Use of electrical resistivity methods for detecting subsurface fresh and saline water and delineating their interfacial configuration: a case study of the eastern Dead Sea coastal aquifers, Jordan

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Abstract The alluvial aquifer is the primary source of groundwater along the eastern Dead Sea shoreline, Jordan. Over the last 20 years, salinity has risen in some existing wells and several new wells have encountered brackish water in areas thought to contain fresh water. A good linear correlation exists between the water resistivity and the chloride concentration of groundwater and shows that the salinity is the most important factor controlling resistivity. Two-dimensional electrical tomography (ET) integrated with geoelectrical soundings were employed to delineate different water-bearing formations and the configuration of the interface between them. The present hydrological system and the related brines and interfaces are controlled by the Dead Sea base level, presently at 410 m b.s.l. Resistivity measurements show a dominant trend of decreasing resistivity (thus increasing salinity) with depth and westward towards the Dead Sea. Accordingly, three zones with different resistivity values were detected, corresponding to three different water-bearing formations: (1) strata saturated with fresh to slightly brackish groundwater; (2) a transition zone of brine mixed with fresh to brackish groundwater; (3) a water-bearing formation containing Dead Sea brine. In addition, a low resistivity unit containing brine was detected above the 1955 Dead Sea base level, which was interpreted as having remained unflushed by infiltrating rain.

Résumé L'aquifère alluvial est la première ressource en eau souterraine le long de la Cote Est de la Mer Morte, Jordanie. Sur les 20 dernières années, la salinité a augmenté dans certains puits existants tandis que les eaux saumâtres sont apparues dans des puits récemment construits. Une bonne relation linéaire existe entre la résistivité de l'eau et la concentration en chlorures des eaux souterraines et montre dés lors que la salinité est le facteur dominant de la résistivité. Une tomographie électrique (ET) à deux dimensions intégrée avec des sondages géoélectriques a été employée pour délimiter les différentes masses d'eau et l'interface qui les sépare. Le système hydrogéologique actuel, les saumures et l'interface eau douce – saumures, sont contrôlées par le niveau de la Mer Morte, 410 m sous le niveau moyen des mers. Les mesures montrent une augmentation de la salinité avec la profondeur et vers la Mer Morte. Trois zones de différentes résistivités ont été détectées, correspondant à trois formations aquifères distinctes : (1) les strates saturées par de l'eau douce à légèrement saumâtre ; (2) une zone de transition entre les saumures mélangées avec les eaux souterraines douces à saumâtres (3) les saumures de la Mer Morte rentrées dans un aquifère. De plus, une unité de faible résistivité contenant des saumures à été détectée sous le niveau de 1955 de la Mer Morte, décrite auparavant comme ayant été resté lessivé par les eaux de pluie infiltrantes.

Resumen El acuífero aluvial es la fuente principal de agua subterránea a lo largo de la línea de costa oriental del Mar Muerto, Jordania. Durante los últimos 20 años, la salinidad se ha incrementado en algunos pozos existentes y varios pozos nuevos han interceptado agua salina en áreas que se pensaba contenían agua fresca. Existe una correlación linear buena entre la resistividad del agua y la concentración de cloruro en agua subterránea lo cual muestra que la salinidad es el factor más importante que controla la resistividad. Se utilizó tomografía eléctrica bidimensional (ET) integrada con sondeos geoeléctricos para delimitar distintas formaciones portadoras de agua y la configuración del contacto entre ellas. El sistema hidrológico actual y las salmueras relacionadas están controlados por el nivel base del Mar Muerto, que se localiza actualmente a 410m por debajo del nivel del mar. Las mediciones de resistividad muestran una tendencia dominante de resistividad decreciente (es decir salinidad ascendente) con la profundidad y hacia el oeste en dirección del Mar Muerto. En consistencia con esta tendencia se detectaron tres zonas con diferentes valores de resistividad las cuales corresponden a tres formaciones acuíferas distintas: (1) estratos saturados con agua subterránea fresca a ligeramente salada; (2) una zona de

Received: 10 June 2004 / Accepted: 1 March 2006
Published online: 30 May 2006

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DOI 10.1007/s10040-006-0034-3

transición de agua subterránea salada a fresca mezclada con salmueras; (3) formación acuífera conteniendo salmuera del Mar Muerto. Además se detectó una unidad de baja resistividad que contiene salmuera por encima del nivel de base que tenía el Mar Muerto en el año 1955, lo cual se interpretó como agua de lluvia infiltrada que permanecía sin lavarse.

