

Using Thermal Infrared Imagery (TIR) for Illustrating the Submarine Groundwater Discharge into the Eastern Shoreline of the Dead Sea-Jordan

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Abstract: Many of thermal anomalies that are indicator of discharge zones of warmer water were observed along the Dead Sea shoreline at the areas of Zarka Ma'in, Zara and Al-Mujeb. The groundwater discharge locations were mapped along eastern shores of the Dead Sea by using aerial thermal infrared imagery ($\lambda = 8-13 \mu\text{m}$). A digital thermal infrared camera was used for this purpose in December 2005 at the nighttime. The principle of using this method is depending on the difference of the temperature between the sea surface water and the groundwater. The average groundwater temperature in the Dead Sea area is about 33 centigrade. It discharges into the cooler Dead Sea water 12 centigrade. The temperatures of the mixing two types of water (the discharge and the Dead Sea Water) were about 26 centigrade at some spots. These increasing of the Dead Sea temperatures are due to the groundwater discharge. The groundwater discharge was identified by thermal infrared images surveys. The survey provides sharp images of the shoreline of the Dead Sea (pixel size of about 4-5 m).

Key words: Jordan, thermal infrared, Dead Sea, discharge

INTRODUCTION

The Dead Sea is a hypersaline terminal lake with a surface area of approximately 760 km² and a maximal depth of about 316 m. It is located in the central part of the Jordan Rift Valley, which extends from Lake Tiberias in the north to the Gulf of Aqaba at the south and includes The Jordan River at the North, the Dead Sea region, the southern Ghors (Haditha, Mazra, Safi), Wadi Araba and the Gulf of Aqaba. Geologically, the Dead Sea lake situated within the large Dead Sea basin. The Dead Sea is subdivided into two basins, the south very shallow basin and the deep North basin (Fig. 1).

The direct discharge of groundwater into the coastal zone has received increased attention in the last few years as it is now recognized that this process may represent a potentially important pathway for material transport (dissolved solids). Understanding SGD is important for both a component of the general water cycle, potential resource and to coastal environmental management. Generally almost all coastal zones are subject to flow of groundwater either as submarine springs or propagated seepage. In some deep aquifer, which has fractures or other breaches in the overlying, confining layers, allowing groundwater to flow into the

sea? The groundwater might be flow directly to the sea wherever a coastal aquifer is connected to the sea, in addition to fresh groundwater from land. The re-circulated seawater is driven through bottom sediments by a number of processes might be discharge into the sea. The groundwater seepage near shorelines is result from hydraulic gradients on land and this seepage may contribute to flow further out on the shelf from confined aquifers^[1]. Submarine Groundwater Discharge (SGD) in general occurs everywhere through permeable sediments if the hydraulic head of aquifers is above sea level^[2,3].

The term SGD has been used in different ways over the years. SGD was defined by^[4] as a direct groundwater outflow across the ocean-land interface into the ocean, which would include re-circulated seawater^[5]. Considered SGD to be the sum of net groundwater discharge, outflow due to wave-setup-induced groundwater circulation and outflow due to tidally driven oscillating flow.

According to^[6] in the coastal environment, total water discharge into the ocean consists of surface water discharge and SGD. Submarine pore water exchange occurs across the seabed by SGD and submarine groundwater recharge. The water depth, the

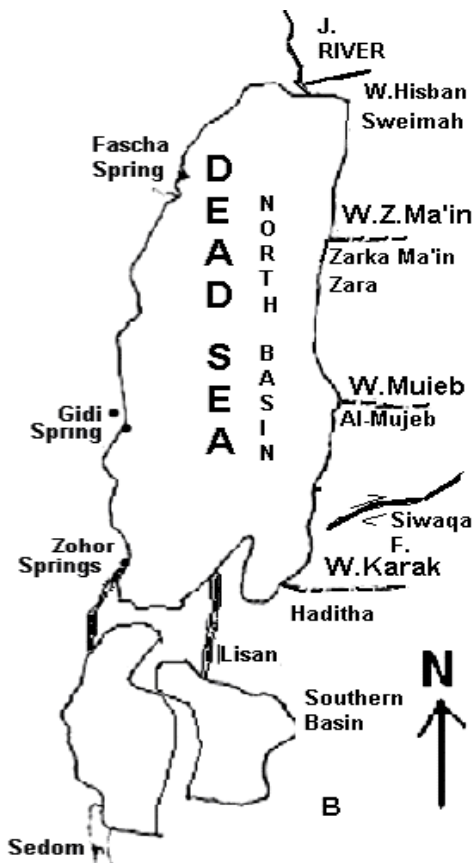


Fig. 1: Sketch for the Dead Sea and the study area

groundwater hydraulics and the geometry of the flow domain are the main parameters for controlling submarine.

