°C, except in two localities where the temperature reaches up to 63°C (Zarqa Ma'in and Zara springs). The temperatures of the thermal water of springs and wells range between 30 and 63°C (Sawarieh and Massarweh, 1996). The springs and wells are currently used for spas recreation, therapeutic purposes and as irrigation water in agricultural activities.

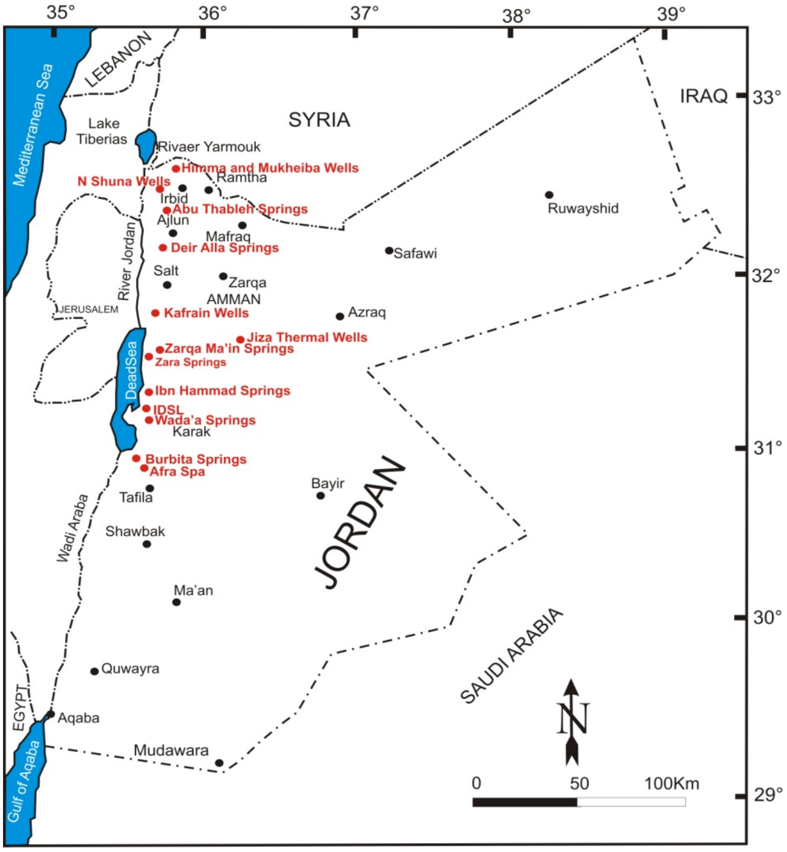


FIGURE 2: Distribution of thermal resources in Jordan (after Sawarieh, 2005)

The geothermal gradient map of Jordan (Figure 3) shows two distinct regions of high geothermal gradients, reaching up to 50°C/km. (Myslil**,** 1988; Sawarieh, 2005). The first region is located in the vicinity of the east Dead Sea escarpment, where many springs discharge thermal water originating from the Lower Cretaceous sandstone. The second one is near the border with Syria and Iraq. In this region several thermal wells discharge water from the Upper Cretaceous limestone.

The Zara – Zarqa Ma'in thermal springs are considered the main geothermal manifestations in Jordan due to their high temperatures and flow rates. Away from the Rift, about 30 km east of Zara – Zarqa Ma'in hot springs, many wells were drilled into the upper aquifer (<350 m depth) in the last three decades, mainly by the private sector for agricultural purposes. Most of these wells discharge thermal water with temperatures up to 46°C despite the fact that the upper aquifer is known as a major source of fresh cold water in Central Jordan. This might be due to the presence of many faults, of different trends and types, affecting the study area, especially in the eastern parts (Jiza region) where the hottest thermal wells are located close to some of these faults. This strongly suggests that the two-aquifer systems are hydraulically connected by faults, where the thermal water from the lower aquifer flows upwards to the upper aquifer, raising the water temperature in the vicinity of these faults (Sawarieh, 2005).

Thermal water sources in Jordan are classified as low-enthalpy geothermal sources, therefore, electric power generation is unlikely to be possible, but they are quite suitable for direct use such as for; spas, fish farming, space heating for selected constructions and other direct uses.

This study is focused on the area of thermal springs and deep wells near Zara – Zarqa Ma'in in the west and Dab'a region in the east. The purpose is to assess the heat source, based on the results of the previous studies and by studying temperature and pressure conditions of three deep wells (GTZ-2D, GTZ-4A and GTZ-2D) near the Zara – Zarqa Ma'in springs area. Also, the study aims at providing an initial volumetric geothermal resource assessment for the Zarqa Ma'in – Dab'a area.

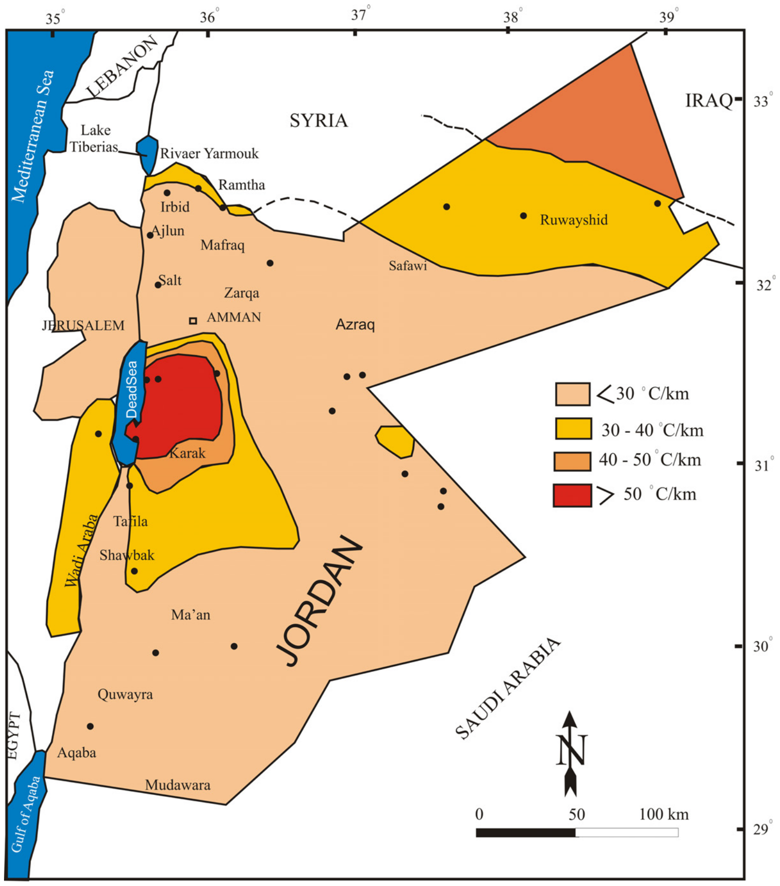


FIGURE 3: Geothermal gradient map of Jordan (after Sawarieh, 2005)

1.3 Previous work on the geothermal anomaly

Several investigations of the geothermal energy potential in Jordan have taken place over the last four decades. Most of these studies were done for, or directed by the Natural Resources Authority (NRA). Thermal waters of Zara – Zarqa Ma'in have been subjected to many studies regarding their chemistry, heat source, therapeutic properties and their potential as an energy source. Only limited work has, however, been done on the thermal wells in the eastern part of the study area; most of these studies are reviewed below.

MacDonald and Partners (1965) carried out the first geothermal investigation in Jordan, which was limited to chemical analyses of the Zarqa Ma'in thermal springs. Bender (1968) described the major and minor spring areas and provided chemical analyses of the Zarqa Ma'in thermal springs. McNitt (1976) reviewed the chemical analyses of the hot spring waters collected by NRA and recommended a geothermal exploration program in the Zarqa Ma'in hot spring field. He also recommended a resistivity survey and drilling to investigate the area. Marinelli (1977) concluded that the east escarpment of the Dead Sea Rift, and particularly the Zarqa Ma'in and Zara area, possessed the most favourable geothermal potential in Jordan and recommended a program for further investigations.
Truesdell (1979) gave a comprehensive evaluation of the geothermal potential based on geochemical evidence. He concluded that the Zarqa Ma'in and Zara springs are fed by waters circulating deep within the Paleozoic Sandstone aquifers, receiving heat from a normal geothermal gradient. He suggested that these waters exist at a maximum temperature of 110°C at depth and are cooled during their ascent and by mixing.

Mabey (1980) studied previous data for the Zarqa Ma'in – Zara area and proposed a program of investigation beginning with an interpretation of magnetic data, then developing a geological model

and undertaking a gravity and geochemical survey. This should be followed by micro-earthquake, thermal gradient, resistivity surveys and finally deep drilling.
Hakki and Teimeh (1981) carried out a detailed geological study of the Zarqa Ma'in – Zara area. Their work related the hottest springs to the highest intensity of shearing in the area.

Salameh and Khudeir (1983) reported on the thermal water system in Jordan and the reservoir temperatures were determined by geothermometers to be around 85°C. Salameh and Rimawi, (1984) studied the isotope content and the hydrochemistry of the thermal springs along the eastern side of the Dead Sea Rift, including those of Zara and Zarqa Ma'in. Salameh and Udluft (1985) studied the Zara – Zarqa Ma'in thermal springs and presented a flow model showing the hydrodynamic pattern of the central part of Jordan, where the groundwater flow in the upper aquifer towards the east while it flows towards the west in the lower aquifer system.

In 1985, based on the results of thermal gradient logs, Kappelmeyer (1985) proposed a 1000 m well in Zarqa Ma'in area to investigate geothermal conditions below the Kurnub sandstone. In late 1985, the NRA drilled well number GTZ-4A. The well was drilled to 407 m and a bottom hole temperature of 46°C was recorded, indicating a temperature gradient of 52.8 °C /km. Galanis et al. (1986) concluded that the heat flow in the Zarqa Ma'in – Zara area is high (up to 472 mW/m^2) and that the area of highest heat flow is associated with the Zarqa Ma'in fault zone rather than the local basaltic eruptions. In 1986, a French company (EnerSystem,1986) concluded that medium enthalpy (140-160°C) geothermal energy could be utilized in Jordan and proposed a pre-feasibility study, followed by the drilling of two deep slim boreholes to 1500-2000 m.

