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Detection and determination of groundwater contamination plume using time-lapse electrical resistivity tomography (ERT) method

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Abstract
Protection of water resources from contamination and detection of the contaminants and their treatments are among the essential issues in the management of water resources. In this work, the time-lapse electrical resistivity tomography (ERT) surveys were conducted along 7 longitudinal lines in the downstream of the Latian dam in Jajrood (Iran), in order to detect the contamination resulting from the direct injection of a saltwater solution in to the saturated zone in the area. To investigate the pollutant quantities affecting the resistivity of this zone, the temperature and electrical conductivity measurement were carried out using a self-recording device during 20 days (before and after the injection). The results obtained from the self-recording device measurements and ERT surveys indicated that in addition to the salt concentration changes in water, the resistivity changes in the saturated zone were dependent on other factors such as the lithology and absorption of contaminants by the subsurface layers. Furthermore, the expansion of contamination toward the geological trend, sedimentation, and groundwater flow direction of the area were shown.

Keywords: *Saltwater, Saturated Zone, Electrical Resistivity Tomography (ERT), Jajrood, Iran.*

1. Introduction

Demand for healthy waters is increasing considerably as the industrial necessity grows simultaneously. However, preserving and recovery of water resources are pretty important aims for many water authorities all around the world. In this paper, the potential influences of the inorganic substances dissolved in groundwater on its electrical conductivity are discussed. Our objective was to roughly evaluate the usefulness of the time-lapse electrical resistivity tomography (ERT) measurements for the detection of contaminants dissolved in groundwater. The surface tracing methods are precious due to the difficulty in accessing groundwater and high costs of conventional methods like drilling to delineate a polluted groundwater. The geophysical methods, and, as a subcategory, the geoelectrical ones are very popular and common to get the best and most reliable results. These methods provide a valuable data on the hydrodynamic properties of groundwater and contaminant plume to forecast their probability and preferential dispersion and diffusion pathways. The efficiency of geoelectrical methods in obtaining precise information in a short time with a low cost has caused a daily increase in the intention to use this method in determination of the contaminated areas in a groundwater [1]. To determine the groundwater flow directions and velocities, the geoelectrical measurements in combination with the salt tracer injections have been used for many years [2-4].To the shallow aquifers, direct current resistivity measurements at the surface allow monitoring a salt tracer spreading over large areas [5-8]. The time observations made for detection of a contaminated area is limited to several days or several weeks, depending on the dilution process [9]. Sufficient information on the changes in the electrical conductivity of water for estimation of the rate of salt in water or the placement of electrodes would be useful for the contamination monitoring measurements [1]. In 1983, Daniel W. Urish [10] investigated the efficiency of the geoelectrical surface methods in revealing the contamination of groundwater. Based on his findings, the results of such studies would have a great influence on the determination of the place of drilling borehole for sampling and mapping the contamination. His method is based up on revealing the static behavior of the contamination mass. It does not record the movement of this mass but determines the contaminated area [10]. In 1992, Kollman and his colleagues [11] investigated the direction and velocity of groundwater in an aquifer at a depth of 3 m in Austria using a geoelectrical method. They conducted geoelectrical sounding and profiling after injection of a saltwater tracer in to the aquifer, and obtained the direction and velocity of groundwater [11]. The lack of full compliance of the designed geoelectrical network with the general direction of groundwater in their investigation, resulted from the shortage of local investigations and lack of a conceptual model from the situation of local aquifer. In this research work, first, the electrical conductivity changes in the saturated zone as a result of injection of saltwater into the saturated zone in different time intervals were investigated and analyzed. In order to analyze the reasons for these changes, the temperature and electrical conductivity of groundwater were measured using a self-recording device at the saturated zone. Then the contamination resulting from the direct injection of saltwater solution into the groundwater was conducted by the ERT method. For this, ERT surveys were carried out along 7 longitudinal lines using a dipole-dipole electrode array in 6 different time intervals. First of all, an ERT survey was conducted at zero time, and it was considered as the background survey. Then a saltwater solution was injected into the saturated zone as the contamination plume in the borehole No. 1 (located in the upstream of the groundwater flow), and simultaneously, measurement of the changes in the conductivity values for groundwater in the borehole No. 2 (Figure 2) was carried out by continuous sampling of water at one-hour time intervals. The ERT surveys were carried out in 5 other times (simultaneous with the injection of saltwater solution, and one, two, three, and four days after the injection). Finally, the results obtained from the direct observations (measurements made using the self-recording device) and those obtained from the indirect observations (geophysical measurements) were compared. The geographic location of the test site is shown in Figure 1. In Figure 2, the locations of the drilled boreholes and also 7 longitudinal lines of the ERT surveys in the area are demonstrated.