Rundquist *et al.*^[7] pioneered the idea of using the thermal infrared remote sensing for quantitative analysis of hydrology of flow-through lakes. They obtained the data from Thermal Infrared Multi Spectral (TIMS) airborne scanner in 8.2-12.2 micron range, from NASA National Space Technology Laboratory (NSTL). They selected four lakes in the Sand Hills with greater potential for inference of the zones on intensive groundwater seepage. They detected also the thermal variability and possible groundwater discharge zones to these locations.

The water discharge to the Dead Sea was estimated by^[8] by using water balance calculations. They compared the water balance before (predevelopment) and after water resources development. They found that the amount of water that used to flow into the Dead Sea before development was 1980 MM³ year⁻¹ and after development (present day) is about 617 MM³ year⁻¹ for the total catchments area of the Dead Sea.

Burnett and Dulaiova^[9] compared the results of the ground water discharge, which they obtained by using the continuous measurement of radon-222 for estimating groundwater discharge into the coastal zone with results of other studies in the same area using methods such as radium isotopes (Ra-223, Ra-224) and the automated seepage meters. They found that the results were comparable for the three approaches in the august readings. But in October the radon measurements indicate similar but slightly higher rates of flow than those calculated from the automated seepage meter. The estimate based on radium isotopes indicates a flow about a factor of two greater.

Erica *et al.*^[10] used high-resolution airborne thermal infrared imagery to locate mine pools and discharges in Kettle Creek watershed-Pennsylvania.

The emitted Thermal Infrared Radiation (TIR) was used to measuring surface water temperatures by^[11]. These methods were used to evaluate the accuracy of stream and lake radiant temperatures derived from airborne (MASTER, 5-15 m) and satellite (ASTER 90 m, Landsat ETM+60 m resolution) TIR images. They found that agreement between images temperatures and ground temperatures does not always imply that accurate temperatures have been recovered from TIR images. They concluded that an assessment of thermal stratification should be made in any field area before TIR images are use to measure water temperatures.

Shaban *et al.*^[12] applied airborne thermal infrared to recognize groundwater discharge along coastal stretch of Lebanon and to compare the results which they got with the results which got by Food and Agriculture Organization (FAO) for the same area and using the same technique. They recognized twenty-seven major SGDs. As well they did a correlation between SGDs and geologic controls on the land after doing interpretation of the satellite images.^[13] used the thermal images taken by the Advanced Spaceborne Thermal Emission and reflection Radiometer and Reflection Radiometer (ASTER) in order to measure the temperature of the Yugama lake of crater on Kusatsu-Shirane volcano in Jaban. They found that the split-window algorithm applied to ASTER images are suitable for monitoring thermal changes in active volcanic lakes.

Geological settings: Most eastern part of the investigated area is covered by outcropping rocks of cretaceous age. While the west wards, the oldest formations of middle Cambrian are exposed. Close to the Eastern shoreline of the Dead Sea, Triassic and lower cretaceous rock restricted along the shoreline of the Dead Sea. Volcanic eruptions occur in many places

Table 1: Chronological sequence of the lithological units in the Dead Sea area (Internal reports, NRA)

