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INTEGRATED HYDROGEOPHYSICAL SURVEY FOR MONITORING WATER INFILTRATION TO SUBSURFACE AQUIFER

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مسح هيدروجيوفيزيقى متكامل لمراقبة تسرب المياه إلى الخزان الجوفى

الخلاصة: تم إجراء مسح جيوفيزيقى متعدد الطرق فى أحد الخزانات الخاصة بهيئة مياه مدينة توسان فى أريزونا بالولايات المتحدة الامريكية والهدف من هذه الدراسة هو استخدام الطرق الجيوفيزيقية فى مراقبة تسرب المياه إلى خزان المياه الجوفية. و يسمح استخدام هذا الخزان لاعادة ضخ المياه إلى الأرض بوضع مجسات جيوفيزيقية متعددة لمتابعة تسرب المياه مما يتيح عمل مقارنة للبيانات المسجلة لفترات طويلة، كما يساعد هذا المسح الهيدروجيوفيزيقى فى معرفة و متابعة كمية واتجاه تدفق المياه إلى الخزان الجوفي.

وقد تم استخدام أربع طرق جيوفيزيقية لمراقبة تسرب و تصريف المياه إلى الخزان الجوفى لتسجيل بيانات تفصيلية عن تسرب المياه فى الطبقات الضحلة والعميقة.

ويعتبر إجراء هذا المسح هو وسيلة لتحسين مفهوم استخدام التقنيات الكهربية والكهرومغناطيسية المختلفة ويفيد أيضاً فى معرفة إمكانية كل طريقة وإستخداماتها لمراقبة تسرب المياه.

ABSTRACT: *Multiple geophysical surveys were conducted in the Tucson water recharge basins facility, Arizona, USA. The purpose of the geophysical investigation was to monitor water infiltration into the aquifer. This recharge basin provides controlled conditions for effective comparative analysis of data yielded through hydrogeophysical field-based investigations where sensors can be deployed for extended time periods.*

Resource managers need to thoroughly understand the water flow into the aquifer in order to predict water budget of the groundwater system. Specifically, the geophysical surveys will aid in understanding and monitoring the amount and direction of water flow from the recharge basin to the subsurface groundwater aquifer.

Our geophysical investigation of the water recharge basin included gravity, electromagnetic induction (EMI), electrical resistance tomography (ERT) and controlled source audio magnetotellurics (CSAMT) methods. These surveys were designed to monitor field-scale water infiltration and drainage, and gather more detailed data on shallow and deep-water flow. The goal of this survey is to improve our understanding of the different electrical and electromagnetic techniques and to determine the limitations of each method for monitoring applications.

INTRODUCTION

Worldwide, some of the fastest rates of population growth are occurring in arid and semi-arid regions. Major cities within these regions are either currently or will soon face water supply shortages. The sustainable development of these regions can be achieved only through an improved, quantitative understanding of basin-scale hydrology. Accurate determination of recharge is critical to this improved understanding and necessary for the establishment of a sustainable water budget at the basin scale.

Unfortunately, measuring of soil water content over large areas is difficult and expensive. Common procedure such as “neutron scattering” and “time domain reflectometry” require a great deal of manpower or are too destructive for repeated measurements at the same location. Further, these methods are time-consuming to perform, especially over large areas of extremely heterogeneous rangelands. Moreover, these methods are incapable of monitoring the water content over the entire thickness of the deep vadose zones that are typical in arid and semi-arid regions.

As a result, there is a definite need for a quick and nondestructive measurement method for soil water content measurement over large areas (Bouwer, 1989, Gee and Hillel, 1988).

Geophysical measurements have the capacity to add valuable data for the construction and calibration of hydrologic models. The key advantages of geophysical methods are their abilities to make rapid, inexpensive, noninvasive and nondestructive measurements.