Duffield et al. (1987) studied the age, chemical composition and geothermal significance of Cenozoic basalt near the Jordan Rift Valley. The study showed that the lavas were too old and of too small volume to represent the surface expression of an active reservoir of magma within the crust.

Between 1987 and 1988, the Strojexport Company drilled two deep wells at Zarqa Ma'in – Zara area (Trimaj, 1987). Well GTZ-2D was drilled to a depth of 1314 m. A bottom hole temperature of 68.8°C was determined with a temperature gradient of 55°C /km down to around 300 m, falling to around 10-15°C/km between 400 m and the bottom of the well. Well GTZ-3D was drilled to a depth of 1100 m; the maximum measured temperature in the well was 55.4°C at the depth interval of 242.5-318.5 m, which lies in the Triassic sandstone of the Zarqa Group.

Myslil (1988) re-evaluated the heat flow data presented by Galanis et al. (1986) and included recent data and presented temperature gradient maps and identified two favourable zones for future exploration. The most favourable area was the eastern escarpment of the Dead Sea Rift, north of El-Lisan where gradients of 50°C /km could be expected. The second area was the region near the border with Syria and Iraq where temperature gradients of the order of 40°C/km were identified. Based on hydrogeological and hydrochemical data from the thermal wells near Queen Alia Airport, Sawarieh (1990) concluded that there is mixing between the thermal water of the lower deep sandstone aquifer and the fresh cold water of the upper limestone aquifer (B2/A7). Dermage and Tournage (1990) reported also on the potential and uses of the geothermal resources in Jordan.

Sawarieh and Massarweh (1996) studied the thermal springs in the Zara and Zarqa Ma'in area. The conclusion of the study was that the heat source in the Zara – Zarqa Ma'in area seemed to be due to deep circulation of water in a more or less normal geothermal gradient. Saudi (1999) used Sawarieh's (1990) data and concluded that the maximum reservoir temperature predicted by calculation of various geothermometers exceeds 100°C. In the years 2001-2003, the NRA conducted a study on the shallow thermal wells in the Jiza region. In the course of this project, geological, hydrogeological, hydrochemical and geophysical investigations were made. The main outcome of this work was that the thermal water in the area was a result of a mixing process between different types of water (meteoric origin) and the highest temperature predicted by using a mineral saturation index for the deep aquifer was about 115°C.

Sawarieh (2005) presented a PhD thesis on a detailed hydrogeological and hydrochemical study on the thermal water in Central Jordan. The study concluded that the thermal water in shallow thermal wells in the Jiza region resulted from mixing between the thermal chloride water of the lower aquifer with the bicarbonate water of the upper aquifer via conduits (faults), raising water temperature in the vicinity of these faults.

During 2004-2005, a joint venture project was carried out by West Japan Engineering Consultants, Inc. and GeothermEx, Inc., USA to evaluate all the available data and information related to the geothermal fluids in Jordan. Their study was based mainly on the available data from NRA and Sawarieh's studies and concentrated on the shallow thermal wells in central Jordan. The study presented a model referring the presence of the thermal water in the shallow wells in central Jordan to local convection within the upper aquifer without any mixing with the lower aquifer water.

2. GEOLOGICAL SETTING

2.1 Overview of the geology of Jordan

The dominant structural feature in Jordan is the north-south trending Dead Sea Rift. It forms an active part of the African-Syrian Rift, which extends for about 6000 km, from East Africa through the Red Sea, Wadi Araba, Dead Sea, and Jordan Valley to South Turkey (Burdon, 1959).

In the Miocene, the Arabian plate separated from the African plate and continued its movement to the north, creating the transverse fault system in the Miocene-Pliocene. This system was accompanied by a group of tensional faults trending NW-SE, dextral shears trending E-W and compressional structures trending NE-SW; then the Dead Sea Rift was created. It trends nearly N-S and extends from the Gulf of Aqaba to south Turkey with a total length of 1100 km. It consists of two faults: The southern fault, the Risha or Wadi Araba Fault, and the northern Fault, the Jordan Valley Fault. The Wadi Araba Fault extends from the Gulf of Aqaba to the Risha area in the middle of Wadi Araba and extends to the Dead Sea basin along its eastern shore, ending at its northeast corner. The Jordan Valley fault starts in the southwest part of the Dead Sea and continues to the north along its western shore to the east of Tiberias Lake (Quennell, 1956; Freund et al., 1970). Many faults with different trends and ages have developed. The different trends are due to different stress fields resulting from different tectonic movements at different times (Figure 4).

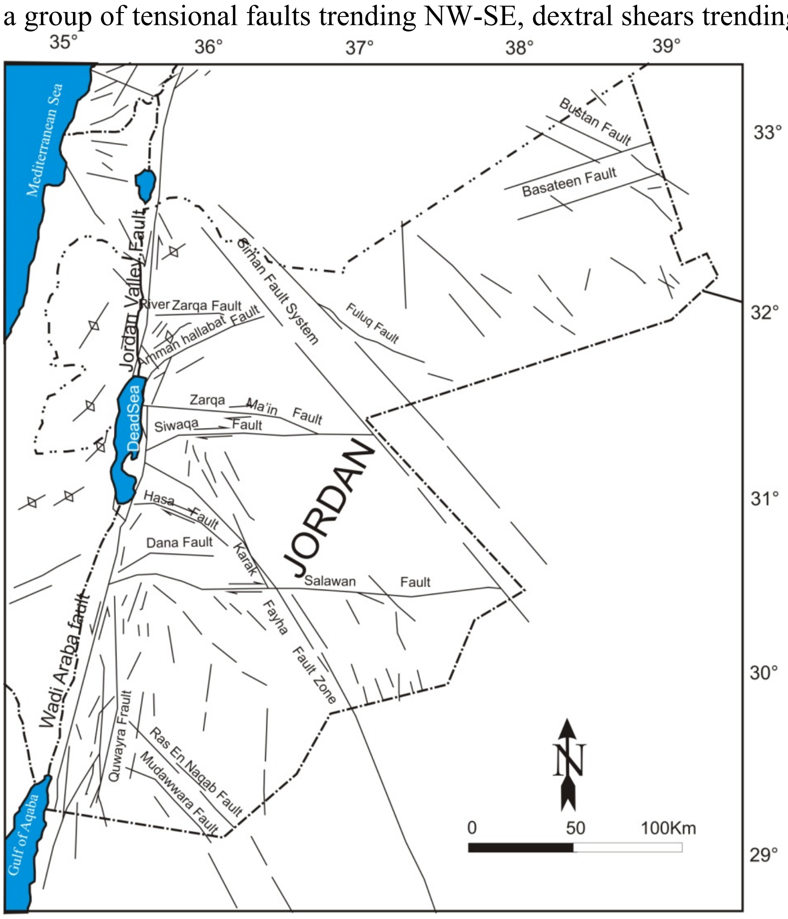


FIGURE 4: The structural map of Jordan (modified from Diabat and Masri, 2002)

The main fault trends are N-S sinistral strike-slip faults, E-W dextral strike-slip faults, NW-SE tensional faults and NE-SW compressional faults. The intersection of the fault systems has acted locally as conduits for the Neogene-Pleistocene basaltic intrusions and flows. Several of the E-W faults are traceable for tens of kilometres from the Rift inside the country. Examples are: Siwaqa Fault, traceable for about 150 km (Masri, 2002) and the Zarqa Ma'in fault, traceable for about 50 km (Abu Ajameih, 1980). The offset along these faults generally decreases eastward where they are associated with or merge into monoclinal flexures.

Sedimentary rocks cover almost the whole area of Jordan with a thickness of more than 5000 m in the Azraq Basin. The Precambrian basement rocks are only exposed in the southwest part of the country (Aqaba region). According to Bender (1974) the sedimentation began in Late Pre-Cambrian with the deposition of the Saramuj conglomerates. During the Cambro-Ordovician, the Salib sandstone, Burj Dolomite shale, Umm Ishrin, Disi and Umm Sahm sandstones (Ram group) were deposited throughout Jordan and northwest Saudi Arabia. Then the Khrayim group (silty sandstone series) of Ordovician-Silurian age was deposited during the major marine transgression, which occurred from Lower to Middle Ordovician up to lower Devonian. In North Jordan, the alteration of transgressions and regressions during Triassic and Jurassic resulted in the deposition of the Zarqa complex. From Cretaceous to Eocene the whole country was covered by an extensive marine transgression which caused the deposition of the Kurnub, Ajlun and Belqa groups. In the Upper Eocene, the sea regressed and a period of erosion began which lasted to the present day. This period has been characterized by volcanic activity resulting in extensive basalt flows mainly in northeast Jordan and extended to Syria and Saudi Arabia, and, by localized lacustrine and fluviatile deposits, in the Azraq and Jafer basins as well as the Rift Valley. Table 1 summarises the main lithological sequences found in Jordan.

2.2 Structural setting of the study area

The main structural element governing the morphology, hydrology and hydrogeology of Jordan is the Rift fault zone, which trends nearly N-S and extends southwards beyond the Gulf of Aqaba into the Red Sea and northwards through Lebanon into Turkey (Figure 5).