Period	Age	Group	Unit	Lithology				
Quaternary	Recent	Jordan Valley	River, Terrace	Gravel, Clay, Sand				
	Pleistocene		Lisan	Marl, Gravel, Clay, Gypsum, Sand				
Tertiary	Pliocene	Belqa	Undifferentiated	Conglomerate, Marl				
	Miocene							
	Oligocene							
	Eocene							
	Paleocene							
Upper Cretaceous	Maestrichtian	Ajlun	Wadi Shallala(B5)	No data at Dead Sea area				
	Companian		Umm Rijam(B4)	Limestone, Chert				
	Santonian		Muwaqqar(B3)	Chalky Marl				
	Turonian		Al Hasa(B2a) Amman(B2b)	Phosphate Silic. Limestone				
			W. Ghudran(B1)	Chalky Marl, Chalk				
Lower Cretaceous	Albian Aptian Neocomian	Kurbub	Wadi Es Sir(A7)	Limestone				
			Shueib(A5-6)	Marly Limestone				
			Hummar(A4)	Dolomitic Limestone				
			Fuheis(A3)	Marl				
			Na'ur(A1-2)	Marly Limestone				
Permo Triassic	Zarqa-Ma'in	Dardur Ma'in Umm Irna	n The Dead The Dead Umm Sahn	White Sand Stone Varicolored Sandstone Lst., Shale, marl, dolomite. Sandstone, Marl, Shale Sandstone, Siltstone, Clay Sandstone, Siltst., Shale				
					Silurian	No Strata	Present i	Sea Area
Cambrian	Safi	Disi Umm Ishrin Burj Salib	No Strata at the Dead Sea Sandstone, Siltstone Dolomite, Shale, Sandst. Sandstone, Siltstone					
				Pre-Cambrian	Safi	Not presented	In the Dead Sea Area	

of the Area but mostly in the western part along the Dead Sea shoreline. The stratigraphical lowest outcropping member is the Cambrian; Umm Ishrin formation consists of Sandstone followed up by Triassic Zarka Ma'in group consisting of sandstones, Limestone and Shale, Followed up by the lower Cretaceous Kurnub sandstone and the upper Cretaceous Ajlun group being mainly a carbonate-dominated sequence. Belqa group upper Cretaceous-Tertiary follows it. This group is missing in the end northern part of the study area. The youngest geological units are the quaternary Lisan marl of Pleistocene age and the basalt flows dated 0.6 Ma BP. Table 1 shows the lithological units in the Dead Sea area.

Different structural features characterize the Dead Sea area as Dead Sea transform fault system, which is the major active strike-slip fault system S-N direction. Jabal Shihan Fault trending EW, Zarka Ma'in Fault trending E, Mukawir-Wadi el Wala Fault zone trending E.W. While El-Maslubia fault trending E-W, Wadi el Hiri fault trending NE-SW, Wadi er Rashsha trending NE-SW, Humrat Ma'in trending NE-SW, The Karak Al-Fiha fault zone-Trending NW-SE, Zara fault trending N-S, The Shihan Siwaqa structure trend NE-SW. It trends NW-SE in the northern part of the area.

Hydrogeological aspects: The bedrock at the Dead Sea area is typically highly fractured at the surface and subsurface extending greater than tens of meter. The fractures are often composed of two sets of fractures at approximately right angles to each other, they may be observed directly in exposed bedrock. These fractures are widely distributed throughout the Dead Sea area.

These fractures are the principal sources of secondary permeability in many bedrock aquifers. The recharge occurs chiefly through these faults and fractures. Then might be serving as paths for groundwater lateral and vertical movements.

Mountains, hills and wadies characterize the topography of the Dead Sea area; the topography of the mountains commonly having steep slopes from east to west toward the Dead Sea coast.

As well the Dead Sea area is characterized by high differences in the hydraulic head. It reaches about 1300 m above the shore of the Dead Sea, which provide the impetus for groundwater movement from the high head to the low head.

The main major aquifer systems within the Dead Sea basin are the upper aquifer Amman/Al Hisa/Wadi Es-Sir (B₂-A₇) system and the lower aquifer system Kurnub and older age sandstone formations (Zarka, Ram and Disi).

Amman Al Hisa Wadi Es-Sir Aquifer system (B₂-A₇) is form one of the most important and extensive aquifer system in the study area. It consists of two formations: The Wadi Es-Sir (A₇) and Amman silicifeid limestone (B₂). The B₂ and the A₇ formations are hydraulically connected due to its limited lateral extend.

This aquifer outcropping to the east of the Dead Sea area in the areas characterized relatively as high rainfall. The B₂/A₇ formations consist of limestone, intercalated with laminas of marl. The upper part contains phosphatic limestone and silicified phosphate. The Wadi Ghudran (B₁) forms the middle part of this aquifer system consists of marl and chalky marl and consider as a minor aquitard within the system. The thickness of this system is ranging between 170 and 325 m.