During an infiltration event, the water content of geological media is generally assumed to be the only

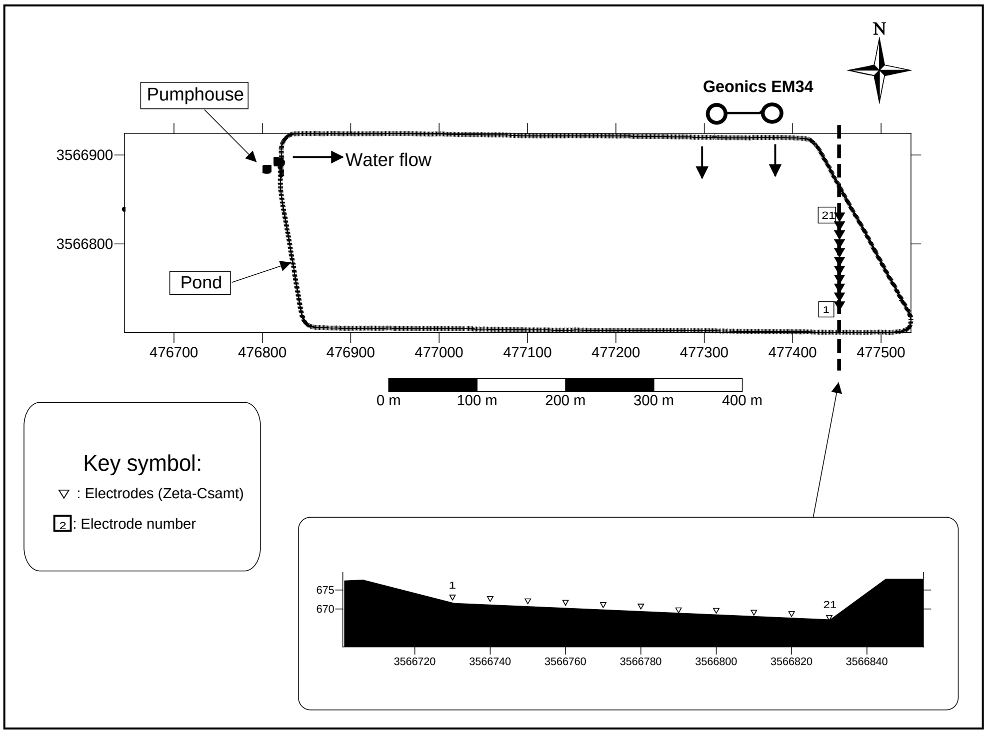

Fig. (1): Geophysical equipment setup inside the recharge basin.