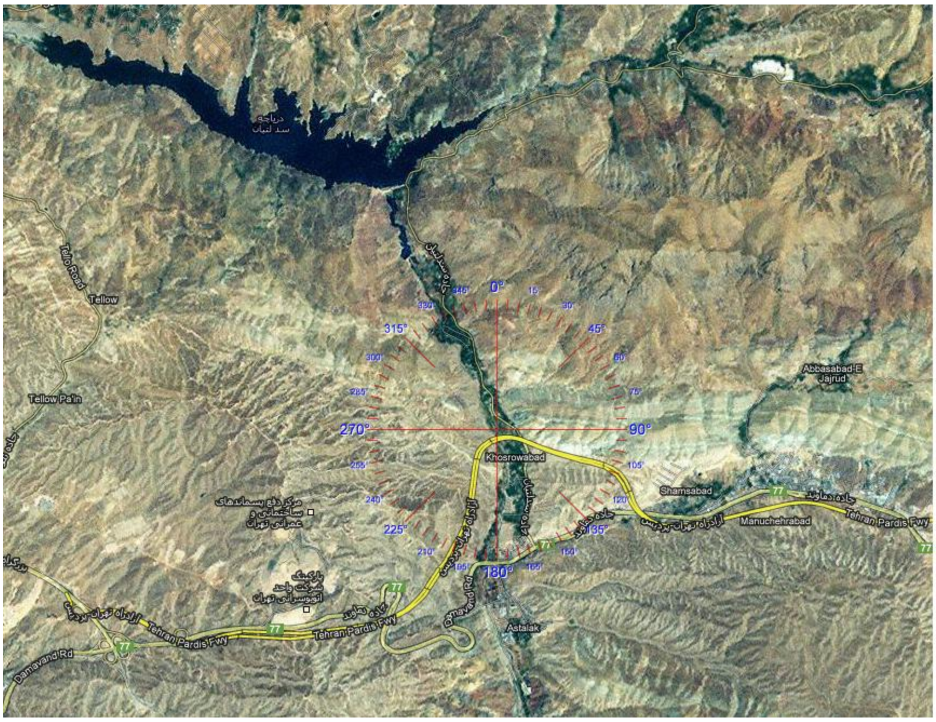

Figure 1. Geographic location of studied area.