Keywords Salt-water/fresh-water relations · Resistivity methods · Dead Sea · Jordan

Introduction

The alluvial fan along the eastern margin of the Dead Sea (hereafter denoted DS), Jordan, consists of fine to coarse-grained siliciclastic sand and pebble-size gravel with thin intercalations of laminated marl of Holocene age. The alluvial shallow aquifer is the primary source of water for domestic, municipal, agricultural, and industrial use in the region, and is an important economic resource for the state. The water in the aquifer has historically been fresh and suitable for most potable uses. Parker (1970) notes that the water quality on the eastern side of the DS shoreline is good and the salinity rarely exceeds 800 mg/L; it is slightly alkaline (pH 7.5–8.0), calcium and magnesium are the predominant cations, and bicarbonate the most important anion.

Over the last three decades, total dissolved solids (TDS) levels have risen in wells located within the coastal shallow aquifer where DS levels have been dropping rapidly. In old wells, which belong to the Arab Potash Company (APC), TDS levels have risen from approximately 800 mg/L to more than 5,000 mg/L (APC, 2002, personal communication). In addition, several new wells (e.g., Isal 2–4, Fig. 1) drilled by the APC in 1994 encountered brackish water (TDS of 4,212–5,430 mg/L) in portions of the DS coastal area previously thought to