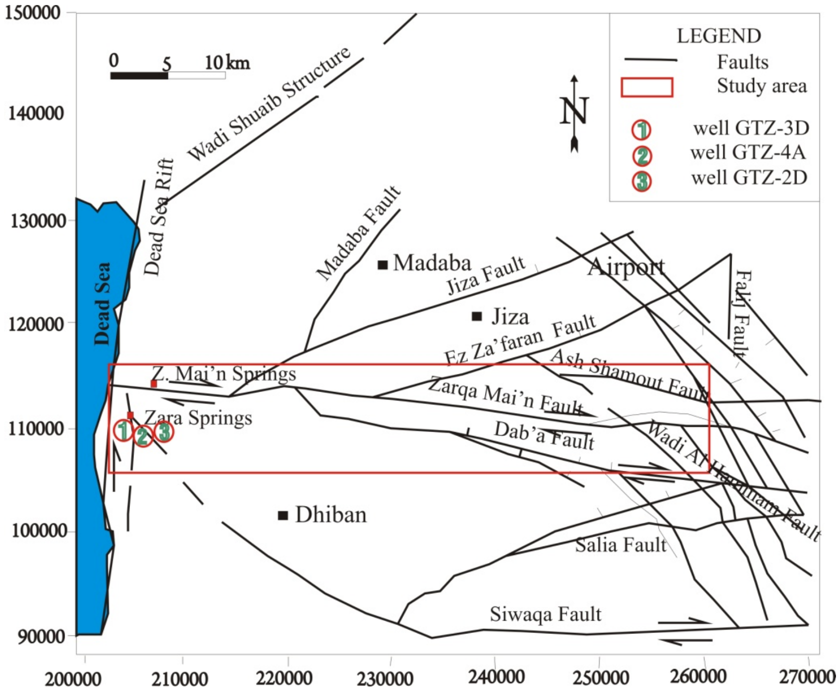


FIGURE 5: Major faults in the study area and locations of deep wells (after Sawarieh, 2005)

Away from the Dead Sea Rift, the geological units generally dip very gently, up to three degrees, to the east-northeast. Local disturbances have occurred adjacent to the main faults. Along the slopes bordering the Dead Sea the area is highly block faulted, resulting in random strikes and dips of the tilted blocks. The area shows flat undulations and is intersected by a network of numerous fault trends of different behaviour and displacement. The dominated structures in the area are the E-W, NE-SW, NW-SE and N-S faults associated with faulted blocks as horsts, grabens and tilted blocks.

TABLE 1: Lithological sequences in Jordan (compiled from NRA open files)

Period	Age	Group	Formation	Lithology
Quaternary	Holocene (Recent)		Fan, talus, terrace, river	Sand, clay, gravel
	Pleistocene	Jordan Valley	Lisan ??	Marl, clay, gypsum, sand, gravel
Tertiary	Pliocene Miocene Oligocene		Undifferentiated	Conglomerate, marl
	Eocene Paleocene	Belqa	Wadi Shallala (B5) Umm Rijam (B4)	Sandstone Chert, limestone
Upper Cretaceous	Maestrichtion Companion Santonian		Muwaqqar (B3) Al Hasa (B2a) Amman (B2b) W. Ghudran (B1)	Chalk, marl Phosphate Silicified limestone Chalk, chalky marl
	Turonian Cenomanian	Ajlun	Wadi Es Sir (A7) Shueib (A5-6) Hummar (A4) Fuheis (A3) Na'ur (A1-2)	Limestone Marly limestone Dolomitic limestone Marl Marly limestone
Lower Cretaceous	Albian Aptian Neocomian	Kurnub	Kurnub sandstone	White sandstone, dol. Varicoloured sandstone Lst., shale, marl, dol.
Permo-Triassic		Zarqa	Dardur Ma'in Umm Irna	Sandstone, marl, shale Sandstone, silt, caly Sandstone, siltst., shale
Silurian Ordovician		Khryim	Khushsha Mudawwara Dubaydib Hiswah sandstone	Sandstone, shale Sandstone, sahe, mud Sandstone, shale Mudstone, sandstone
Ordovician Cambrian		Ram	Umm Sahim Disi Umm Ishrin Burj dolomite Salib	Sandstone Sandstone Sandstone, siltstone Shale, dol, sandstone Sandstone, siltstone
Pre-Cambrian		Safi	Saramuj conglomerates	Conglomerates

2.3 Major faults

The study area is dissected by numerous faults with several trends, due to different strain patterns, which probably originated in the Precambrian and early Paleozoic. The faults have been covered by Paleozoic and Cretaceous sediments. The different trends are due to different stress fields resulting from the different tectonic movements at different times, from the Late Cretaceous to Tertiary and Quaternary. The main fault trends are E-W dextral strike-slip faults, NW-SE tensional faults and NE-SW compressional faults (Diabat and Masri, 2002):

E–W trending faults:
The E-W trending faults originated as normal faults during the creation of the Transverse Fault System in Miocene; then they reactivated as strike-slip faults during the creation of the Dead Sea Rift in Mid Miocene-Pleistocene. This fault trend dissected the study area into four regional blocks, trending E-W. The Zarqa Ma'in, Daba'a and Siwaqa faults are the major faults of this trend (see Figure 5).

Zarqa Ma'in fault. This is the most important structural feature in the study area. The fault strikes E-W and can be traced eastwards for a distance of 50 km from the Dead Sea. The fault originated as a normal fault and was reactivated during later stages as dextral shear. This is evidenced from the presence of the horizontal slickenside on the fault plane, the variation of down throw on both sides of the fault, and the presence of the compressional and tensional structures on the left and right bands of the fault, respectively (Diabat and Masri, 2002). In Wadi Zarqa Ma'in, the down faulted Na'ur formation (A12) on the southern side stands against the Kurnub sandstone on the northern side of the wadi where all the thermal springs are located as typical fault contact springs. Volcanic activities took place during the Neogene age, caused intrusions along the fault system and formed the volcanic cone of Hammamat Umm Hasan, which stands as a high peak opposite to Hammam El Amir thermal spring.

Dab'a fault. This fault branches from the Zarqa Ma'in fault in a WNW - ESE direction and extends for more than 75 km in the study area with a down throw of about 50 m in a north-northeasterly direction. It could be of a dextral strike-slip nature accompanied by transtensional and transpressional structures (Diabat and Masri, 2002).

NE-SW trending faults
Ez Za'afaran fault branches from the Zarqa Ma'in fault and extends for about 30 km in the study area. It started as normal fault with vertical displacement of more than 150 m in areas near the desert highway (Al Hunjul, 1995). The fault was then reactivated to a dextral strike-slip nature and demonstrated transpressional structures and elongated compressional hills parallel to the fault (Sawarieh, 2005).

Jiza and Madaba faults branch from the Zarqa Ma'in fault. The Jiza fault extends from south Madaba city through Jiza town to Queen Alia International Airport. Over most of its extension it is covered by superficial deposits.

2.3 Folding

The folding in the study area is of three types: gentle folding associated with regional compression, folding occurring adjacent to the faults, and folding directly associated with drag during faulting and folding in interference structures caused by the interaction of E-W and NW-SE faulting influences. Dips across the fault blocks, which are presumed to be away from edge structures, are predictably moderate with most beds-strikes aligned sub-parallel to the major fault trends. These structural features illustrate that the faulting and folding are in all cases closely associated and have been generated in response to the same stress system (Diabat and Masri, 2002). A major folding feature in Zarqa Ma'in area is the Wadi Zarqa Ma'in syncline, which plunges westwards. The axis is approximately along the wadi and parallel to the Zarqa Ma'in Fault. The syncline can be traced to a location one km northeast of Muleih village in the southern part of the study area. There are several prominent domal structures, which also form topographical heights scattered throughout the study area.

3. OVERVIEW OF JORDAN'S GROUNDWATER RESOURCES

The groundwater aquifers of Jordan are divided into three main complexes:

- Deep sandstone aquifer complex.
- Upper Cretaceous aquifer complex.
- Shallow aquifer complex.

3.1 Deep sandstone aquifer complex

This complex forms one unit in southern Jordan. To the north, gradually thickening limestone and marls separate it into two aquifer systems which, nonetheless, remain hydraulically interconnected (Salameh and Bannayan, 1993).

Disi group aquifer (Palaeozoic):
In the north, this is the oldest aquifer, and the deepest water-bearing sediment sequence in Jordan, consisting of sandstones and quartzite. It crops out only in the southern part of Jordan and along the Wadi Araba - Dead Sea Rift Valley. It underlies the entire area of Jordan. The southern part of the complex forms the fresh water aquifer of the upper Wadi Yutum - Disi-Mudawwara area. The main flow of the groundwater in this system is directed in a northeast direction. Only in the southern parts, where a groundwater divide in the Rum area separates a small southern region, so the groundwater moves towards the west and south.

Kurnub and Zerka group of Jurassic-Lower Cretaceous age:
This is also a sandstone aquifer underlying the area of Jordan and overlying the Disi group aquifer. It crops out along the lower Zerka River basin and along the escarpment of the Dead Sea, in the Wadi Araba and Disi region. Wells drilled in this fine-grained sandstone aquifer have fairly good yields. Direct recharge, however, is limited to small outcrop areas. The groundwater in this aquifer, aside from the recharge areas, is mineralized. The Kurnub - Zerka aquifer system is being exploited mainly in the lower Zerka River catchment and in the Baq'a areas. The direction of groundwater flow in this aquifer system is towards the northeast in the southern part of Jordan, towards the west in Central Jordan and towards the southwest in northern Jordan (Salameh and Udluft, 1985). The sandstone aquifer complex (Disi and Zerka/Kurnub) is interconnected through the Khreim group and is regarded as one basal aquifer and hydraulic complex.

3.2 Upper Cretaceous hydraulic complex

This complex consists of an alternating sequence of limestones, dolomites, marlstones and chert beds. The total thickness in Central Jordan is about 700 m. The limestone and dolomite units form excellent aquifers. The lower portions of this sequence (A1/2) consist of about 200 m of marls and limestone that possess, in some areas, relatively high permeabilities and form a potential aquifer. An aquitards (A3), made up of about 80 m of marl and shale, overlies the A1/2 and separates it from the overlying A4 aquifer. The latter consists of pure semi-crystalline karstic limestones and hence has very high permeability and porosity. The A4 aquifer crops out along the highlands and is recharged there. To the east, this aquifer is confined by the overlying aquitard consisting of marls and limestones (A5/6).