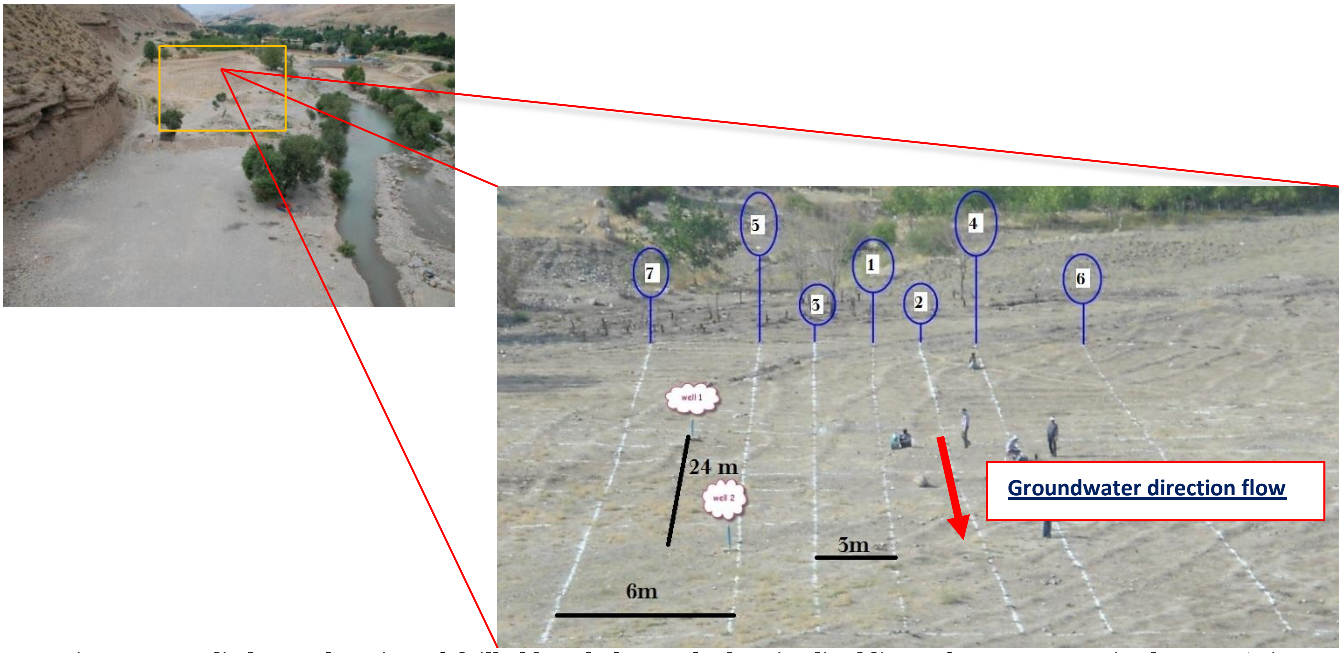

Figure 2. Studied area, location of drilled boreholes, and 7 longitudinal lines of ERT surveys in the area (View toward northwest).

2. Geological setting

The test site was situated 25 Km east of Tehran, downstream Latian dam, upstream Jajrood village, and southwest bank of the dam at the outlet of the river located beneath the Tehran-Pardis Freeway Bridge. Knowledge on the geological trend and background variations in the electrical conductivity is helpful to specify the amount of salt to be injected or to place the electrodes for the monitoring measurements. The geological information of the studied area was obtained via the hydrological and geological evaluations and two boreholes drilled in the studied area. The main geological feature of the studied area, as shown in Figure 3, is the Hezardareh formation. The observable specifications of the alluvial formations included the following: high thickness of about 1200 m and its homogeneity; its regular bedding; locally contain layers and lenses of clay and sandstone; good and hardened cement; average size of rubbles (10-25 cm); color of light grey; high slope of layers (till 90 degrees) and their folding; and semi-circular rubbles, 90% of which are from the Karaj formation and 10% from other rocks or formations. The information obtained from borehole No.1 is shown in Figure 4.

Figure 3. Hezardareh formation in studied area.

2.1. Temperature and electrical conductivity (EC) changes of groundwater in studied area

The decomposed ions can move in water as a result of electrical potential. Thus, by entering an electric current to the solution, its EC can be measured. The capacity of a solution to conduct current is a function of the concentration ions and the rate of motion of these ions in the solution. The amount of EC of water is influenced by its temperature. As the temperature of water increases, its EC increases as well. Thus EC of water should be measured simultaneously with the temperature [12]. The numeric EC values for different types of water are given in Table 1.