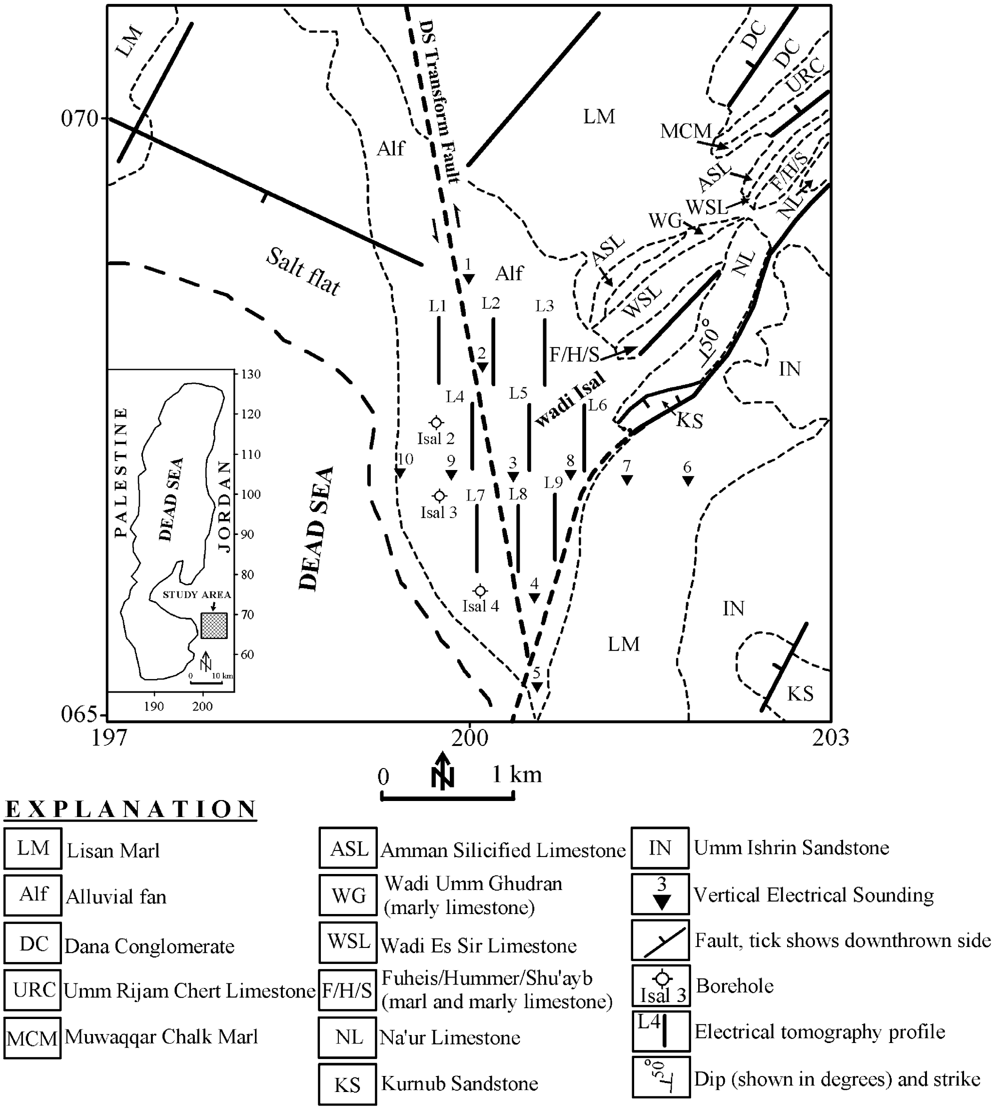

Fig. 1 Surficial geological formations of the study area (Powell 1988), showing locations of electrical tomography profiles and geoelectrical soundings

DOI 10.1007/s10040-006-0034-3

contain fresh water. Furthermore, in the summer of 2002, the water table in the Isal 4 well was drawn down from 9.45 to 20.8 m. In recent years, sinkhole-collapse features have appeared adjacent to the DS shoreline and have become a serious hydrogeological and geotechnical problem (Batayneh et al. 2002).

Due to the scarcity of boreholes in the area which could provide information on the configuration of the different water bodies, two-dimensional electrical tomography (see section Electrical prospecting), utilizing a Wenner array configuration, were performed on nine N-S oriented profiles with several aims: (1) verification of the presence of the different water-bearing formations and estimation of their depth and thickness (generally, the water bodies involved in the study area include freshwater, DS brine and the interface in between); (2) monitoring the changes of the interface configuration as a result of changes of the water table depth; (3) finding the relationship between the resistivity variations and the different configurations of the water-bearing formations; and (4) mapping the water table in the shallow aquifer and selecting new location(s) for drilling.

Results from two roughly N–S and E–W oriented vertical electrical sounding (VES) traverses (Fig. 1) in the Wadi Isal area carried out by El-Isa et al. (1995) within the framework of the Isal Dam Project were taken and presented in order to achieve these aims.

General background

Jordan's surface morphology is dominated by mountainous terrain on the west, which is associated with the DS Transform Fault. The difference in elevation between the rugged highlands and the Jordan Valley in which the DS is located is about 1,300 m. This relief difference occurs over less than a 6-km distance in an E–W direction. The Jordan Valley geomorphic zone is characterized by E–W-trending deeply incised wadis. It is terminated on the west by an escarpment facing the DS. The DS, which is located in the northern part of the Syrian-African rift, is the terminal lake of the Jordan River system, which is the main perennial tributary to the lake (Fig. 1). The DS is known for having the lowest lake level in the world: ~410 m b.s.l. It is located in an extremely arid environment with an annual average precipitation of 70 mm, but it is much higher in the eastern highlands, exceeding 400 mm. The runoff regime in the region is one of flash flooding, which occurs in the large wadis during the rainy winter season. The climate of the region is very hot in summer (April to August) with temperatures in excess of 45°C and less than −5°C in the eastern highlands in winter (November to January). The DS water is a brine with salinity of 340 g/L and density of 1.23 g/mL.

The changes in the DS level have an important effect on the hydrological system in its vicinity. In historical times, there is evidence of DS levels, for tens of years, reaching as high as some 375 m b.s.l. in the 12th, 13th and 16th centuries A.D. sc (Klein and Flohn 1987). In the beginning of the 20th century, the DS level was some 390 m b.s.l. (Fig. 2). Since the early 1960s, large amounts of fresh water have been diverted for irrigation and municipal purposes from the sources of the Jordan River, thereby decreasing the water input to the lake. This diversion and an evaporation rate of about 1 m/year (see below) have resulted in a significant lowering of the water level of the DS to some 410 m b.s.l. (Fig. 2). The decline in the DS water level is followed by a decline in groundwater level (Yechieli et al. 1995). The disconnection of the southern shallow DS Basin from the main water body, which occurred in 1976, has clearly verified the decline in the DS level. The drop in the DS level at rates of about 0.5 m/year since the 1960s was given by Klein and Flohn (1987) and of 0.8 m/year in the 1980s by Anati and Shasha (1989). Yechieli et al. (1998) note that the decrease in the DS level is to continue until a new