The B₂-A₇ aquifer system receives direct recharge from the rainfall and indirect recharge from the adjacent aquifer and from surrounding areas. But the direct recharge is limited at some areas located farther to the east of the Dead Sea due to the overlying by low permeability strata as Muwaqqar Chalk Formation (B₃).

The discharge occurred from the aquifer through the base flow of the wadies, spring flows and subsurface outflow toward the Dead Sea. Some amount leaks downward to recharge the deep aquifer. This aquifer is defined as unsaturated zone at the east of Dead Sea, because it crops out at this area and it is essentially an unconfined aquifer.

Lower Aquifer System This aquifer system includes the sandstone formations from different ages. The formations are Kurnub Sandstone group aquifer from the age of lower cretaceous, lower Zarka sandstone and shale from age of Triassic and Ram group sand stone from Cambrian age. These aquifers are connecting with each other. 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 the north part of the Dead Sea at Wadi Zarka Ma'in area and Wadi Hidan and might reach to about 900 m.

The main component rock constituent of this aquifer is sandstone. The aquifer becomes extremely complex due to shale and clays contents. Because that the permeability are different in lateral and vertical directions. At some local areas lower Zarqa shale and clays form an aquiclude confining the underlying saturated Cambrian sandstone (Umm Ishrin and Disi). But in most of the study area the Zarqa shale and clays is absent from the formation. Therefore the whole sequence can be treated as one hydraulic connected aquifer. This lower aquifer system underlies the most of the study area with total thickness more than 600 m at

some areas. As well it is exposed at the area of very low rainfall rates. Then the recharge of this aquifer system from the rainfall is very low and negligible because most of the recharge from the rainfall loss by the evaporation process. Then the main recharge source to this aquifer system is the downward leakage from the upper aquifer system and aquitards at the east of Dead Sea through the weakness zones as faults and fractured present in the A₁₋₆. The major outflow from the aquifer takes place along the Dead Sea in the form of springs and seepages from Kurnub sandstone crops out along the Dead Sea shoreline. The main discharge as springs is from Zara and Zarqa Ma'in areas as thermal hot springs. As well the main discharge takes place as subsurface outflow toward the Dead Sea with different directions.

There are two minor aquifers in the Dead Sea area. Na'ur aquifer (A₁₋₂) consists of limestones intercalated with thick sequences of marl. It crops out at the Dead Sea area. This aquifer becomes as aquitard locally in some places to the east of the Dead Sea. The second minor aquifer is Hummar (A₄). It consists of dolomitic limestones with a secondary permeability due to the presence of fractures and joints within the limestone consist of this aquifer. Some springs issue from these aquifers to the east of the Dead Sea as Al Zarka spring at the upper of the Zarka Ma'in.

The formations of Fuheis (A₃) and Shueib (A₅₋₆) are forming a main aquitards in the area. In some places these include the minor aquifer mentioned above. They separate the Lower main aquifer and upper main aquifer.

MATERIALS AND METHODS

The thermal fingerprint is based on a pronounced thermal gradient between the groundwater and ambient surface conditions. The thermal infrared Imagery is an effective method to quickly assess large-scale areas and acquire information about specific locations of groundwater discharge.

This study exploited an idea of using temperature differences between groundwater and surface water in the Dead Sea to delineate zones of comprehensive groundwater-sea surface water exchanges. The groundwater temperature is relatively stable and it is as an average temperature of the area, while the temperatures of the surface water are changeable with changing the seasons. Thermal infrared only measures surface temperatures so its application is limited to the surface seawater.

To circumscribe the groundwater discharge zones, a thermal infrared survey was flown parallel over the study area at the eastern shoreline of the Dead Sea.

