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Application of time-domain electromagnetic method in mapping saltwater intrusion of a coastal alluvial aquifer, North Oman

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ABSTRACT

One-third of the population of Oman depends on the groundwater extracted from the alluvium deposits located along the coast of the Gulf of Oman. However, groundwater depletion and seawater intrusion constitute major challenges along the coastal water accumulations in Oman. The objective of this study is to locate the extent of seawater intrusion and to map the shallow alluvial aquifer in the region, where water accumulates from the rain or the flooding at AlKhod dam. In order to assess the effect of groundwater infiltration, which recharges the aquifer and fights the seawater invasion, a quantitative approach for the groundwater quality and distribution is required to provide reasonable knowledge on the spatial distribution of the aquifers, their thickness and the type of sediments. When groundwater wells and their subsurface geologic and electrical logs are not available or not deep enough, surface geophysical surveys can be considered due to their low cost and short acquisition time. The application of time-domain electromagnetic (TDEM) method in Al-Khod area, Oman has proven to be a successful tool in mapping the fresh/saline water interface and for locating the depth of fresh water aquifer. The depths and inland extents of the saline zone were mapped along three N–S TDEM profiles. The depths to the freshwater table and saline interface calculated from TDEM closely match the available well data.

1. Introduction

The intrusion of sea water into alluvial aquifer is a potential source of groundwater pollution in coastal zones. The depth to saline water, inland intrusion and degree of salinization should typically be monitored through a network of piezometers. However, to drill many wells is expensive and only provides information at the specific drilling location. Surface electric and electromagnetic geophysical methods can provide rapid and cost effective delineation and characterization of the intrusion as well as mapping water quality (Young et al., 1998). Contrary to well drilling, TDEM may reveal 3D subsurface variations for quite larger areas at reasonable cost and with relatively high precession.

Time domain electromagnetic (TDEM) sounding is a fast and accurate mean for mapping the depth, thickness and lateral extent of saline intrusion in the coastal areas (e.g. Kontar and Ozorovich, 2006; Al-Garni and El-Kaliouby, 2011). The characteristics of the TDEM responses of the earth to a pulsed primary signal from a large wire loop laid on the ground surface yield information about the variations of the electrical resistivity with depth. TDEM method has been widely used to map saline zones in the coastal alluvial plains, as it offers significant advantages over the conventional resistivity sounding in signal focusing, depth penetration and speed of operation.

The study area is located at the AlKhod town in the lower reaches of Samail Catchment, which extends from the interior mountainous region of Oman into the coastal plain, north of Muscat (Fig. 1). The geophysical field measurements were conducted around AlKhod dam, which represents the oldest and largest recharge dam in Oman. The objective of this dam is to impede Wadi flow from Samail catchment to enhance the aquifer's recharge, providing adequate supply and forming a hydraulic barrier to mitigate the seawater intrusion (Abdalla and AlRawahi, 2013).

The geological cross section of AlKhod Fan, that extends from the dam area to the coastal zone consists of alluvium over 300 m thick across most of the coastal plain, with the maximum recorded depth of more than 600 m at the site on an alluvial terrace. AlKhod Fan comprises a sequence of alluvial deposits, where Wadi Samail drains onto the coastal plain from the northern Oman Mountains, near Seeb (East of Muscat). Three major units dominate the lithological succession of the alluvium: upper, middle and lower gravel units. The upper gravel unit is composed predominantly of large-size gravels including boulders. This unit is loose and very poorly sorted of permeable alluvium with good water quality that makes it the main aquifer zone. The middle unit is discontinuous clayey gravel, which is found in the form of lenses and inter-bedded claystone bands between the upper and lower gravel units. The lower unit is cemented gravel, which is more compacted and conglomeratic, due to the cementation caused by the pressure exerted