The A5/6 aquitard is overlain by the most important aquifer of the sequence, namely the Massive Silicified Sandy Units A7-B2, which is made up of limestones, chert-limestones, sandy limestones and marly limestones. It crops out along the highland and is recharged there. To the east, like the A4 aquifer, it goes over a confined aquifer, overlain by layers of marls.

The whole aquifer complex is overlain in the eastern desert by a thick marly layer (B3), forming a competent confining bed. Therefore, in some locations, flowing artesian wells are drilled into this aquifer. The groundwater flow in this complex is directed from the recharge mounds in the eastern highlands, partly to the western escarpment within the faulted blocks and mainly to the east, where it discharges along deeply incised wadis or flows further eastwards. Along its way to the east, a part of the water seeps to the underlying sandstone aquifer complex, and the other parts appear in Azraq and Sirhan basins as spring discharges (Salameh and Udluft, 1985).

3.3 Shallow aquifers hydraulic complex

This complex consists of two main systems:

The basalt aquifer:
Basalts extend from the Syrian Jabel Druz area southward to the Azraq and Wadi Dhuleil region, forming a good aquifer of significant hydrogeological importance. The recharge to this aquifer system is provided by precipitation in the elevated area of Jabel Druz. From there the groundwater moves radially in all directions. Geological structures favoured the formation of three main discharge zones namely, the upper Yarmouk River basin, the Wadi Zerka basin and the Azraq basin. (Salameh and Bannayan, 1993)

Sedimentary rocks and alluvial deposits of Tertiary and Quaternary ages:
These rocks form local aquifers partly overlying the previously mentioned aquifer complexes or are separated from them by aquitards. They are distributed all over the country, but are mainly concentrated in the eastern desert, Wadi Araba - Jordan Valley, Jafr Basin and the Yarmouk River area.

Recharge takes place directly into these aquifers or via the underlying basalt aquifer, as in the case of the Azraq basin, or from the surrounding aquifers, like the Jordan and Wadi Araba valleys. The groundwater flow in this system, in the eastern desert, is directed radially towards the Azraq oasis and towards El-Jafr from the west and south of the Jafr basin. The groundwater flow in the main valley fills depends on the underground conditions. But it mainly takes place from the escarpments in the valley deposits.

3.4 Groundwater basins

Groundwater basins or groundwater balance areas are those areas which can be separated and defined to include appropriate and regionally important aquifer systems. The groundwater divides are either aquifer limits or important and relevant geomorphologic or geologic features. Groundwater basins in Jordan are also separated according to the same criteria, with some of these basins' recharge and discharge taking place within the same basin. In most basins more than one aquifer complex is present and, hence, any definition of groundwater basins should refer to a certain aquifer system and not necessarily to all aquifer systems underlying the basins.

4. HYDROLOGY OF THE STUDY AREA

4.1 Introduction

The study area extends from Madaba in the north to Wadi Mujib in the south. The Dead Sea forms the western boundary, while the surface water divided between Mujib and Azraq basins is the eastern border of the area. The study area drains westwards to the Dead Sea via two major wadis, Wadi Zarqa Ma'in and Wadi Waleh and their numerous tributaries. The tributaries are dry except for a short period after rainfall. Perennial base flow is seen only on the lowest sections downstream of Wadi Waleh/Heidan and on the lowest parts of Wadi Zarqa Ma'in from a short distance east of the Zarqa Ma'in thermal springs. The base flow in the two wadis is derived from a number of springs and seepages, there are more than 100 springs and many seepages along the lower reaches of Wadi Zarqa Ma'in. Most of these are thermal water discharge outlets with temperatures ranging from 30 to 63°C.

4.2 Hydrogeology of the study area

The study area consists of two sub-catchments; Wadi Waleh, which forms the northern third of the Wadi Mujib groundwater catchment and Wadi Zarqa Ma'in to the northwest of Wadi Waleh sub-catchment. The Paleozoic, Mesozoic and Cenozoic sedimentary rocks with some basic intrusions underlie the area. The Mesozoic sequence, especially the Cretaceous carbonate sedimentary rocks, is dominant in the study area with a thickness of about 1000 m. The Middle to Lower and the pre-Cretaceous sedimentary and intrusive rocks crop out along the valley slopes in the lower reaches of Wadi Waleh and Wadi Zarqa Ma'in. The Tertiary carbonate rocks are found in the eastern parts of the area. Pleistocene basalt flows associated with plugs, cones and vents are present in the lower reaches of Wadi Zarqa Ma'in. The Paleozoic to Cenozoic sedimentary rocks in the basin generally have the structure of monoclinal flexure at low angles, disturbed by faults. The major trending E-W fault is the Siwaqa fault zone just at the border of the southern edge of the study area. It bisects the groundwater in Wadi Mujib catchment into two parts; the southern and northern parts are of interest of this present study. Within the study area, the Zarqa Ma'in fault zone is the major E-W trending fault (Sawarieh, 2005).

4.3 Aquifers

The Mesozoic sediments in Jordan form a sequence of aquifers and aquitards (see Table 2). Therefore, this sequence in the study area is grouped into two major aquifers, the upper aquifer (B2/A7) and the lower aquifer (the sandstone of the Kurnub and older ages), and one major aquitard (A1-6), which separates these two major aquifers.

TABLE 2: Aquifers and aquitards within the lithological section of the study area (Sawarieh, 2005)

Age	Group	Formation	Hydrogeology
Tertiary	Belqa, 350 m	B4: Umm Rijam B3: Muwaqqar chalk-marl	Aquitard
Upper Cretaceous		B2b: Al Hasa phosphorite B2a: Amman silicified limestone B1: Wadi Umm Ghudran	Upper aquifer
	Ajlun, 500 m	A7: Wadi es Sir	
		A5-A6: Shueib A4: Hummar A3: Fuheis A1-2: Na'ur	Aquitard
Lower Cretaceous	Kurnub, 220 m	K: Kurnub	Lower aquifer
Permo-Triassic	Zarqa, 170 m	Dardur sandstone Ma'in sandstone Umm Irna sandstone	
Middle to upper Cambrian	Ram, 250 m	Umm Ishrin sandstone	
Lower Cambrian		Burj dolomite-shale	

4.3.1 The upper aquifer system (B2/A7)

This is the most important and extensive aquifer system in the study area. It is composed of the Wadi Es Sir Formation (A7), including the Khureij Limestone Formation of the Ajlun Group of Turonian age and Wadi Ghudran and Amman Formations (B1 and B2) of the Belqa Group of Campanian age. The B2/A7 materials are limestones, chert-limestones and marl intercalations. The upper part contains phosphatic limestone and silicified phosphate. The middle part (B1) consists of marl and chalky marl and acts as a minor aquitard within the system. But due to its limited lateral extent, the B2 and the A7 are hydraulically connected. The aquifer crops out in the highlands in the western part of the area where rainfall is relatively high. Despite that, it is unsaturated due to the lowering of the potentiometric surface by the Rift and the major wadis deeply intersecting the area. The aquifer thickness ranges from 170 to 327 m. The aquifer is overlain by the Muwaqqar chalk Formation (B3) and the Umm Rijam Limestone Formation (B4) in the eastern parts of the study area, and underlain by thick impervious marl to marly limestone layers of the Shueib Formation (A5-6) all over the study area.

Most of the recharge enters the (B2/A7) aquifer in the structurally high outcrop areas along the western highlands, where rainfall is relatively high, and where the aquifer crops out on the west flank of the mountain blocks of Amman, Madaba and Ma'in. The main outflows from the aquifer are manifested in the form of springs. Most of the large springs that discharge regional flows within Wadi Waleh sub-catchment are located in the lower reaches of the Wadi Waleh/Heidan (Sawarieh, 2005).

4.3.2 The lower sandstone aquifer

The aquifer system includes the Kurnub group sandstone and the Lower Zarqa sandy shale and sandstones together with the underlying Cambrian sandstone. It crops out along the Dead Sea shore and in the lower reaches of Wadi Zarqa Ma'in and Wadi Waleh/Heidan. The thickness of this aquifer system is more than 600 m in Wadi Zarqa Ma'in. The predominant rock constituent is sandstone. But due to the presence of shale and clays, the aquifer becomes extremely complex with many differences in permeability in the lateral and vertical directions. The impermeable zones are of relatively limited lateral extent and individual aquifers within the system are to some extent interconnected. In Zarqa Ma'in area the lower Zarqa shale and clays form a local aquiclude, confining the underlying saturated Cambrian sandstone. This in turn forms a local artesian aquifer in the Cambrian in which the geothermal water is believed to occur. The Zarqa shale and clays are absent in most parts of the study area so the whole sequence can be treated as one hydraulically connected aquifer. The average permeability of the whole aquifer is 4.48×10^{-5} m/s (Salameh and Udluft, 1985).

The lower aquifer sandstones are exposed in the low rainfall areas along the Dead Sea coast. So, direct recharge to the aquifer within the study area is limited to these outcrops and can be neglected. The main recharge to the lower aquifer is the downward leakage from the upper aquifer system in the eastern parts of Jordan. The major outflow from the aquifer is the thermal springs in Zara and Zarqa Ma'in areas (Sawarieh, 2005).

4.4 Aquitards

The Na'ur, Fuheis, Hummar and Shueib formations (A1-6) are the main aquitards which separate the two main aquifer systems in the study area. These aquitards consist of about 400 m of marl and marly limestone intercalated occasionally with limestone bands.