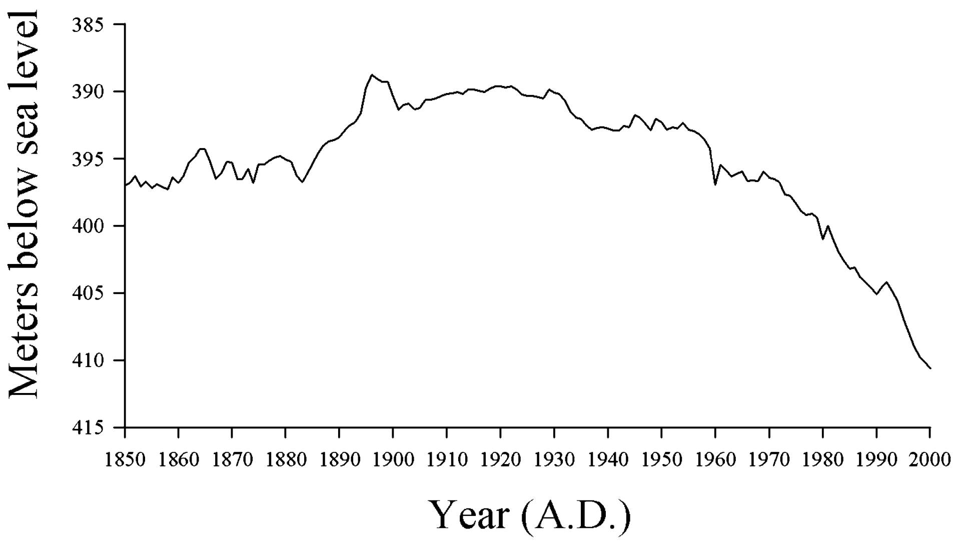

Fig. 2 Historical (b.s.l.) and recent Dead Sea levels (after Klein and Flohn 1987; El-Isa et al. 1995)

 DOI 10.1007/s10040-006-0034-3

equilibrium in the water balance is reached, in about 400 years, at 100–150 m below the present level.

Hydrogeology of the area

The major structural feature in the study area is the eastern border of the DS Rift, where several large normal faults exist. The coastal plain between the faults and the DS consists mainly of Quaternary continental sediments. These constitute clastics (clay, sand and gravel) deposited in fan deltas, with some intercalations of lacustrine sediments (clay, gypsum and aragonite) of the Lisan Marl Formation of Pleistocene age (Powell 1988). The width of the coastal plain varies greatly, from about 1 km in the southern parts of the study area to more than 5 km in the northern parts (Fig. 1).

Four main aquifers are distinguished in the area surrounding the DS (Powell 1988): the deepest and thickest consists of the sandstone sequence of the Ram Group of Late Cambrian age, unconformably overlain by the sandstone sequence of the Lower Cretaceous Kurnub Sandstone (KS) Group. The limestone and dolomite sequence of the Upper Cretaceous Ajlun and Balqa Groups is the third aquifer. These comprise the most important and extensive aquifer in the region because of their wide outcrop in the eastern highlands catchment area. The shallowest aquifer is the alluvial Quaternary aquifer which is bordered by the faults of the eastern margin of the DS Transform Fault (Fig. 1). The main source of fresh-water recharge into the Quaternary aquifer is lateral flow across these faults from the Ajlun and Balqa Groups aquifer, which is replenished in the mountain area some 5–10 km to the east. Flash floods in the Jordan Valley also infiltrate and recharge the Quaternary aquifer.