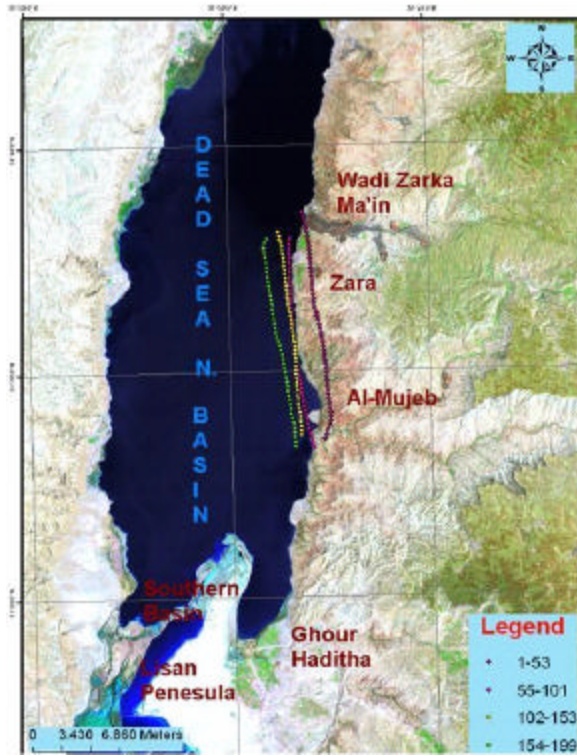


Fig. 2: Flight strip along the Eastern shores of the Dead Sea

Four flight lines (strips) were taken between Zarka Main area and south Al-Mujeb for an area approximately 75 km² Fig. 2.

The thermal Infrared Imagery was performed using a thermal infrared camera was fixed at the bottom of the small commercial plane. The survey was performing in December 2005 (winter season) and the time was between 19 and 20 h. This time and season were chosen to maximize temperature differentials between the groundwater and sea surface temperatures and to take an advantage of the lack of shadows cover, which can shield an anomaly from the TIR. The survey was performed at 1300-1600 m elevations. The TIR survey consisted high-resolution (4-8 m) imagery depending on the height of the plane. There was about 10-40% TIR image footprint overlap between adjacent flight lines and about 25-40% also footprint overlap between the images along the same flight line. Survey conditions were good for identifying discharge zones: clear sky, ambient air temperature 20-21°C and expected groundwater temperatures of 35°C at Zarka Ma'in, Zara and south Zara areas which have a hot springs and it expected about 26°C at Al-Mujeb and adjacent areas. The coordinates of the images were obtained from a stationary GBS stations. One of these stations was fixed

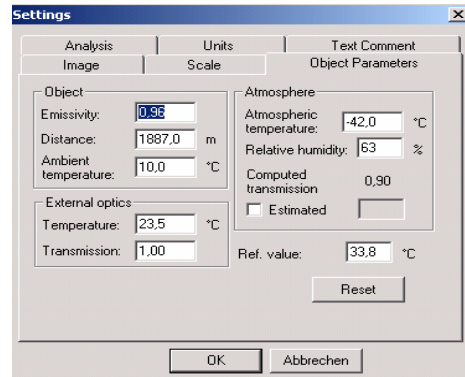
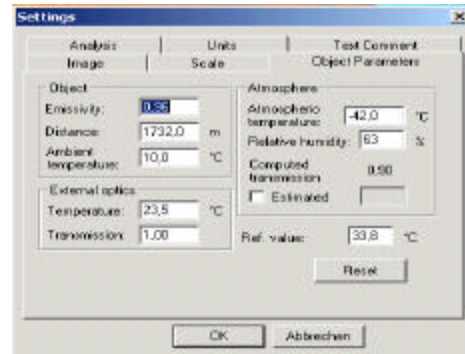
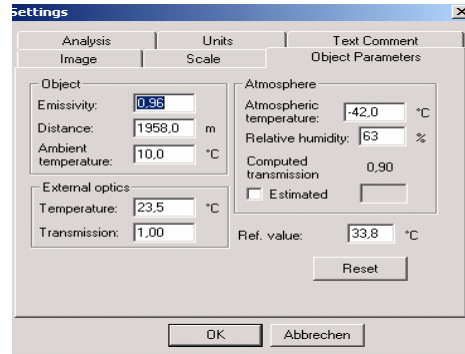


Fig. 3: Settings in thermal Infrared camera

inside the plane top of the thermal camera and the second GBS station was fixed on the ground at the airport. The coordinates were taken continuously from the starting point at the airport to the end point back to the airport.