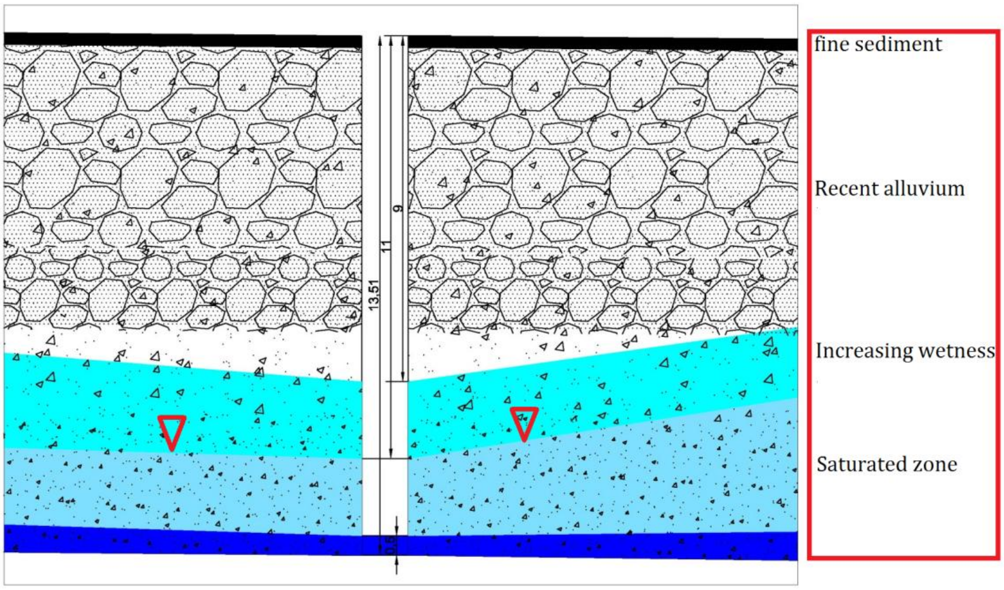

Figure 4. Geological information about studied area obtained from borehole No. 1 drilled in area.

Table 1. Numeric EC values for different types of water [13].

Type of water	EC
clean	50
Very Clean	500
Brine	1000
Very brine	30000

The factors changing EC of underground water include the soil moisture, level of groundwater, temperature, and concentration of the ions existing in the groundwater [1]. The changes in temperature and EC of water in the saturated zone were measured by a self-recording device. Measuring the temperature of the water in a well, is of great importance for the thermodynamic computations with regard to the chemistry of the water. It can give information about the other hydraulic properties of water and its resistivity properties or can relate to them [12]. The temperature of groundwater in the two boreholes No. 1 and 2 during 20 days was divided into two parts before and after injection (Figure 5a). The sum of water volume was equal to 1000L, and 300Kg of salt was added to it. It should be mentioned that the water used for preparation of the solution was taken from Jajrood River. The saltwater solution was injected in borehole No. 1 from 8:15 to 8:50 in the morning on Thursday 20/09/2012.

The temperature variation from 14.1 ^{o}C to 14.3 ^{o}C in borehole No. 1, shows a smooth temperature variation before injection. After injection, the variation increased from 14.1 to 16.4 ^{o}C in the first day, decreased in an exponential form, and reached 14.5 ^{o}C. The temperature change in borehole No. 2 varied from 14.3 to 14.9 ^{o}C before injection, and from 14.5 to 14.7 ^{o}C after injection. Figure 5b also indicates EC changes of groundwater in the two boreholes No. 1 and 2.

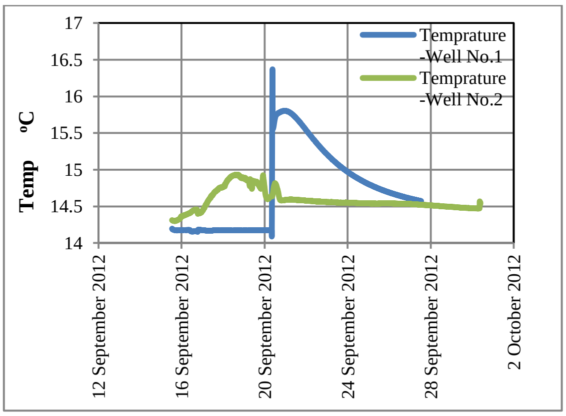

Figure 5a. Temperature changes of groundwater in two control boreholes.

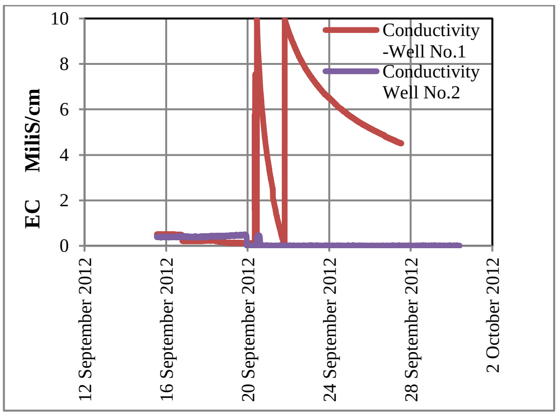

Figure 5b. Chart for EC changes of groundwater in two control boreholes.

EC of water can result from variation in temperature based on the following equations [14]:

$$\sigma = \sigma_0 f(T) \quad (1)$$

T, T_0 Fluid temperature at time t, t_0

σ, σ_0 EC of fluid

F(T) Factor of changing fluid temperature

$$F(T) = \frac{1+\alpha_T(T-18)}{1+\alpha_T(T_0-18)} \quad (2)$$

α_T Temperature coefficient, decreasing with T

$$\alpha_T[\pm 18^\circ C] \approx 0.025^\circ C^{-1} \quad (3)$$

The equation (1) was developed for temperatures around 18 ^oC. As groundwater temperatures are lower, this is just a rough approximation. In Figure 6, the calculated results obtained were plotted using the Dachnov equation. This diagram shows the relative changes in the electrical resistivity due to temperature changes.