Electrical prospecting

Two-dimensional inversion techniques are becoming increasingly common and often satisfactory to assess the resolution and determine the limitations of the data set, as shown by Dahlin (1996) and Dahlin and Loke (1998). Nine electrical tomography profiles (L1–L9; Fig. 1) were measured across the area, using Iris Syscal R2 resistivity equipment with a Wenner configuration and 32 electrodes, 5 m apart. The survey traverses were oriented N-S. The method is based on measuring the electrical potentials between one electrode pair (M-N) while transmitting a direct current between another electrode pair (A-B; Fig. 3a). Figure 3b illustrates the pseudo-depth distribution of data points for the Wenner array configuration, used in this study, for a 32-electrode array.

The data were processed with the inversion algorithm, RES2DINV, proposed by Loke and Barker (1996) to obtain a resistivity section. The inversion routine used by the program RES2DINV is based on the smoothness constrained, least-squares method inversion algorithm (deGroot-Hedlin and Constable 1990; Sasaki 1992). The two-dimensional model used in this program divides the subsurface into a number of rectangular blocks (Loke and Barker 1996), and the resistivity of the blocks is adjusted in an iterative manner to minimize the difference between the measured and calculated apparent resistivity values. The latter are calculated by the finite-difference method of Dey and Morrison (1979).

Resistivity field data collected using the Wenner array from individual survey lines were inverted individually to generate a two-dimensional Wenner resistivity model. The inversions were performed on a Pentium III 733 MHz PC with 128 MB of RAM. An initial model is produced, from which a response is calculated and compared to the

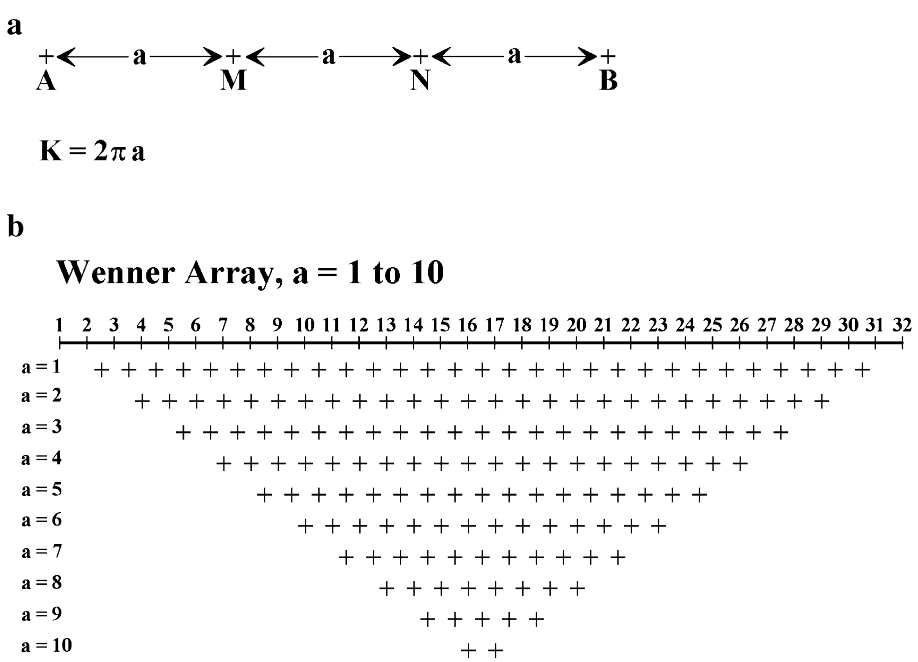

Fig. 3 **a** Wenner resistivity array with its geometric factor. **b** Pseudo-depth distribution of data points for the Wenner array configuration