5. SOURCES OF HEAT

5.1 Introduction

Two main hypotheses were presented recently, to define possible heat sources for the high temperatures in Zara-Zarqa Ma'in and Jiza thermal springs and wells or well fields. These are

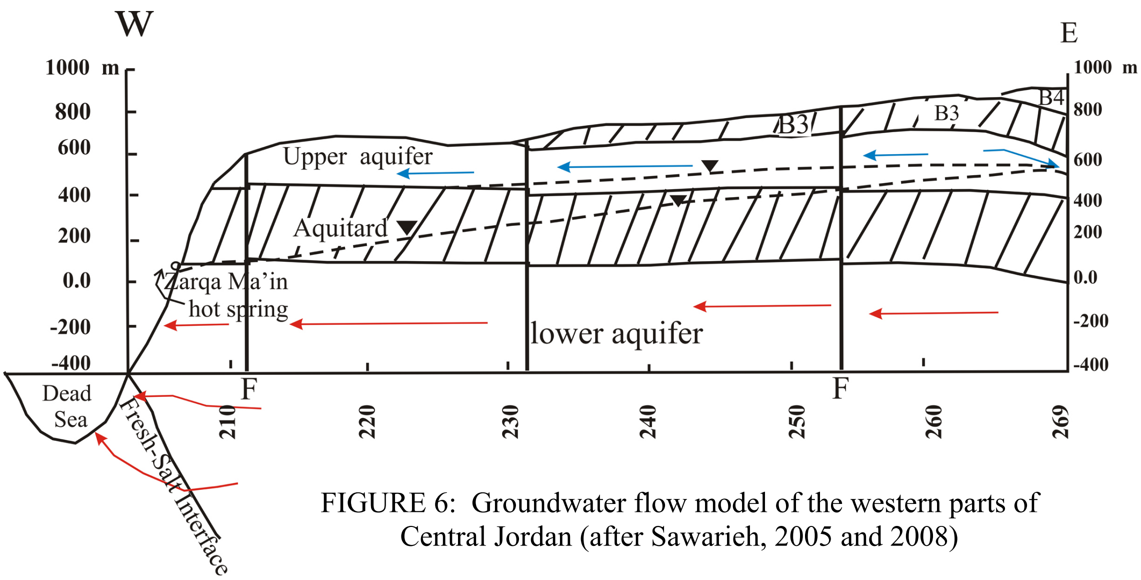


FIGURE 6: Groundwater flow model of the western parts of Central Jordan (after Sawarieh, 2005 and 2008)

summarized in two studies of the area. The first is the detailed hydrogeological and hydrochemical study on thermal water in Central Jordan carried out by Sawarieh (2005). The study concluded that the thermal water in shallow thermal wells in the region results from mixing between the thermal chloride water of the lower aquifer complex with the bicarbonate water of the upper aquifer complex via conduits (faults), which raises water temperature in the vicinity of these faults (Figure 6).

According to this study, there is a hydraulic connection between the two-aquifer systems within the study area. This allows the thermal water from the lower aquifer to flow up via faults (conduits) to the upper aquifer, raising the water temperature in vicinity of these faults. Despite the head differences between the two aquifers, the faulting system may introduce a reverse head around the faults. Also, the water is driven toward the upper aquifer by a gradient caused by the lower density of the water in the hotter parts of the system.

Sawarieh (2005) also used GeoSys/RockFlow modelling software to simulate the water flow and the heat transport in 2D along a vertical cross-section, crossing Dab'a fault. The simulation results (Figure 7) show a clear up-coning effect of warm water at the fault, i.e. higher temperature along the vertical fracture. And the vertical heat transport in the model area without fractures is much less pronounced, which shows the relative importance of heat transport by water movement compared to heat conduction in the aquifer material and stagnant water.

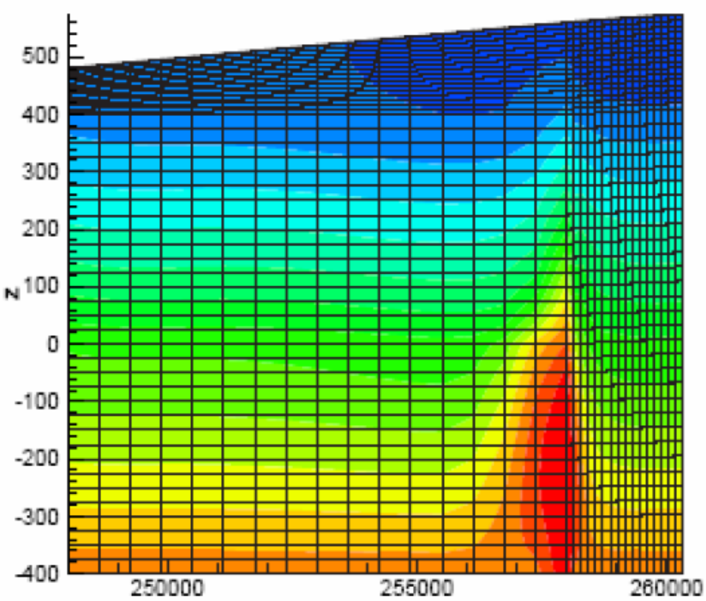


FIGURE 7: Vertical temperature distribution in the aquifer (Sawarieh, 2005)

Sawarieh (2005) estimated the reservoir temperatures by using cation (Na-K and K/Mg) and silica (quartz and chalcedony) geothermometers. The results show a disagreement between all the geothermometer estimations. Therefore, an enthalpy-silica diagram is used for better temperature estimations based on mixing models. The diagram shows that the maximum reservoir temperature in Zara – Zarqa Ma'in is probably about 105°C. It also shows that the estimated reservoir temperature for the thermal wells ranges from 65 to 105°C, depending on the mixing ratio of the lower and upper aquifer. The chemical and isotope analysis (Sawarieh, 2005) carried out, confirmed that the thermal well water is a mixture of two components: bicarbonate water from the upper aquifer and chloride water from the lower aquifer. The location of high Cl concentrations and higher water temperatures along Dab'a and Wadi El Hammam faults suggests that these faults are the main upflow zones of the thermal water.

The second study was carried out during 2004-2005. It was a joint venture project by West Japan Engineering Consultants, Inc. and GeothermEx, Inc., USA to evaluate all available data and information related to the geothermal fluids in Jordan. Their study was based mainly on the available data from NRA and the Sawarieh studies (1990, 2005) and concentrated on the shallow thermal wells in Central Jordan. The study presented a model explaining the presence of the thermal water in the shallow wells in Central Jordan by local convection within the upper aquifer without any mixing with the lower aquifer water. The main recommendation of this study was to drill a deep well in Central Jordan. They considered the basic groundwater flow pattern in the study area which has been outlined by Salameh and Udluft (1985) (see Figure 8).

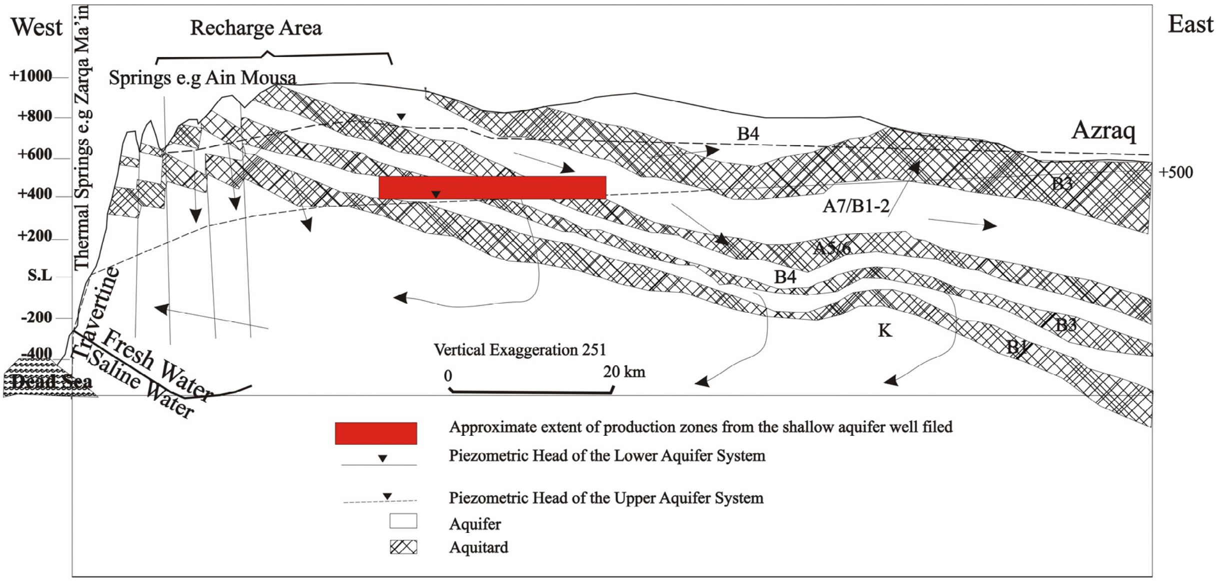


FIGURE 8: Geological cross-section with hydrodynamic pattern of the central part of Jordan (Salameh and Udluft, 1985)

To confirm this hydrogeological model, they developed a numerical simulation model which represented a vertical cross-section (2D model) of the area (Figure 9), using 6,650 separate gridblocks.

The surface layer of the model was in connection with the atmosphere at 25°C, and the bottom (at a depth of 4.5 km) was at 135°C (creating a background conductive gradient of 24.4°C/km). Recharge was in the form of 20°C meteoric water at the surface near the western end. And the discharge occurred at Zara – Zarqa Ma'in.

5.2 Conceptual model

A detailed study was carried out for the three main deep wells in Zara – Zarqa Ma'in area (GTZ-2D, GTZ-4A and GTZ-3D) (location, see Figure 5). These wells were drilled between 1976 and 1985 by Strojecxport, Foreign Trade Corporation, Prague, for NRA. The distance between these wells is about 3.5 km, with a maximum well bottom temperature of about 68.8°C for well GTZ-2D. Appendix I gives information on the wells and temperature log data.