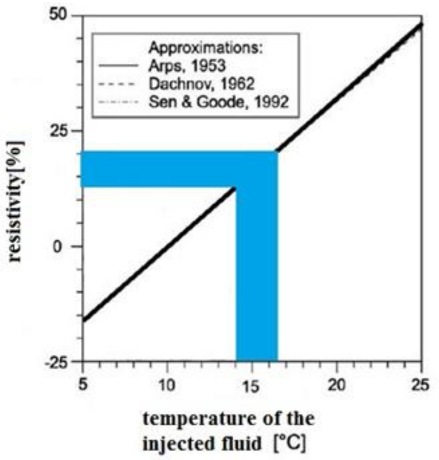

Figure 6. Chart of relative change in electrical resistivity of groundwater due to temperature variation.

As it can be seen in Figure 6, the variation in temperature (which was 0.2 ^oC before injection) resulted in resistivity changes of approximately 0.8%, showing low changes. The temperature change, which was 2.3 ^oC after injection, resulted in 7% resistivity. At borehole No. 2, the resistivity changes were 2% before injection, and 1% after injection. This result can be justified because of the dilution of saltwater in groundwater leading to a relatively homogeneous resistivity medium (i.e. groundwater). At this borehole, higher changes in temperature after injection also caused formation of a more homogeneous resistivity medium at this borehole.

As the concentration of ions increases, the relation between the concentration of ions and EC of the solution becomes linear. The composition of ions dissolved in groundwater, depends on the geological background. The rate of ions can be different due to various reasons including the change in the components solved in the water, leaching processes in the vadose or unsaturated zone and also the processes of saturated zone [1]. The changes in EC of the saturated zone, is divided into two parts (before and after injection). By looking at the results obtained from the EC measurements, the trends are obvious (Figure 5b). The evaluated relative groundwater conductivity variation in borehole No. 1, displayed a smooth trend from 0.1 to 0.2 mS/cm before injection. This trend increased from 0.1 to 10 mS/cm in the first day, and decreased exponentially to 4.3 mS/cm. The conductivity change in borehole No. 2 before injection was 0 to 0.2 mS/cm, and after injection, it changed from 0 to 0.1 mS/cm. The composition of the ions dissolved in groundwater depends on the geological background. The ions content can vary for different reasons, e.g. varying dissolved components in precipitation water, leaching processes in the vadose zone, and processes in the saturated zone. These processes depend on the climatic conditions, intensity of biological degradation, residence time of water in the subsurface, and flow conditions in the ground water [1].

3. Results

By pumping water within one hour from borehole No. 2, it was found that the approximate direction of the groundwater flow was N315, which accords with the general direction of groundwater, surface water, and hydraulic gradient of the area. After pumping water for one hour from borehole No. 2, the direction of groundwater entry into the borehole was observed and measured to be about N315. As shown in Figure 2, borehole No. 1 was drilled at a distance of 24 m from borehole No. 2, and in the southeast direction of this borehole so that azimuth from borehole No. 1 to borehole No. 2 was approximately N315 (i.e. in the groundwater flow direction).The upstream and downstream of the groundwater flow could easily be observed in boreholes No. 1 and 2, respectively, indicating the hydraulic gradient of the studied area. Also, while measuring EC of groundwater by the self-recording device, the velocity of groundwater was also measured to be 6 m per day. Pouring a dye tracer into the groundwater in borehole No. 1 and taking it in borehole No. 2 made it possible to measure the velocity and direction of groundwater flow in the area. By taking into account the changes in the electrical conductivity and temperature, the followings are expected:

- Decreasing resistivity of groundwater exponentially after injection in borehole No. 1, and its movement toward groundwater flow direction (borehole No. 2).
- No evidence of contamination at the 4th day after injection.
- Changes in conductivity depending on other factors such as lithology and contamination absorption by the subsurface layers in addition to changes in concentration and temperature of groundwater.

These results were confirmed by the geoelectrical and geological field observations in the studied area.