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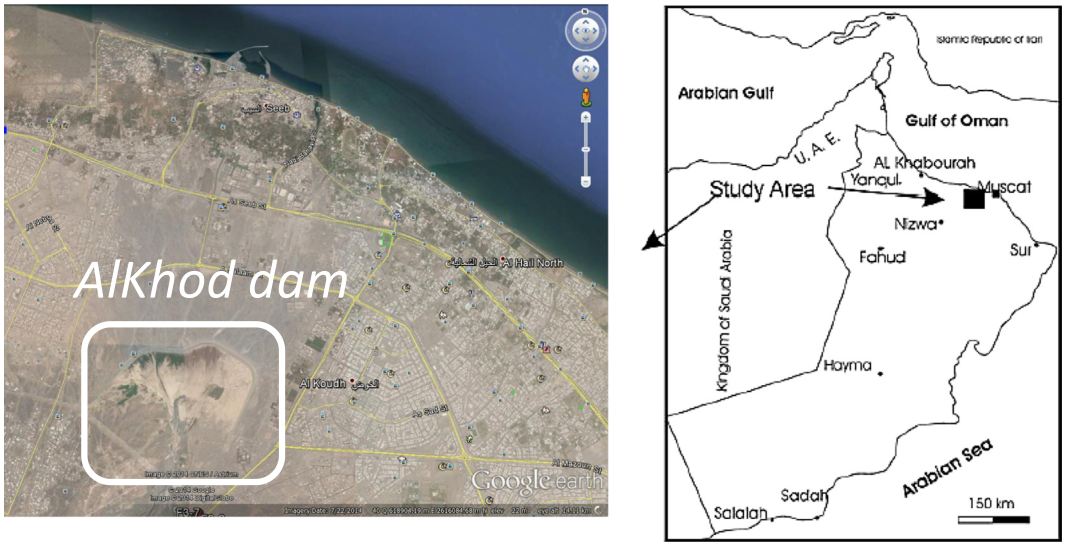


Fig. 1. Location of the study area showing AlKhod dam.

by the overlying sediments (Young et al., 2004; Abdalla and AlRawahi, 2013). Fig. 2 shows a road cut photo showing silty sand intercalated with wadi gravels, pebbles and clays. The figure also shows a representative lithological log from a well in the downstream of AlKhod dam for the first 100 m depth.

The hydrogeological characteristics of this coastal plain show that the saline zone, which advances a few kilometers inland due to seawater intrusion, underlies an important fresh water resource in the layers of loose sand and gravel. Groundwater from the alluvial coastal aquifer is the main source of drinking and irrigation in Northern Oman. Increased abstraction from water wells, declining the water levels, and causing saline intrusion, which can contaminate the potable water supply for Muscat. For these reasons, there is a great concern and a pressing requirement to assess the available groundwater reserve in the northern coastal plain aquifer (Young et al., 1998).

2. TDEM method

Electromagnetic methods have been a group of the primary geophysical methods used in hydrogeological investigations, because of its ability to distinguish between rock units of different resistivities. The time domain electromagnetic (TDEM) soundings have been used extensively to map changes in groundwater quality, which depend on the variation of the electrical conductivity. The ability to acquire vertical and lateral data without drilling makes the TDEM technique quite cost effective, as a non-destructive and non-invasive method, especially in the reconnaissance mapping of the lateral extent of salt-water intrusion, estimating its approximate depth and any changes within the salt-water transition zone (McNeill, 1990; Shah et al., 2007). TDEM soundings are particularly well-suited to delineate the layered structures of interest in geologic, as well as groundwater exploration and for