The thermal infrared imagery was carried out as the following procedures:

- The flight paths were drawn down on a geo-referenced Land7 satellite image to determine the coordinates for each flight line at the office
- The flight elevation from the standard sea level to obtain the require resolution, the overlapping

percentage and ground coverage area of the images was determined

- An initial site characterization was performed and the study area was reviewed for existing land use and irrigation areas
- The thermal camera was prepared and calibrated for the sky temperature and the humidity and sharpness
- Then the thermal camera was fixed at the bottom of the plane and the GBSs stations were also fixed

After carrying out the Imagery many steps for interpretation and processing were carried out.

- Identification and cataloguing of discharge zones by thermal Imagery
- Geological field investigations based on the identification of potential groundwater discharge zones, e.g., fractured zones, lineaments
- Each images strip was calibrated relating to the flight elevation, the water temperature, atmospheric temperature at the flight height and the relative humidity by using the camera software as showed in Fig. 3

RESULTS AND DISCUSSION

The thermal infrared imagery was succeeding to identify the submarine groundwater discharge zones in the Dead Sea area. Because the amount of the water that discharged into the Dead Sea is too large. As well, the difference of the temperature between the groundwater at the area and the surface temperature of the Dead Sea water in wintertime is high enough to recognize by the thermal infrared imagery. In wintertime, the temperature of the groundwater in the Dead Sea surrounding areas is higher than that of the surface water of the Dead Sea itself. As well, the field conditions for the imagery survey were ideal and the resolution of thermal signatures from upwelling groundwater was clear. On the other hand, the surface seawater temperatures were collected at the same time when the thermal infrared imagery was taking. The agreement between the temperatures from the aerial thermal infrared imagery and the temperatures measured directly by using the thermometer were quite good less than 1 centigrade.

The results of the thermal imagery survey indicate that there are groundwater discharge zones into the Dead Sea. These zones are characterized by high temperature compared to other zones where no discharges occur (Fig. 4-6).

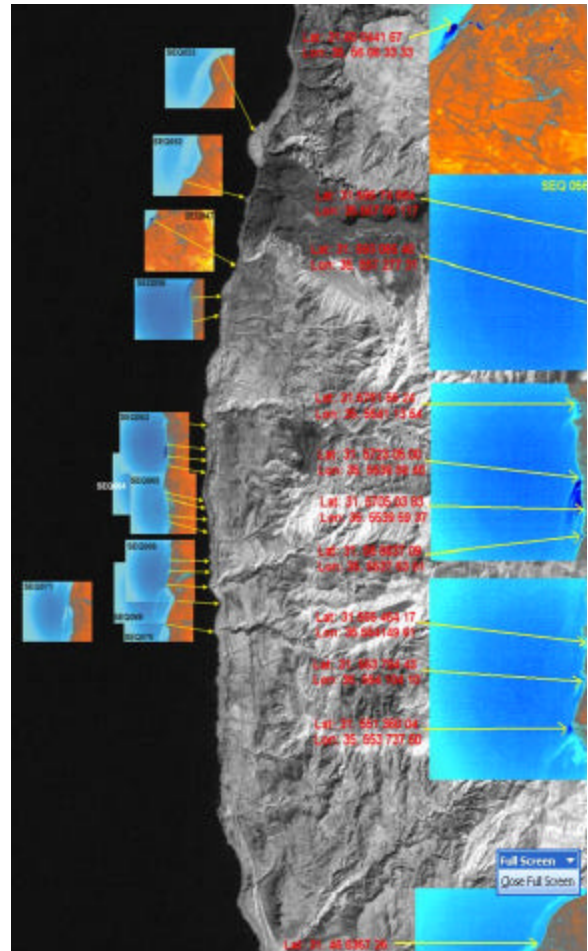


Fig. 4: Illustrating the location of groundwater discharge to the eastern shores of the Dead Sea

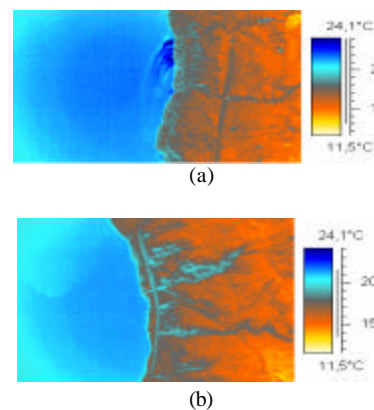


Fig. 5: TIR imagery with T scale in Zara (a) and in Mujeb (b)