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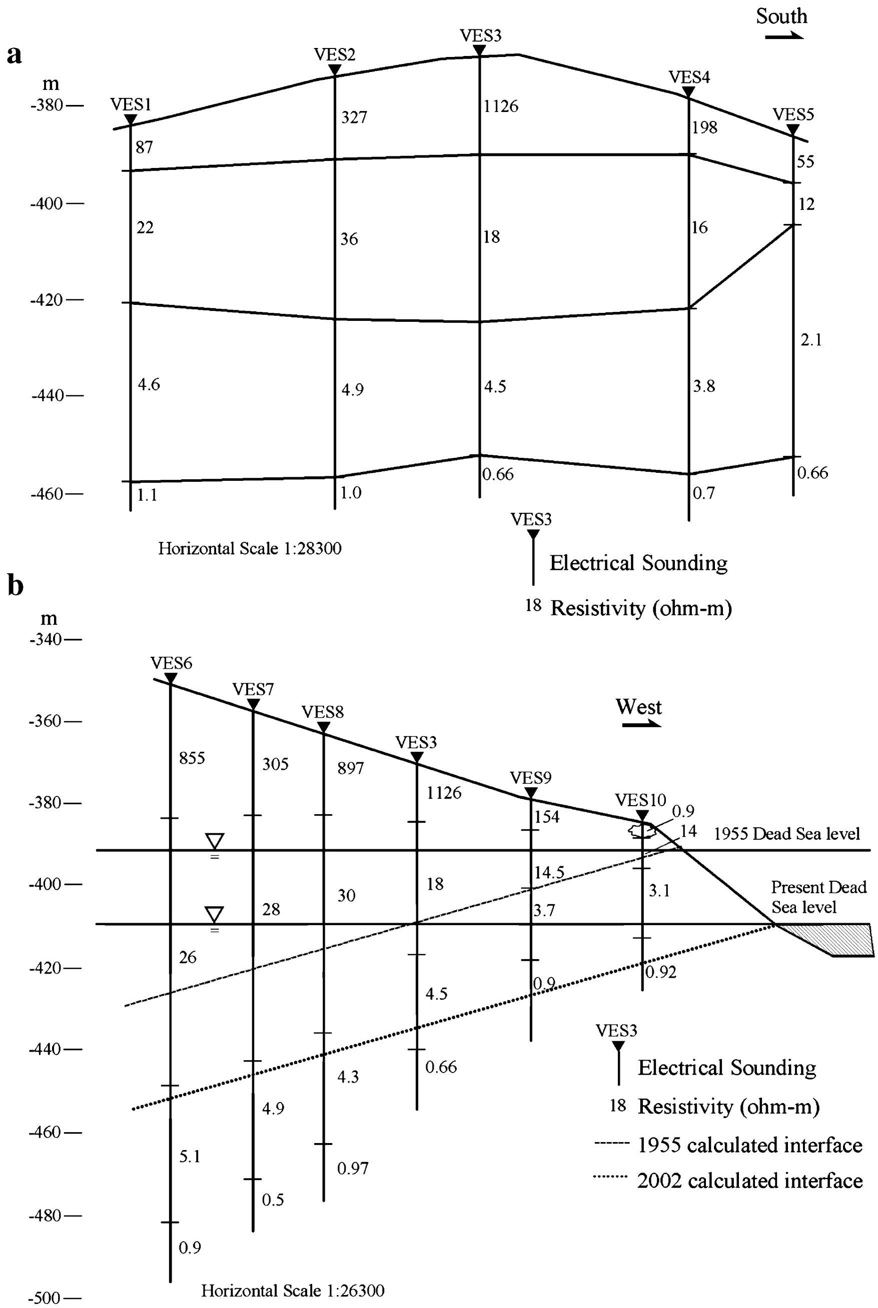

Fig. 4 **a** N–S-oriented VES traverse along the study area. **b** E–W-oriented VES traverse along the study area. Location of interface was calculated according to the Ghyben-Herzberg approximation

measured data. The starting model is then modified in such a way as to reduce the differences between the model response and the measured data; these differences are quantified as a root-mean-square (RMS) error value. This process continues iteratively until the RMS error falls to within acceptable limits, usually below 5%, or until the change between RMS values calculated for consecutive iterations becomes insignificant. The RMS error values calculated for individual two-dimensional Wenner models range from 2.3 to 5.2%. The low RMS error values of below 5% indicate that good fits between the observed and calculated data were achieved at the end of the inversion process, and that measurement noise was low.

Field results

Surface resistivity methods have been used for groundwater research for many years. Earth resistivities are related to important geologic parameters of the subsurface including types of rocks and fluids present, porosity, and degree of saturation (Griffiths and Barker 1993). It was shown by Parasnis (1956, 1966) that the electrical resistivity of rocks and minerals, except for massive sulfides and graphite, vary in a wide range between 1 to 10^7 ohm-m, whereas salt water has a resistivity below 1 ohm-m. Thus, salt water can be easily distinguished from almost any combination of lithological types.