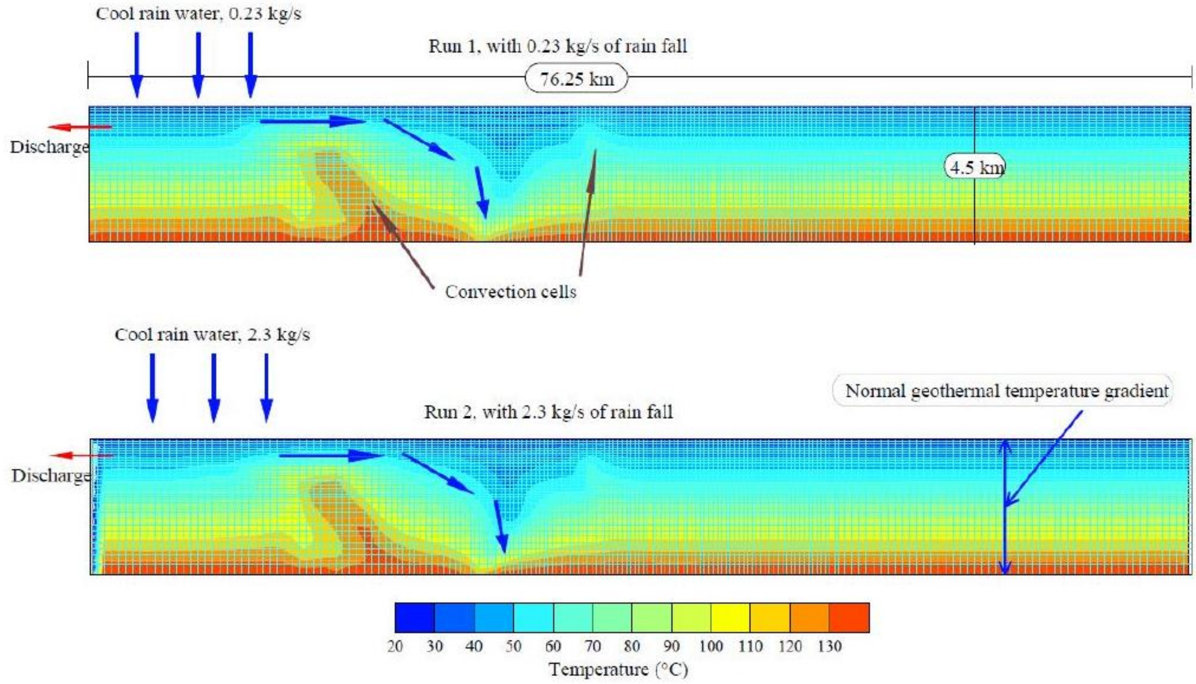


FIGURE 9: Initial-state temperature distribution according to a numerical model of the shallow aquifer, Jordan (Courtesy of West Japan Engineering Consultants, Inc.)

Temperature cross-section through Zara – Zarqa Mai'n Area:
Figure 10 shows a W-E temperature cross-section in the western part of the study area based on the deep wells. The hottest part seems to be intersected by well GTZ-2D (bottom well temperature of 68.8°C). This appears to be influenced by the main fault that trends parallel to Zarqa Ma'in fault (E-W trending fault).

The total depth of GTZ-2D is 1314 m (Salib Arkosic sandstone formation of lower Cambrian). The well penetrates the upper aquifer (B2/A7) between 112 and -268 m. It extends to the lower aquifer (starting at depth of 268 m) via A1-6 aquitard. According to a detailed evaluation of the temperature well log data compared with the lithological column of the wells, the most permeable zones of well GTZ-2D are the following:

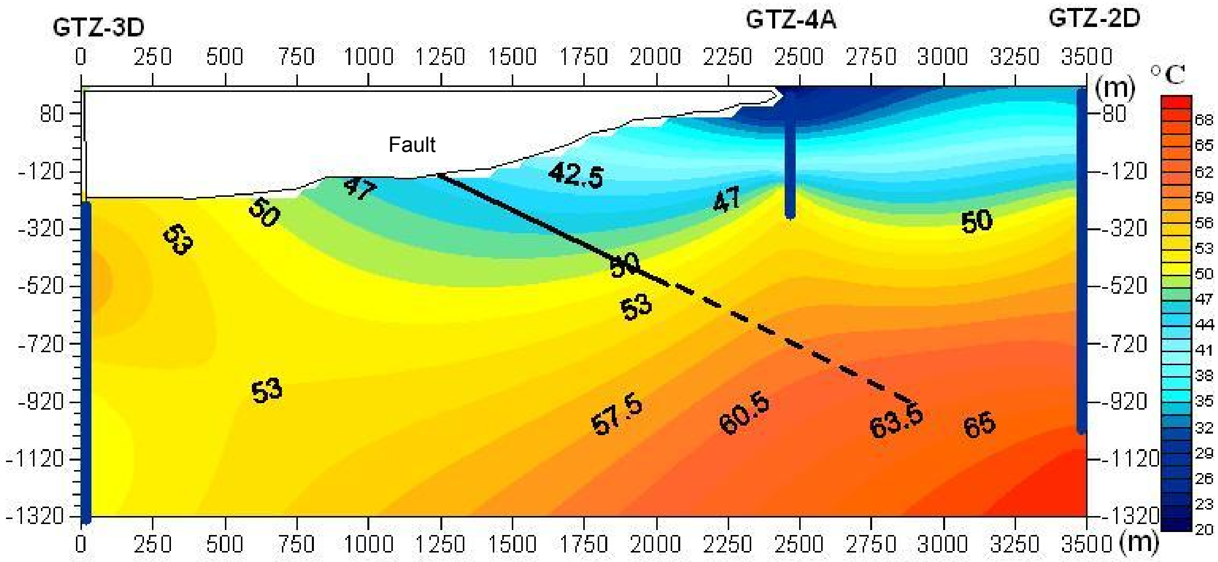
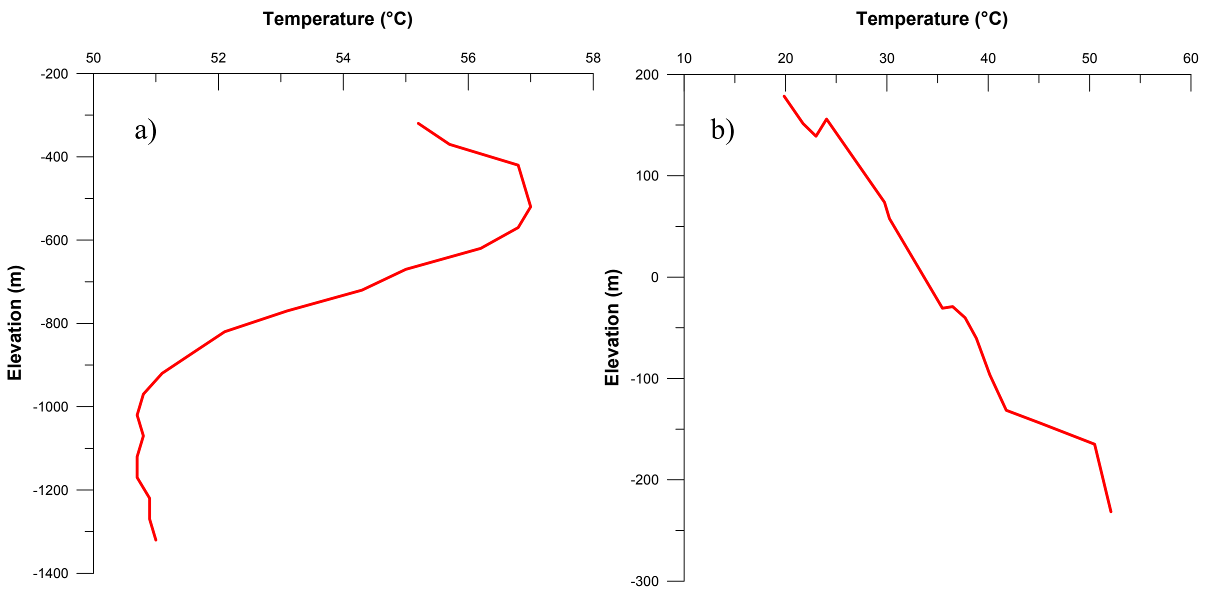


FIGURE 10: W-E temperature cross-section of the deep wells in the western parts of the study area

- Lower Cretaceous – kurnub sandstones. The main permeable zone seems to be at a depth range of 396 - 463.5 m.
- Triassic Sandstone. The main permeable zone of this formation is at 597-619 m depth.
- Lower Cambrian. This entire complex seems have good permeability, but the most permeable zone is considered to be at a depth of 1204-1222 m.

Well GTZ-4A, with a total depth of 407 m, is about 1 km west of GTZ-2D (see Figure 10). The bottom-hole temperature is about 46°C, indicating a geothermal gradient of 52.8°C/km. GTZ-3D in Zarqa Ma'in area, is about 3.5 km west of GTZ-2D, and the temperature profile of this well (1100 m in depth) shows that the outflow seems to be located in the depth interval from 242.5 to 318.5 m which lies in the Triassic sandstone (of the lower aquifer). The temperature decreases from 55.4°C in the aquifer zone to 51°C at the bottom of the hole (Figure 11). Therefore, the most likely way to find hotter water in this case is to intercept the vertical faulting system at deeper levels.



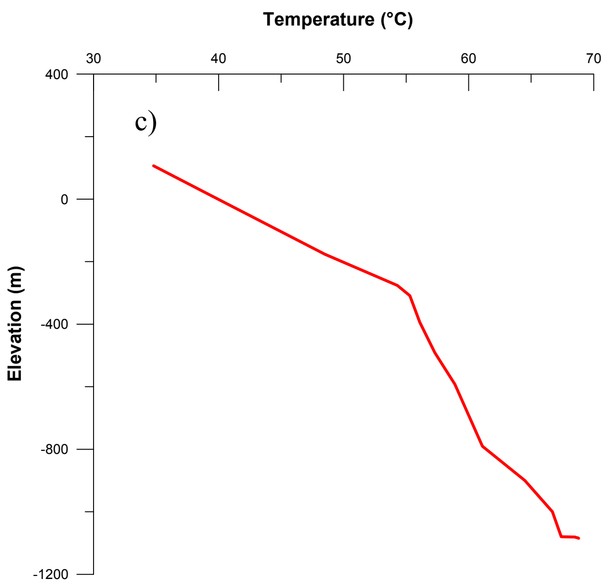


FIGURE 11: Temperature profiles for the deep wells; a) GTZ-3D; b) GTZ-4A; and c) GTZ-2D

The study area is dissected by numerous faults of different trends, which suggest that there is a hydraulic connection between the two aquifers in the study area. The temperature cross-section for the three wells shows an up-flow from the lower aquifer to the upper aquifer, which is in agreement with the model proposed by Sawarieh (2005). It is, of course, not possible to reach a final conclusion from only three deep boreholes in the Zara – Zarqa Ma'in area.