Figure 4 shows groundwater discharge zones in the areas of Zarka Ma'in, Zara and Mujeb and the

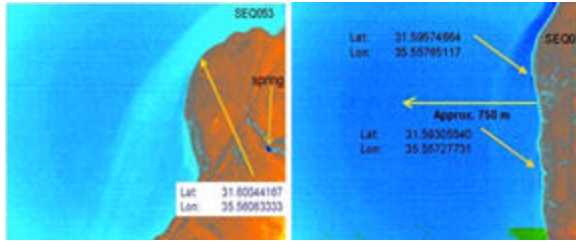


Fig. 6a: Groundwater flow distribution in Zarka Ma'in indicated by TIR images

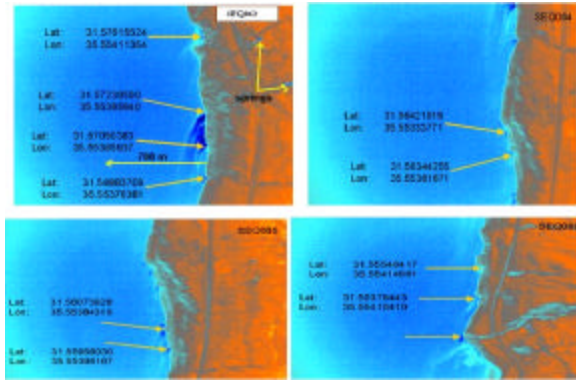


Fig. 6b: Groundwater flow distribution in Zara indicated by TIR images

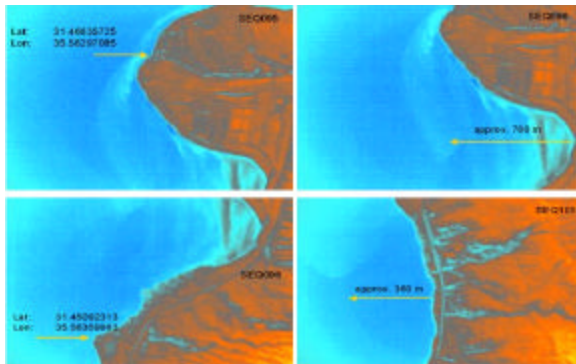


Fig. 6c: Groundwater flow distribution in Mujeb indicated by TIR images

coordinates for these zones. The thermal infrared images show that the highest groundwater discharges are found close to the Dead Sea shorelines.

The main discharge zone obtained from the thermal infrared images in Zarka Ma'in area has coordinates 31.61080324 N and 35.56301848 E (Decimal coordinate), the other main zone in the same area has coordinate 31.59574664 N and 35.55765117 E.

Table 2: Coordinates of some of the discharge zones along the eastern shoreline of the Dead Sea

Area name	Coordinate (Geographic decimal)			
	Coordinate		Coordinate	
	N	E	N	E
Zarka	31.60044167	35.56063333	31.59574664	35.55765117
Ma'in	31.61080324	35.56301848	31.59305540	35.55727731
Zara	31.57615524	35.55411354	31.57230500	35.55385840
	31.57050383	35.55395937	31.56883709	35.55376381
	31.56421919	35.55337771	31.56344255	35.55361671
	31.56073928	35.55384319	31.55958030	35.55396167
	31.54414031	35.55489140		
Mujeb	31.46635725	35.56297085	31.45092313	35.56359963

On the other hand the main discharge zones in Zara area lie between coordinates of 31.57230500 N, 35.55385840 E and 31.57050383 N, 35.55395937 E, while in Mujeb area it lie at 31.46635725 N and 35.56297085 E.

Some discharge zones and the coordinates are shown in Table 2.

CONCLUSION

The Dead Sea area is very complicated in view of groundwater discharge. Because of the geological structures of the area. Using thermal infrared imagery was very useful to determine the zones of the groundwater discharge into the sea or the ocean.

Using thermal infrared imagery in the Dead Sea area showed many zones where the groundwater discharges into the eastern shores of the Dead Sea. The main zones of groundwater discharge located at three places. The first zone was at Al-Mujeb area at the southern part of the Dead Sea, the second zone was at Zarka Main area and the third main zone was at Zara area at the middle part of the Dead Sae. As well the thermal infrared imagery was very useful for determining the spring locations.

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