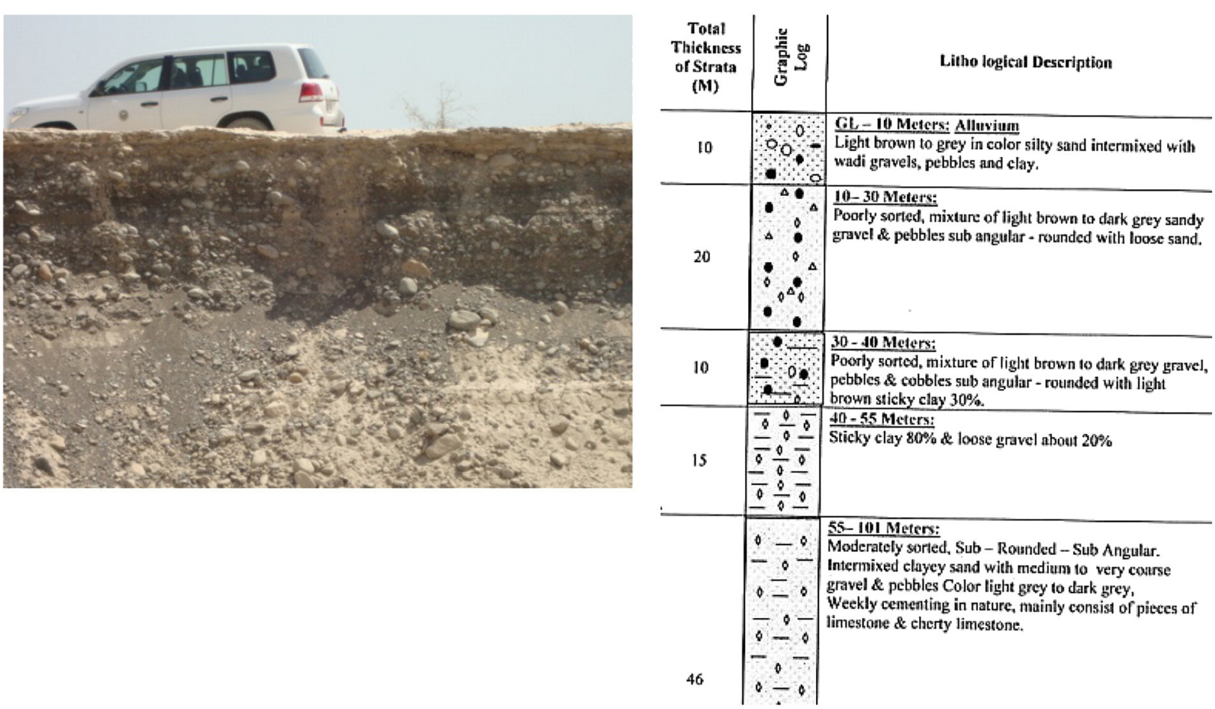
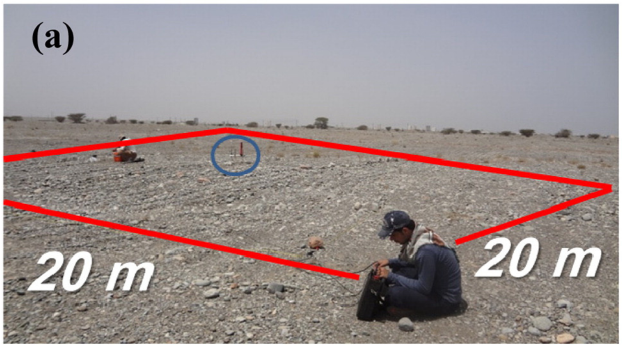


Fig. 2. Field photo showing wadi gravel and silt from a road cut and the lithologic log from a well in the study area.



(b)

Transmitter	Receiver	Rx Coil
Geonics EM47	Protem	HF-1D
Area: 20mx20m Current: 3-4 A TOT: 1.5us	Base Freq. 237.5 (u), 62.5 (v) and 25(H) Hz Time gates: 20	Area: 31.4 m^2

Fig. 3. TDEM central loop sounding setup employed (a) and its field parameters (b).

mapping the boundaries between fresh-water and salt-water in coastal aquifers, because of its ability to detect good conductors, such as clay and shale, as well as saline water environment (Kontar and Ozorovich, 2006; Al-Garni and El-Kaliouby, 2011; Rajab and El-Naqa, 2013). TDEM method is particularly effective in areas with dry surface and it can explore the ground at depths ranging between a few meters to several hundred meters, whereas other geophysical methods such as DC resistivity fails due to the high contact resistance between the electrodes and surface layer and long array to achieve the desired depth (McNeill, 1990).

In TDEM method, current pulses are sent through a large loop laid on the ground. The rapid decay of current at the end of each pulse generates a magnetic field in the vicinity of the loop, which diffuses into the earth. Eddy currents induced by the time-varying magnetic field generate, in turn, secondary magnetic field in the electrically conductive earth. The amplitude and rate of decay of these secondary fields are measured at the surface and analyzed in terms of the variation in electrical resistivity with depth (McNeill, 1994; Shah et al., 2007; Al-Garni and El-Kaliouby, 2011).