3.1. Geophysical surveys

To verify the conclusion made in the previous section, the ERT method was performed at the test site. By applying the 3D ERT method, the hydrodynamic specifications of the aquifer and the subsurface geometric distribution of the electrical conductivity was obtained. The inhomogeneity with certain electrical specifications was detected, and their distribution was specified. The ERT field data obtained was inverted to achieve models of subsurface electrical specifications, and then, these models were compared with the simultaneous results obtained from the direct observation of the salt tracer as the control device.

3.2. Data acquisition

To evaluate both the lateral and vertical resistivity variations, measurements along a profile and with expanding electrode configurations, the time-lapse ERT surveys were conducted using dipole-dipole array. The data obtained was analyzed after being processed. Designing the survey lines was carried out, considering the importance of survey path for contamination detection, general direction of groundwater flow, and executive state of the plan of this research. The dipole-dipole measurements on each survey line were first made with 12 m intervals. For speeding up the survey of lines, the current electrodes were fixed, and the 12 m distanced potential electrodes were moved further until the desired n was obtained. Then, the current electrodes were moved 3 m forward along the line, and again, the potential electrodes were moved from n =1 to the desired n, and the movements were continued until the desired n (maximum n = 8) was obtained. After completion of drilling the boreholes, whose positions are shown in Figure 2, and before injection of the saltwater solution in borehole No. 1, the ERT survey of longitudinal lines was conducted (background survey). Then, further ERT surveys were made simultaneously with the injection, and 1 day, 2 days, 3 days, and 4 days after the injection.

4. Results

After acquiring the ERT data, a 2D inverse modeling was made on the apparent resistivity field data obtained from each survey line at different times. Then the inverted 2D resistivity data was combined to construct the 3D time resistivity sections for the depths of 11 and 15 m. The horizontal axis X on Figures 7a and 7b shows the distance of the dipole-dipole array center in each measurement from the beginning of the survey lines with a northwest-southeast direction. The horizontal axis Y also shows the distances of the survey lines from each other, and the vertical axis shows the time in which each day was specified by 10 time units.

4.1. 3D resistivity time section in depth of 11 m

The 3D resistivity time section for depth of 11 m is shown in Figure 7a. As it can be seen, before the injection into the saturated zone, the resistivity in the 3D section was 220 to 250 Ωm. Simultaneously, with the injection of saltwater solution, an approximate 20 Ωm reduction in resistivity was clearly observed in the section. At the times of one day (20 units) and 2 days after the injection (30 units), the contamination as the resistivity of the studied area, decreased.

4.2. 3D resistivity time section in depth of 15 m

Figure 7b demonstrates the 3D resistivity time section for depth of 15 m. As it can be seen, before the injection, the resistivity value was 125 to 150 Ωm. Reduction in the resistivity values can be observed simultaneously with the injection of the saltwater solution (10 time-units on the vertical axis), one day (20 time-units), 2 days (30 time-units), and 3 days (40 time-units) after the injection of saltwater solution. On the 4th day after the injection of saltwater solution, almost no sign of contamination was observed on the 3D resistivity time section, implying a sign of strong dilution of contamination. The contamination spread toward southeast, which was the same direction as the groundwater flow. At the time of one day (20 units) and 2 days after the injection (30 units), we observed contamination as the resistivity of the studied area decreased.