To support the previous conclusion on the up-flow, the PREDYP program of the ICEBOX, Geothermal Reservoir Engineering Software for Windows (Arason et al., 2004), was used to compute the wellbore pressure in a static water column for the three investigated wells (GTZ-2D, GTZ-4A and GTZ-3D), with the output as pressure in bars-g. The pressure cross-section in Figure 12 shows the calculated pressure

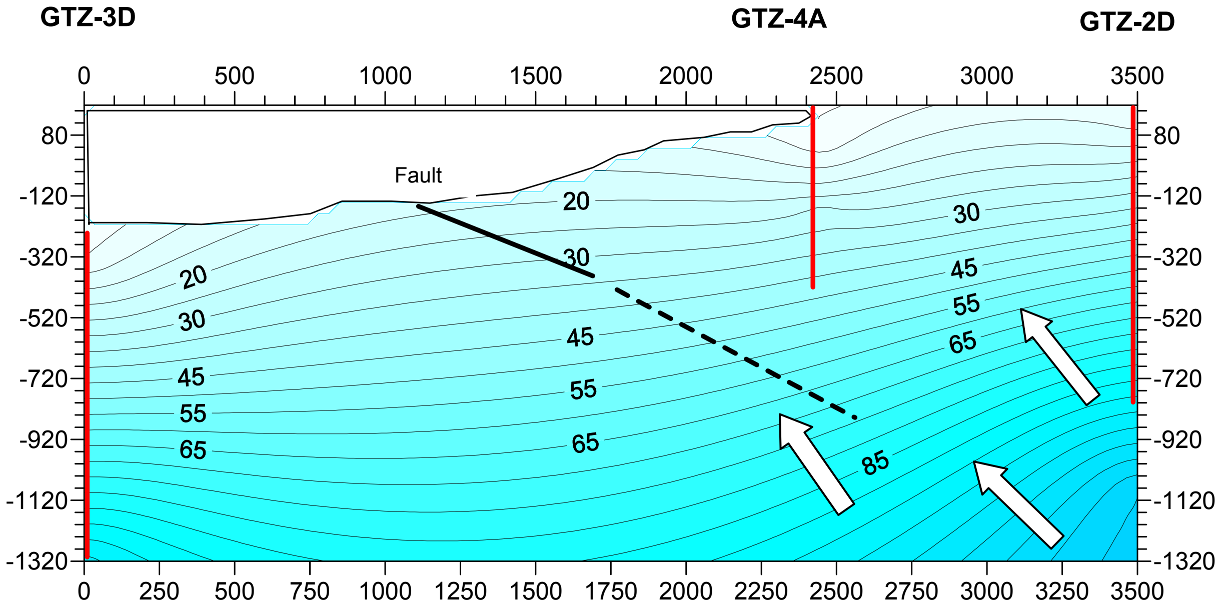


FIGURE 12: Cross-section of wellbore pressure distribution of the deep wells in the western parts of the study area

distribution as well as the variable surface elevation. The arrows show the direction of fluid flow indicated by the pressure distribution. As mentioned before, the study area is dissected by numerous faults of different trends, which suggests that there is a hydraulic connection between the two aquifers in the study area.

6. VOLUMETRIC GEOTHERMAL RESOURCE ASSESSMENT

6.1 Theory

The most important factor in a geothermal assessment, when using the volumetric method, is an estimation of the volume of the geothermal system. Based on this and the reservoir temperature, the total heat stored in a volume of both rock matrix and water in the pores is estimated. A volumetric assessment is often used for the first stage assessment when data are limited, such as basic geophysical and geological information, which is required for such calculations.

For simplicity, we assume that the volume of the reservoir is a box, and the study will be focused on the most active area between Zarqa Ma'in and Dab'a faults and the extension fault, with a best guess of about 400 km^2 for the surface area. In this study, the box has a surface area A in the *xy* plane, and height $Z_1 - Z_0$ (thickness) along the z-axis (the depth), where Z_1 and Z_0 are the lower and upper depth limits of the geothermal system, respectively. When the volume of the geothermal system has been assessed the choice has to be made on how to calculate the usable heat that the system contains. For simplicity it can be assumed that the heat capacity and temperature are homogeneous in the *xy* plane. The heat content of the system can then be calculated by integrating the product of the estimated heat capacity per unit-volume $C(z)$ and the difference of the estimated temperature curve $T(z)$ of the system and the cut-off temperature T_0.

The cut-off temperature is the reference temperature for the case in question, i.e. the base temperature from which the heat is integrated. Therefore Equation 1 was used to calculate the heat energy in the system. The method of calculation is also based on the shape of the temperature curve, i.e. whether it is fixed, linearly increasing or nonlinear. If the temperature curve is nonlinear we often assume for high temperature that the shape of the curve follows the shape of the boiling curve:

$$T(z) = x.96{,}56(z + z_{Delta})^{0.2085} \tag{1}$$

where x is a ratio factor describing the deviation from the true boiling curve that runs from zero to one, z_{Delta} is a translation in the z direction in order to fulfil the upper boundary conditions T_0 at z_0. A linear temperature gradient is also often assumed (see below). The total energy content is then given by:

$$Q = A\int_{z_0}^{z_1} C(z)\left[T(z) - T_0\right] \mathrm{dz} \tag{2}$$

Only a small portion of the total heat in the system is recoverable and therefore we define a recovery factor, R, which is the ratio of the heat which we can recover over the total heat in the system. The recoverable heat is therefore:

$$Q_H = RQ \tag{3}$$

For further simplification, the heat capacity in the sub-volume can be considered to be homogeneous for the whole system:

$$C = s_R(1-\phi)\rho_R + s_W\phi\rho_W \tag{4}$$

where s_R = The specific heat of the rock (kJ/kg °C);
s_W = The specific heat of the water (kJ/kg °C);
ρ_R = The density of the rock (kg/m^3);
ρ_W = The density of the rock (kg/m^3);
φ = The porosity of the rock.

6.2 Monte Carlo calculations

The Monte Carlo simulation method is used to deal with the complex scenario that describes the distribution of known reservoir parameters by using uncertainty or probability distributions. The uncertainty distributions for every parameter involved in the analysis should be defined as in the following equations (Equations 5 and 6). By using the basic principle in Equation 6, the total heat energy in the geothermal system is the sum of the heat energy from within the rocks and the fluid:

$$E = E_r + E_w = V\,C_r\rho_r \times (1 - \varphi) \times (T_i - T_o) + V\,C_w\rho_w\varphi \times (T_i - T_o) \tag{5}$$

The reservoir thermal power potential is calculated from the heat energy using the relationship:

$$Reserve\ (MW) = \frac{Heat\ energy \times recovery\ factor \times conversion\ efficiency}{serve\ time \times load\ factor} \tag{6}$$

The result is an overall probability distribution for the reserve estimate that quantitatively incorporates the uncertainties involved in all the parameters used (Parini and Riedel, 2000).

The most commonly applied uncertainly distributions are:

- *Constant (rectangular) distribution:* Mostly used when a constant is possible over a certain range of values and when any value within the limits defined is considered equally likely;
- *Triangular distribution:* This is used when the best guess value for a parameter (most likely model value) can be specified along with high and low extremes.

For simplicity of analysis in this study, we have assumed triangular distributions varying within specified limits for several of the parameters, but most have fixed values (Table 3).

TABLE 3: Parameters used in Monte Carlo analysis for Zarqa Ma'in – Dab'a field area

Parameters	Probability distribution	Minimum	Best guess	Maximum
Possible surface area (km^2)	Triangular	300	400	500
Upper depth (m)	Triangular	750	800	950
Lower depth (m)	Triangular	1400	1600	1800
Temperature at upper depth (°C)	Triangular	54	55	58.5
Porosity	Triangular	15	17	19
Rock density (kg/m^3)	Triangular	2550	2600	2650
Cut-off temperature (°C)	Fixed value		25	
Water density (kg/m^3)	Fixed value		985	
Specific heat capacity of rock (kJ/kg °C)	Triangular	900	920	950
Specific heat capacity of fluid (kJ/kg °C)	Fixed value		4400	
Production time (year)	Triangular	25	-	50
Linear temperature gradient (C/km)	Triangular	50	52.5	55
Accessibility (%)	Fixed value		50	
Recovery factor (%)	Triangular	0.5	1.0	1.5

For the study area (Zarqa Ma'in –Dab'a field area), an accurate reservoir area is difficult to estimate. The area for the assessment has been chosen between the Zarqa Ma'in fault and the Dab'a fault, which play (with other major faults) a role in the thermal water occurrence, as was suggested by Sawarieh (2005) as the most promising area to find hotter water. Therefore, the possible surface area was estimated to be around 400 km^2 as a best guess with a minimum of 300 km^2 and a maximum of 500 km^2. The upper and lower depths of the reservoir have been estimated according to the variation of the topography in the study area, and according to the deep circulation of the thermal water in the lower aquifer. The linear temperature gradient is estimated on the basis of previous studies from data from the study of the deep wells drilled in the western part of the study area (wells GTZ-2D, GTZ-3D and GTZ-4A), and from other investigation wells. The recovery factor *R* was chosen to follow an uncertain distribution with a best guess value of 1.0%.

6.3 Results of the volumetric calculation

The medium- to low-temperature geothermal reserves of Zarqa Ma'in – Dab'a field can be used for space heating of buildings near the area, for protected agricultural activities (greenhouses), or for other direct uses. A 100% conversion efficiency and load factor was used in Equation 6. The estimation of the energy was done for two production time scenarios, 25 and 50 years of production time.