3. Field survey

A Geonics Protem-47 system (Fig. 3a), using a 20- by 20-meter square transmitter loop was used to collect the TDEM soundings. A 1-meter-diameter multi-turn loop receiver (Rx) with a 31.4-square-meter effective area measured the secondary magnetic fields at the center of the transmitter loop (Fig. 3a). The Protem-47 transmitter (Tx) used an injection current ranging from 3 to 3.5 amps for the various soundings. Three frequencies were used to collect the voltage data, with preset base frequencies of 237.5 Hz, 62.5 Hz and 25 Hz configured in the Protem TDEM unit to provide information at different depths. The receiver (Rx) unit samples signal amplitudes in terms of 20 subintervals (time gates) during each measurement and collect three voltage data sets for each base frequency.

The apparent resistivity data were plotted as a function of time on a log–log scale. Data points, that deviated severely (a judgment decision) from the curve, were deleted or masked before the inverse modeling. Inverse modeling using IX1D (Interpex), using the smoothed modeling technique, based on Occam's inversion principle (Constable et al., 1987), was used to estimate the geo-electrical distribution of resistivities for each sounding along the profile. A multiple-iteration, smooth-model inversion was computed until the root-mean-square error reached an acceptable limit of about 10% or less. The smooth-model inversion technique minimizes the model roughness subject to the constraint that, the model fits the data to a desired tolerance. After each sounding was inverted using the IX1D, the one-dimensional smooth model for the sounding was imported into one

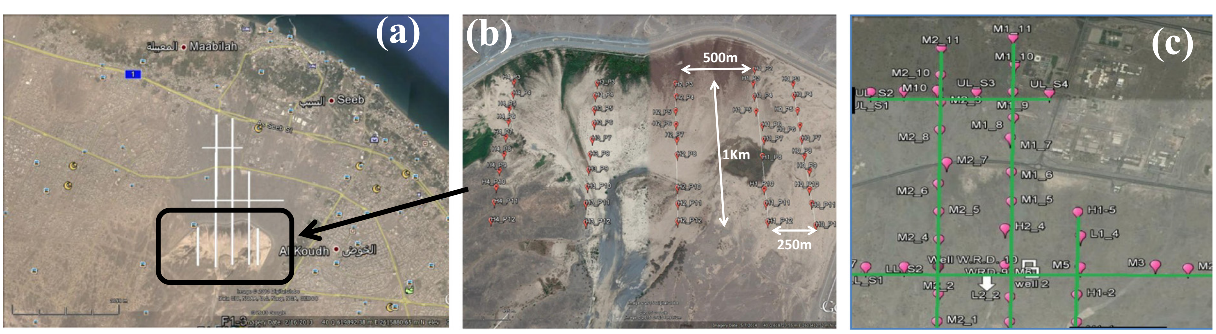


Fig. 4. (a) General view of the TDEM profiles in the study area, (b) 5 N–S profiles behind the dam and (c) 3 N–S profiles in front of the dam towards the sea and 2 E–W profiles.

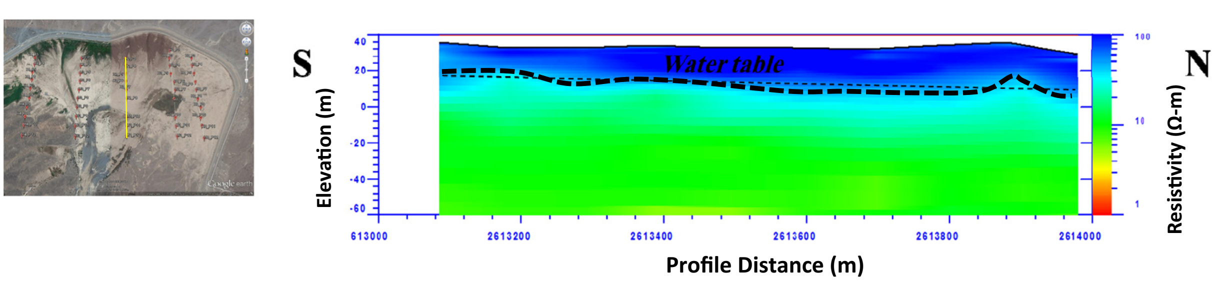


Fig. 5. 2D section showing resistivity distribution based on smooth-model inversion results in the downstream (middle profile) behind AlKhod dam.