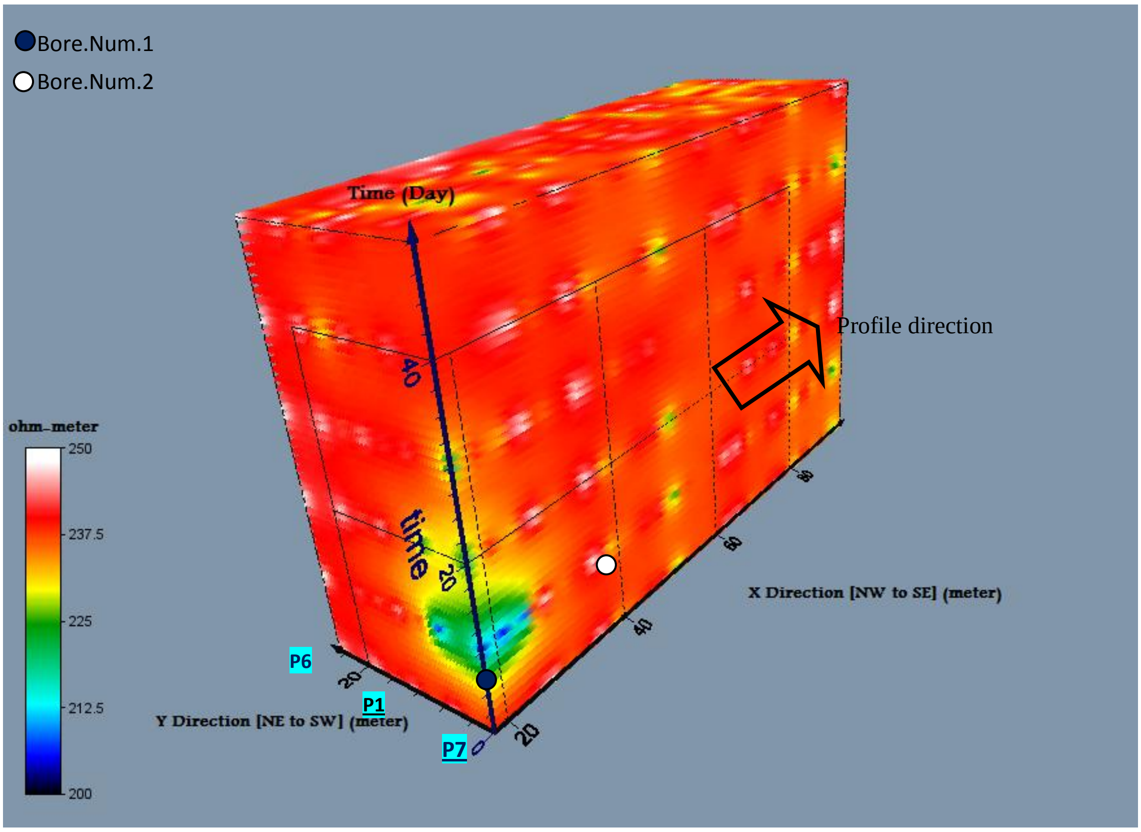

Figure 7.a. 3D resistivity time section for depth of 11 m obtained from 2D inverse modeling of resistivity data from ERT surveys along different longitudinal lines.