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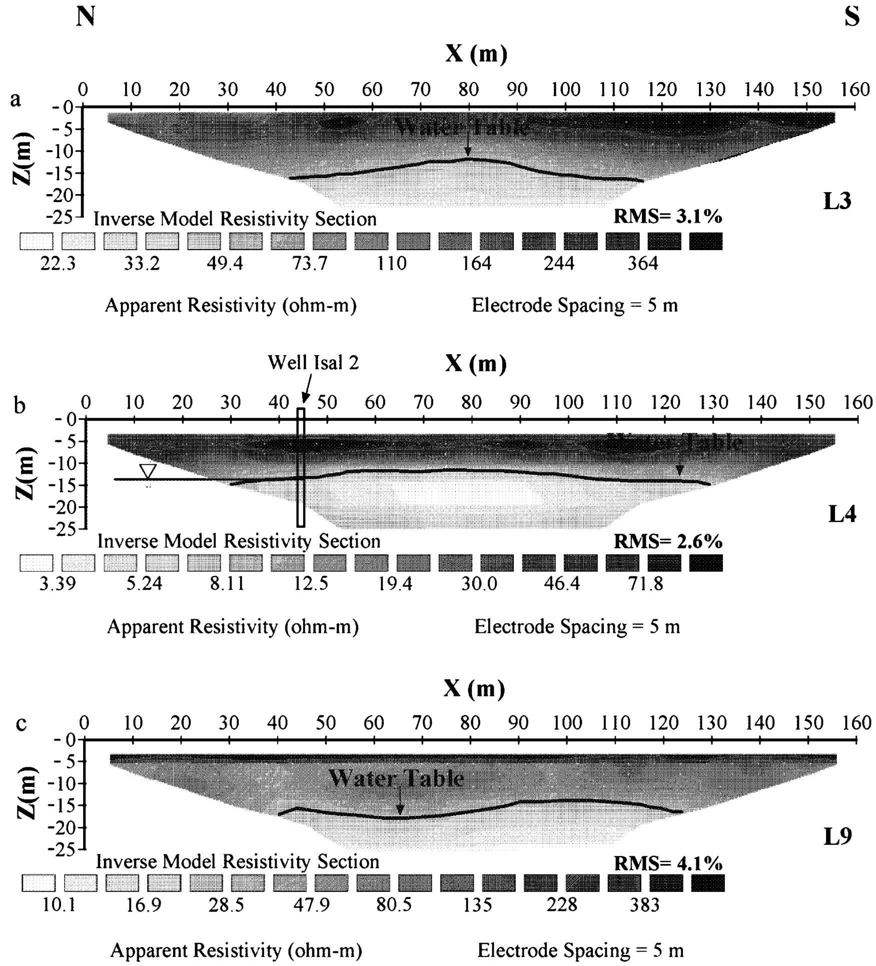

Fig. 5 The result of 2D inversion of Wenner array data for profiles L3 (**a**), L4 (**b**) and L9 (**c**)

Figure 4 shows results from two N–S and E–W-oriented VES traverses in the wadi Isal area (El-Isa et al. 1995). These highlight the configuration of the different water bodies at depths and display some interesting phenomena. The N–S traverse (Fig. 4a) shows that the resistivities decrease (thus salinities increase) with depth and southward, as expected. The resistivity values with depth were subdivided into four zones, as shown in Fig. 4a: (1) resistivities between 55 to 1,126 ohm-m, representing the unconsolidated dry sand and gravel at the surface; (2) resistivities ranging between 12 and 36 ohm-m, reflecting strata saturated with fresh-to-slightly brackish water; (3) resistivities between 2 and 5 ohm-m, reflecting a transition (mixing) zone of brine with fresh-to-slightly brackish groundwater (as seen in Fig. 4a, the transition (mixing) zone is thick (VES 5), corresponding with a thin fresh–brackish water zone); and (4) resistivities below 1 ohm-m, reflecting strata containing DS brine.