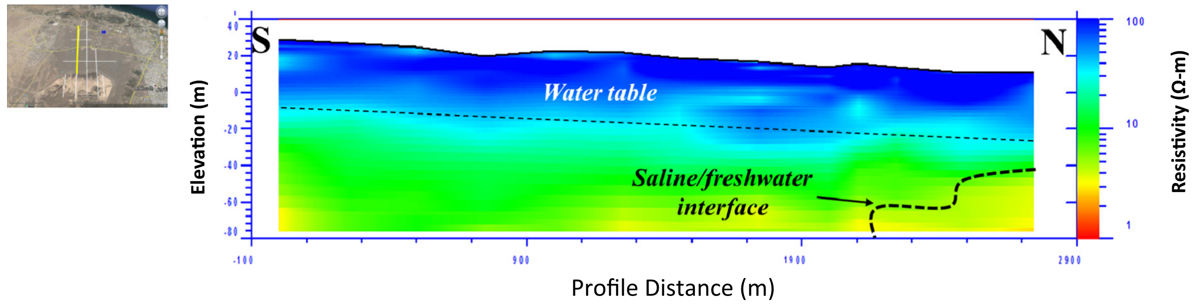


Fig. 6. Resistivity distribution with depth in the upstream of AlKhod dam towards the sea.

profile to generate a 2D geoelectrical cross section with depth (Figs. 5–12).

Seven profiles were selected to determine the variations in electrical properties across the study area from AlKhod dam towards the sea (Fig. 4a). Five N–S profiles were measured in the upstream behind the dam (Fig. 4b), the length of each profile is 1 km with 100 m station interval and 500 m line interval. The middle three profiles were extended further north towards the sea in the downstream part for mapping the saline water intrusion, and two E–W profiles were measured to examine the lateral changes at the southern and coastal parts of the study area in front of the dam (Fig. 4c). We avoided some urban features, such as power/pipe lines that might hinder data collection because of electromagnetic noises.

4. Results

4.1. N–S profiles

The results shown in Figs. 5 and 6 are for one of the N–S profiles starting behind the dam in the downstream part (Fig. 5) and continuing further north after the dam in the upstream part (Fig. 6) towards the sea. Fig. 5 shows three layers of different resistivities, the first upper layer is of relatively high resistivity (100–200 Ω·m) and extends to about 20 m, corresponding to the dry gravels. From 20 to 40 m, the resistivity decreases to 20–40 Ω·m, representing the fresh water saturated gravel, with a water table 20–30 m depth. The third layer extends to more than 90 m depth, showing a decrease in resistivity (5 to 10 Ω·m), due to the presence of clays infiltrated with water from the surface layer and the presence of clayey gravel in the subsurface. These data fit well with the lithologic log (Fig. 2) extracted from one of the wells in the study area in front (downstream) of the dam (Fig. 5).

Fig. 6 shows a similar pattern, but we can notice a lower resistivity in the fourth layer (<5 Ω·m), as we approach northward towards the sea at a depth of 60–80 m, which can be attributed to saline/freshwater interface at the northern stations, since its distance from the sea is about 3 km. The resistivity of the intruded zone increases with distance from the sea towards the land, indicating decreasing salinity. There are zones of low resistivity at the southern and middle parts of the profile, which could be attributed to clayey gravel zones. The top layer above the saline zone has good resolution of horizons, indicating the water table.

Fig. 7 shows another long profile (5 km length) that extends from behind the dam towards the sea. Again, we can notice that, the northern

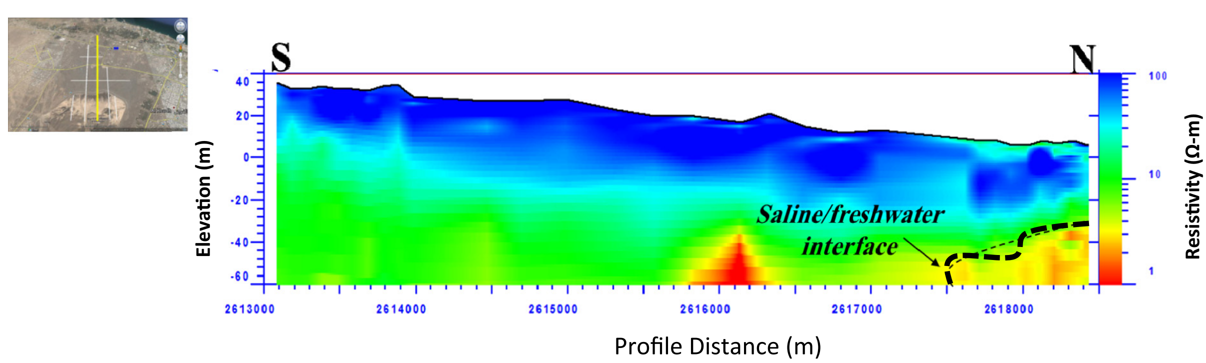


Fig. 7. Resistivity distribution with depth from the upstream of AlKhod dam towards the sea, showing the fresh/saline water interface.