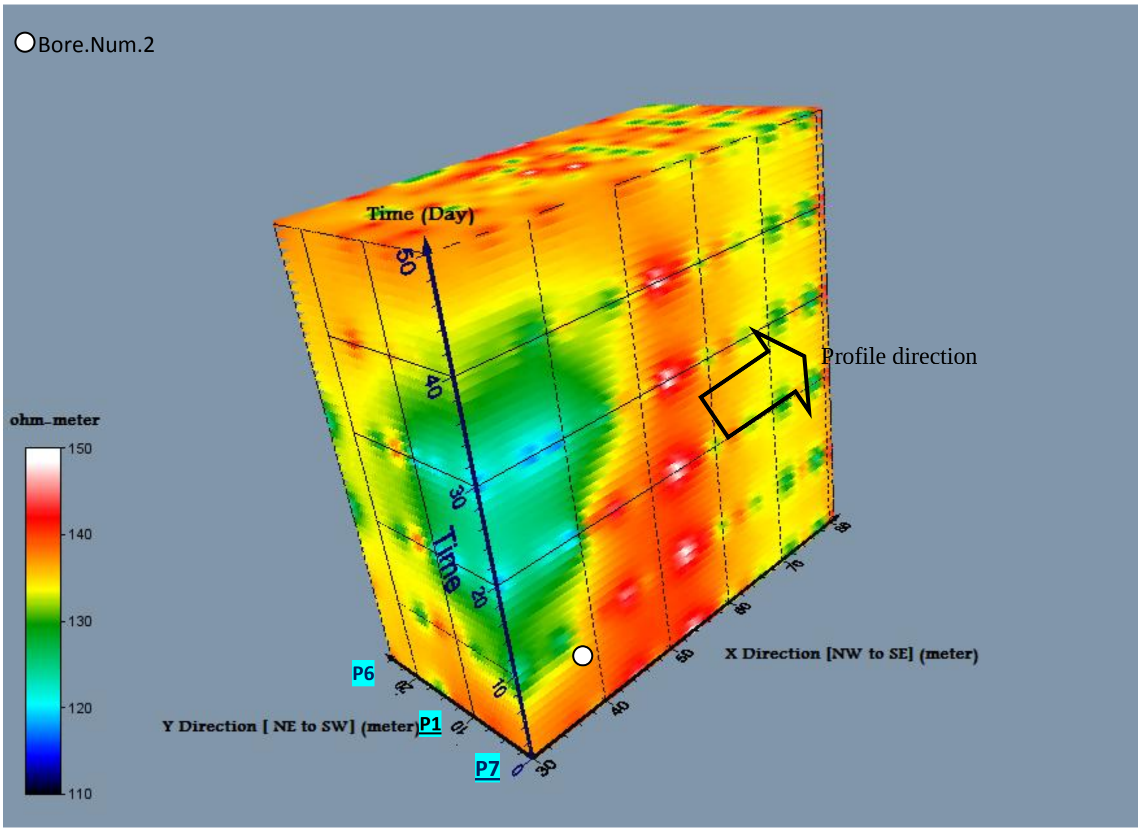

Figure 7.b 3D resistivity time section for depth of 15 m obtained from 2D inverse modeling of resistivity data from ERT surveys along different longitudinal lines.

5. Conclusions

The investigations described in this paper show the ability of the ERT method in detection of contamination. Based on the results of direct observation (measurements made by a self-recording device), the groundwater had a velocity of 6 m per day. It was expected that the groundwater resistivity values, decreased exponentially after the injection into borehole No. 1, and its movement toward borehole No. 2. Also, on the 4th day after injection of the saltwater solution, no sign of contamination was observed in borehole No. 2. Geophysical measurements showed that the spread of contamination toward southeast was more than that toward other directions. This indicates the spread of contamination resulting from geological and sedimentation trend and the direction of groundwater flow. By increasing the depth of penetration, the reduction rate of resistivity decreased compared to the background resistivity, due to the salt absorption by layers, and its dispersal. This is clearly observed in the 3D resistivity time section for depth of 15m obtained using the 2D inverse modeling of the resistivity data of all longitudinal survey lines (acquired before and after the injection). The groundwater flow in the area was in the same direction as the contamination spread (i.e. southeast). In further works, investigations should be carried out concerning natural time-dependent background variation in EC with great attention to details.

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ردیابی و تعیین گستره آلودگی آب زیرزمینی حاصل از نمک طعام با به‌کارگیری روش توموگرافی مقاومت ویژه الکتریکی (ERT)

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چکیده:

پیشگیری و حفاظت از آلودگی منابع آبی و ردیابی آلودگی‌ها و علاج بخشی آن‌ها ازجمله مهم‌ترین ارکان در مدیریت منابع آبی است. در این تحقیق، به‌منظور ردیابی آلودگی حاصل از تزریق مستقیم محلول نمک طعام به آب زیرزمینی (زون اشباع)، برداشت‌های توموگرافی مقاومت ویژه الکتریکی (ERT) در بازه‌های زمانی مختلف در طول ۷ پروفیل طولی در پایین‌دست سد لتیان، بالادست روستای جاجرود و در ساحل جنوب غربی رودخانه خروجی سد واقع در زیر پل آزادراه تهران- پردیس انجام شد. برای بررسی پارامترهای تأثیرگذار بر روی مقاومت ویژه محیط مورد بررسی و هم‌چنین تعیین سرعت آب زیرزمینی، اندازه‌گیری‌های دما و رسانندگی الکتریکی (EC) آب زیرزمینی توسط دستگاه خود ثبات در طول ۲۰ روز (قبل و بعد از تزریق محلول نمک طعام) در زون اشباع برداشت شد. با توجه به مقادیر اندازه‌گیری‌های دستگاه خود ثبات و نتایج برداشت‌های ERT، مقاومت ویژه زون اشباع، علاوه بر تغییرات غلظت نمک در آب، تابع عوامل دیگری همچون لیتولوژی منطقه مورد مطالعه و جذب آلودگی توسط لایه‌ها است. علاوه بر این، بررسی نتایج به‌دست‌آمده حاکی از گسترش آلودگی به‌طرف جنوب شرقی بوده که از روند زمین‌شناسی و رسوب‌گذاری و جهت جریان آب زیرزمینی منطقه پیروی می‌کند.

کلمات کلیدی: نمک طعام، زون اشباع، توموگرافی مقاومت ویژه الکتریکی، جاجرود، ایران.