The E–W traverse (Fig. 4b) shows the same trend of increasing salinity downward and westward towards the DS. The resistivity values with depth were classified into four zones: (1) resistivities between 154 to 1,126 ohm-m, representing the unconsolidated dry sand and gravel at the surface; (2) resistivities ranging between 14 and 30 ohm-m, reflecting strata saturated with fresh-to-slightly brackish water; (3) resistivities between 2 and 5 ohm-m, reflecting a transition (mixing) zone of brine with fresh-to-slightly brackish groundwater; and (4) resistivities below 1 ohm-m, reflecting strata containing DS brine. This is in agreement with the work of Kafri et al. (1997) and Yechieli et al. (2001) at the western DS side.

Two additional features seen in the E–W traverse (Fig. 4b) include: (1) an unflushed brine body (VES 10), above the 1955 DS level (–392 m), and (2) an eastward-dipping interface, calculated in 2002, between the brine and the fresh-water body and a transition (mixing) zone between them.

The resulting images of the Wenner array along survey lines L1–L9 obtained over the study area show similar characteristics in the resistivity sections. As expected, the resistivities decrease (thus salinities increase) at each profile as one goes deeper or westward towards the DS, as expected.

One model line (L3) over the area north and northeast of well Isal 2 (see Fig. 1) was chosen and presented in Fig. 5a. The background model resistivities are characterized prominently by two zones at depth with different

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properties: the first zone of about 15 m thick shows moderate to high resistivity values 40–360 ohm-m, while the second zone shows apparent resistivity values in the range of 22–40 ohm-m. The resistivity values, 40–360 ohm-m, are considered to represent the unconsolidated dry sand and gravel sediments, while the resistivity values, 22–40 ohm-m, correspond to the fresh-to-slightly brackish water saturated rocks.

The resistivity of one two-dimensional model section (L4) over the area to the east of well Isal 3 (see Fig. 1) is presented in Fig. 5b. Along the survey section L4 (Fig. 5b), the surface layer of sediments, about 16 m thick, has resistivity values of between 8 and 72 ohm-m. Below the surface, layer resistivity values range from 3 to 8 ohm-m, reflecting fresh-to-slightly brackish water-saturated rocks.

Figure 5c shows the model section for Wenner resistivity profile L9 across the study area. The anomalies detected show values of apparent resistivities of 30–383 ohm-m from the surface to 13 m depth. Below the surface layer, resistivity values range from 10 to 30 ohm-m, reflecting strata saturated with fresh–brackish water.

Conclusions

Electrical resistivity surveys, utilizing surface electrode arrays, were carried out along the eastern DS coast, with the aim of providing valuable information on the hydrogeologic system of the shallow alluvial aquifer and delineating the salinity of groundwater and its subsurface configuration. The DC resistivity surveys reveal significant variations in subsurface resistivity within the shallow alluvial sediments. The differences in resistivity are associated with the various lithologic types and variations in water saturation. The salinity is found to be the major factor governing the resistivity, as shown by the good correlation between them. As expected, salinity increases downward and westward toward the DS.

Resistivity measurements reveal the presence of four zones of resistivity values from the surface downward: (1) a zone 8–17 m thick of dry sand and gravel strata at the surface was marked by resistivity values in the range of 40 to 1,100 ohm-m (over the entire aquifer this hydrostratigraphic unit plays a significant role in the hydraulic behavior of the groundwater flow system); (2) the underlying zone, which corresponds with fresh-to-slightly brackish water-saturated rocks, was characterized by resistivity values of 5–40 ohm-m; (3) a transition (mixing) zone of brine with fresh-brackish groundwater was marked by resistivity values of 2–5 ohm-m; and (4) a zone of resistivities below 1 ohm-m, reflecting an aquifer containing DS brine. This ideal picture is interrupted locally by the occurrence of low resistivity (residual brines or salts) water-bearing strata above the 1955 DS water level (VES 10, Fig. 4b). This feature is found in the west, closest to the DS and can be interpreted as resulting from the incomplete flushing of brines or salts related to an earlier DS level.

Acknowledgements The author wishes to acknowledge support received from the Natural Resources of Jordan, Iris Syscal R2 resistivity equipment. The following employees of the Natural Resources Authority, Jordan, are thanked for their aid in collection of field data: O. Jaradat, M. Abu Qau'd, Y. Ainbossi, Kh. Mana'seh, S. Al-Khateib and A. Al-Mazaiedeh. Facilities provided by the Research and Studies Department, Al-Balqa' Applied University, Jordan are acknowledged.

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