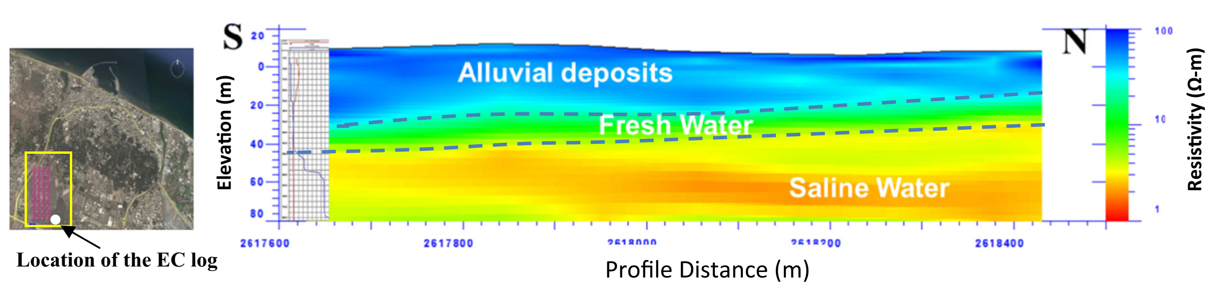


Fig. 8. TDEM profile showing the resistivity distribution with depth in the northern part of the study area close to the sea, as correlated with an EC log from a well near the Southern station.

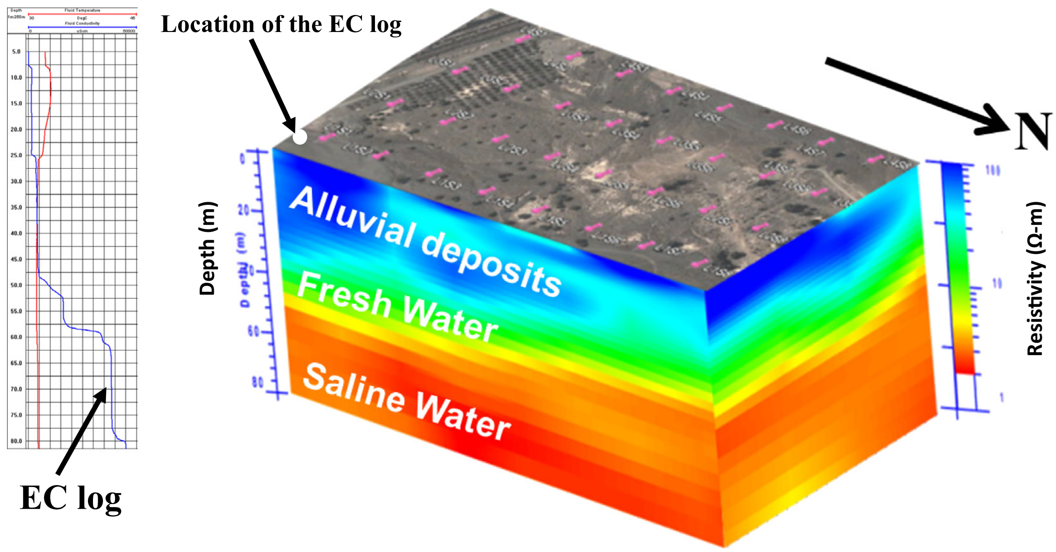


Fig. 9. 3D TDEM plot, showing the resistivity distribution with depth in the northern part of the study area (900 m × 400 m) close from the sea correlated with EC log from a well at the SE corner of the survey area.

stations show very low resistivity since their distance from the sea is about 2 km. There is another low resistivity zone in the middle part of the profile that may be attributed to the phenomenon of upconing of saline water due to intensive pumping of groundwater as the area contains 50 abstraction wells pumping water for domestic supply. However, it might also be attributed to 1D inversion artifact for 3D low resistivity structure.