According to the statistics of the probability distribution in Figure 13, it is seen that 90% lies between 230 and 670 MWth, with a mean value of 440 MWth, estimated for the 25 year period. For the 50 year period, 90% lies between 110 and 340 MWth, with an estimated mean value of 220 MWth.

From the cumulative distribution in Figure 14 it is seen that the volumetric model predicts with 90% confidence that the thermal power potential lies below 320 MWth for 25 years and below 150 MWth for 50 years.

Recoverable heat, with cut-off temperature 10°C, was also calculated using Equation 5 in Section 6.2. The result is that with 90% confidence, the recoverable heat lies between 35 and 238 PJ, and with 90% probability at least 56 PJ can be extracted. This is an estimate of the total recoverable heat from the geothermal system that is suitable for house heating and other direct uses.

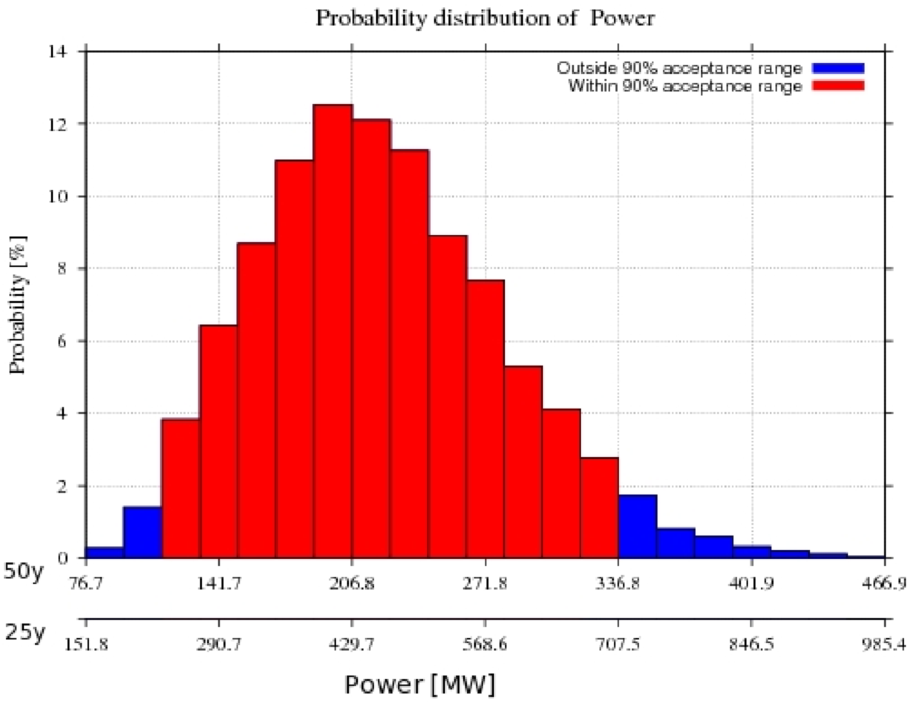


FIGURE 13: Probability distribution of thermal power for Zarqa Mai'n – Dab'a field for 25 and 50 years

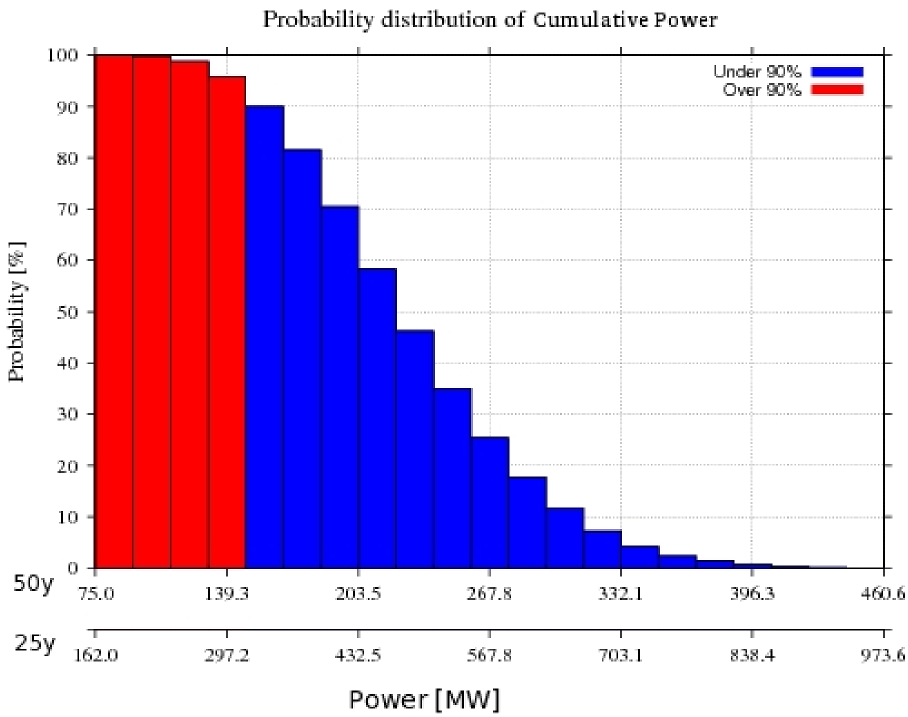


FIGURE 14: Cumulative distribution of thermal power for Zarqa-Mai'n – Dab'a field for 25 and 50 years

7. CONCLUSIONS

Thermal waters of Zara – Zarqa Ma'in have been subject to many studies regarding their chemistry, heat source, therapeutic properties and potential as a source of energy. A detailed study has been carried out for the three main deep wells in the Zara – Zarqa Ma'in area in this project.

The study area is dissected by numerous faults of different trends, which suggests that there is a hydraulic connection between the two aquifers in the study area. The temperature cross-section for the three wells shows an up-coning from the lower aquifer to the upper aquifer, that is in agreement with the model proposed by Sawarieh (2005).

The heat source of the thermal water in the lower aquifer is a result of the deep circulation of water within the Paleozoic sandstones receiving heat from a normal to slightly elevated geothermal gradient.

Volumetric geothermal assessment has been done by using the Monte Carlo method, for the area which lies between Zarqa-Ma'in fault and Dabá fault based on estimating the total heat stored in a volume of both rock matrix and water in the pores.

The medium- to low-temperature geothermal reserve of the Zarqa Ma'in – Dab'a field could be used for space heating in constructions near the area, and for special agricultural activities, needing greenhouses, or other direct uses such as fish farming.

One or two deep wells need to be drilled at a location between the Zarqa Ma'in fault and the Daba'a fault south of Al Jizah.

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This project is dedicated to my late father, who left a great void in me, to my mother, sisters, and brothers for their love and continuous support, and to my lovely wife Safa' for her efforts, moral support and unlimited encouragement and to my twin daughters Lamar and Seedra for their understanding during my absence- with my love to them all. I'm grateful to God for his grace and protection throughout my stay in Iceland and for keeping my beloved family safe.

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APPENDIX I: Information on deep wells

Well ID			**GTZ – 2D Zarqa Ma'in area**	
Coordinate			208,000E - 111,900N	
Total depth			1314 m	
Elevation			210 m a.s.l.	
SWL			200 m	
x	**Depth (m)**	**Elevation (m a.s.l.)**	**Temperature (°C)**	**Pressure (bars-g)**
3500	103.7	106.3	34.8	9.16
3500	200.9	9.1	39.5	18.64
3500	386	-176	48.5	36.67
3500	486	-276	54.3	46.38
3500	519	-309	55.3	49.58
3500	604	-394	56.1	57.83
3500	701.2	-491.2	57.3	67.25
3500	802	-592	58.9	77.03
3500	1000	-790	61.1	96.21
3500	1110	-900	64.5	106.87
3500	1210	-1000	66.7	116.54
3500	1290	-1080	67.4	124.27
3500	1291	-1081	68.5	124.37
3500	1292	-1082	68.6	124.47
3500	1293	-1083	68.7	124.56
3500	1295	-1085	68.8	124.76

Well ID			**GTZ – 4A**	
Coordinate			206,800E - 111500N	
Total depth			407 m	
Elevation			190 m a.s.l.	
SWL			75 m	
x	**Depth (m)**	**Elevation (m a.s.l.)**	**Stabilized temperature (°C)**	**Pressure (bars-g)**
2450	1.60	178.4	19.86	0
2450	28.53	151.5	21.73	0
2450	40.91	139.1	23.01	0
2450	24.05	155.9	24.05	0
2450	106.16	73.8	29.76	0.1
2450	122.32	57.7	30.25	1.68
2450	210.72	-30.7	35.48	10.31
2450	209.12	-29.1	36.48	10.16
2450	220.10	-40.1	37.73	11.23
2450	240.45	-60.5	38.84	13.22
2450	261.40	-81.4	39.60	15.26
2450	276.37	-96.4	40.15	16.72
2450	311.45	-131.5	41.78	20.14
2450	350.00	-144.4	45.20	23.89
2450	390.00	-164.8	50.50	27.78
2450	407.00	-231.4	52.10	29.43

Well ID			**GTZ – 3D**	
Coordinate			204,500 E - 112,100 N	
Total depth			1100 m	
Elevation			Flowing (-270 m)	
SWL			-270 m	
x	**Depth (m)**	**Elevation (m a.s.l.)**	**Stabilized temperature (°C)**	**Pressure (bars-g)**
0	50	-320	55.2	4.84
0	100	-370	55.7	9.68
0	150	-420	56.8	14.52
0	200	-470	56.9	19.36
0	250	-520	57	24.2
0	300	-570	56.8	29.04
0	350	-620	56.2	33.88
0	400	-670	55	38.73
0	450	-720	54.3	43.58
0	500	-770	53.1	48.43
0	550	-820	52.1	53.28
0	600	-870	51.6	58.14
0	650	-920	51.1	63
0	700	-970	50.8	67.87
0	750	-1020	50.7	72.73
0	800	-1070	50.8	77.6
0	850	-1120	50.7	82.46
0	900	-1170	50.7	87.33
0	950	-1220	50.9	92.2
0	1000	-1270	50.9	97.07
0	1050	-1320	51	101.94