The northern part of the study area towards the sea was studied in more details to determine the extension and depth of the saline water interface at better resolution. Four profiles, extend for 900 m length and 400 m width, were measured with 100 m station interval and 100 m line interval, as in Google Earth map of Fig. 8. The depth of saline zone interpreted from the TDEM soundings and the one inferred from the borehole fluid electrical conductivity (EC) logging is correlated. We can notice that, the lower resistivity zone gets shallower, as we approach the sea northward and correlates well with the EC log data of a nearby well located near the southern station of the profile, where the EC starts to increase at a depth of 50 m (2000 µS/cm) and get higher to 3000–4000 µS/cm at 60 m depth, which corresponds to a resistivity range of about 2–3 Ω·m (Fig. 8) corresponding to brackish water. Fig. 9 shows a 3D plot of two N–S (900 m) and E–W (400 m) profiles near the coast, showing the saline/fresh water wedge and its correlation with the measured EC log located at the southeast corner of the surveyed area. The results indicate that the sea water intrusion extends to about 3 km from the shore. The brackish water depth starts from 50 to 60 m and extending upward and northward towards the shore. The base of the saline zone is not well resolved by this loop configuration. A larger TDEM loop size will be required to detect the base of the saline water at depth. It is reported that the depth to sea water extends to 180-200 m based on well data.

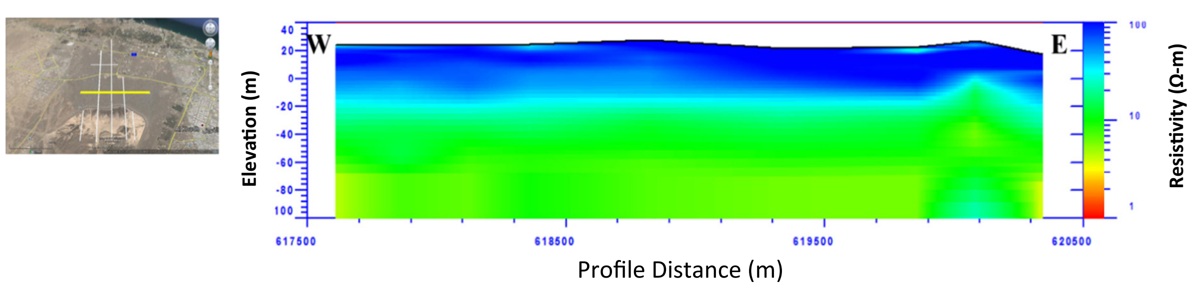


Fig. 10. Lateral resistivity distribution with depth in the southern part of the study area in front of the dam.

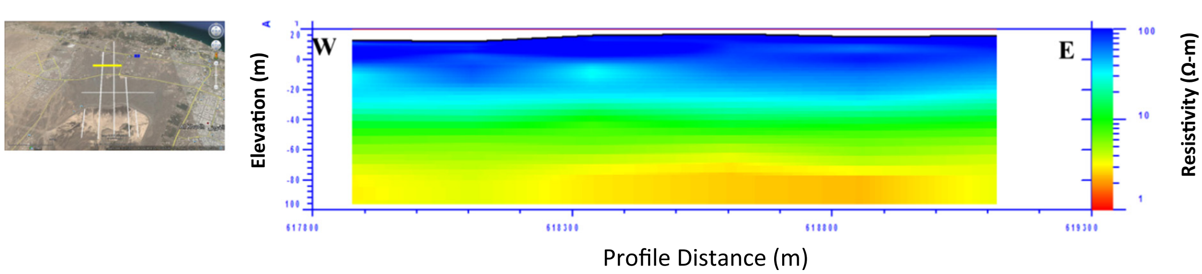


Fig. 11. Lateral resistivity distribution with depth in the northern part of the study area towards the sea.

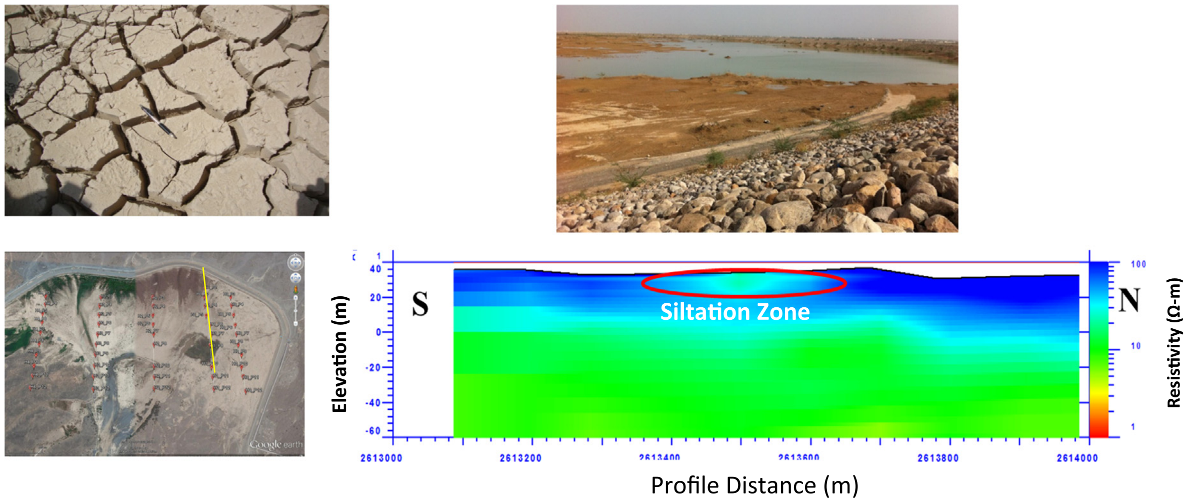


Fig. 12. Lateral resistivity distribution with depth in the downstream (behind AlKhod dam) showing the effect of siltation near the surface.

4.2. E–W profiles

Two E–W profiles at the upstream part were measured to investigate the lateral changes in resistivity in front of the dam and close to the sea. Fig. 10 shows the profile that is inland close to the dam, where it does not show any effect for the salt water intrusion indicating that the water infiltrated from the dam pushed the saline water towards the sea, while the second E–W profile (Fig. 11) at the northern part of the study area shows low resistivity at a depth, that could be due to brackish water, but this low resistivity could also be attributed to the clayey gravel layer.

5. Siltaion effect

The water flowing from the highlands of Oman's mountains towards the coastal plain carries significant portion of silt and sand, which accumulate and deposit at AlKhod dam reservoir and may then infiltrate with the water. The fine particles of the silt, which precipitate within the sediments blocking the interconnected pores and hence reduce the porosity, permeability and infiltration rate (Abdalla and AlRawahi, 2013). Since the only affected area by siltation is the one inside the dam's reservoir, it was important to determine the zones in which the silt infiltrated and its thickness from the surface.

Fig. 12 shows one of the N–S profiles within the dam's reservoir. Fig. 4b showing a low resistivity surface zone that is attributed to the surface water trapped within the thick silt zone causing a slow infiltration of the water, which causes the low resistivity readings within high resistivity surface layer. The other profiles did not show clear silt zones as in Fig. 5. This is because we used a 20 × 20 m loop. In order to better identify thin silt zones, it is recommended to use a smaller loop size (10 × 10 m or 5 × 5 m) to have a higher resolution of the first surface layer.

6. Conclusions

TDEM method is a quick and powerful tool for mapping the fresh/saline water interface and for identifying salinity variation as demonstrated by the current study. It also successfully locates the depth of fresh water alluvial aquifer in AlKhod area, Oman. TDEM offers important advantages over the conventional resistivity depth sounding for mapping the electrically conductive saline zones in the arid environment with improved depth of penetration, depth resolution and speed of acquisition. TDEM has also revealed the role of the recharging dam to counter advance the saline intrusion inland.

To adequately define the relations between the subsurface resistivity measured by the TDEM methods and the spatial changes in water quality, additional borehole-geophysical data are needed for more detailed quantitative interpretation. Further time-lapse TDEM measurements are recommended to monitor the movement of the fresh/saline water interface over time. TDEM measurements with small loop at the dam's reservoir could better delineate the thickness of siltation zones with higher resolution. Running a time-domain induced polarization TDIP survey could be useful to confirm the zones of clayey gravel as it shows high chargeability.

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