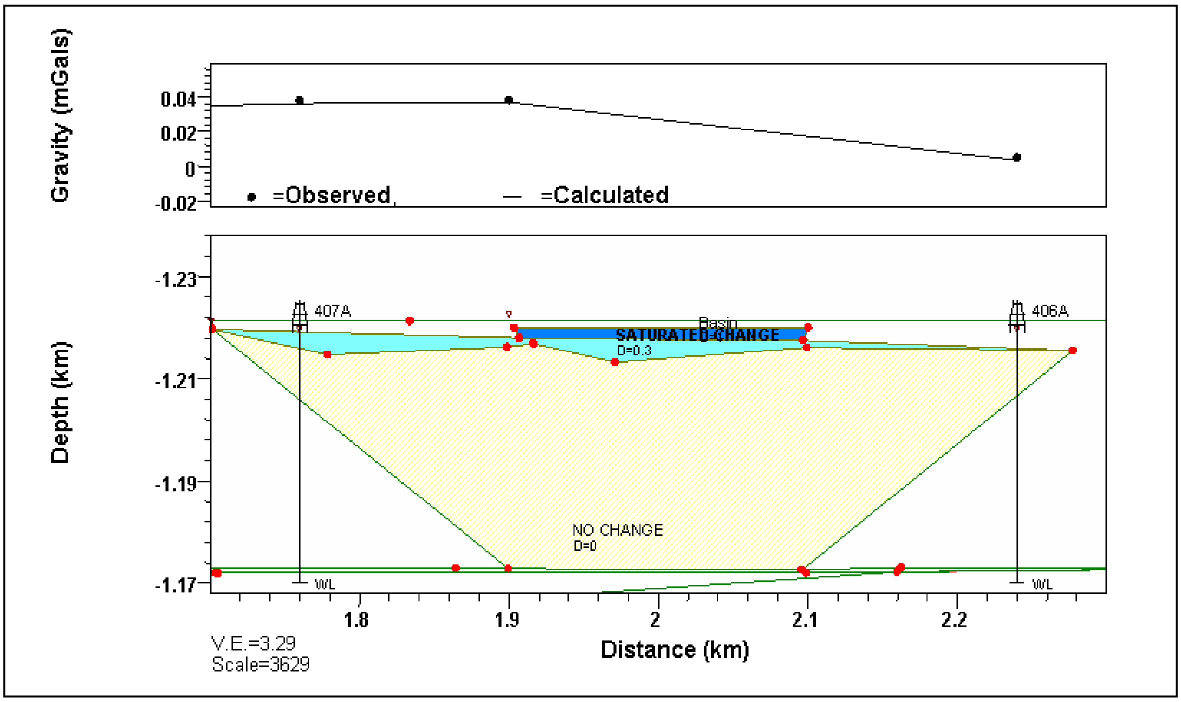

Fig. (2): Gravity response showing the change in gravity due to water infiltration after 7 days of water pumping.

element that undergoes dramatic changes. Therefore tracking the changes in the electrical resistivity has often been regarded as a useful means to delineate the change of the water content in the vadose zone.

Recent investigations with ground conductivity meters have shown that electrical conductivity measurements and electromagnetic induction have the potential for quick noninvasive soil water content measurement (Hendricx et al. 1992; Sheets and Hendricx, 1995). However, few studies have been conducted to investigate the potential of ground conductivity meters to quickly monitor soil water content over large areas. Therefore, the objective of this study is to assess the capability of different geophysical methods including gravity, electrical resistance tomography, electromagnetic induction and controlled source audio-magnetotellurics methods for monitoring changes in water storage during infiltration and drainage of water flow with depth especially for deep vadose zones.

The key to the successful use of geophysics in recharge investigations is the identification of the appropriate geophysical method or methods for monitoring needs. In order to answer this question, it is needed to assess the sensitivity of different methods to the change of water disruption with both time and depth.

FIELD SITE CHARACTERISTICS

An infiltration experiment at the Central Avra Valley Storage and Recovery Project (CAVSRP) was conducted. CAVSRP is a property of the city of Tucson, Arizona, USA where there are three, 20-acre basins that have been in operation in Avra Valley since late 1997. The CAVSARP site includes more than 10 recharge basins. The basins are aligned parallel to one another with each having the larger dimension in a easterly direction. The dimensions of several recharge basins are 650 m east-west by 200 m north-south (Fig. 1). Most of the basins were constructed by excavating about two meters of surface soil. The bottom slopes south to north at 0.42 percent grade. The basin heights, which form the margins of the basin, range between approximately 1.5 m and 2.2 m allowing a maximum water level of approximately 2 m along the northern basin. Depth to groundwater ranges from 100 to 120 m. The 20-acre basin takes one to two days to fill using 15,000 g/m and about one week to drain.

Measurement of the inflow rate, totalized flow, and water depth in each basin is continuous. Each basin has a pressure sensor installed at the deep end to measure water height and a flow meter installed at the inlet pipe. These instruments are connected to a data logger and cellular modem allowing for remote monitoring of basin operations. A visual gauge is read periodically to confirm the accuracy of the pressure sensors. Manual readings of the flow meter are recorded to calibrate the automated flow data.

The soil consists of several hundred meters of alluvial fill. A well near the southern boundary of the site penetrated 795 m without encountering bedrock. Depth to water table is in excess of 100 m at the site. Water used at the site is transferred from Colorado River.

The site includes facilities to set up geophysical equipment and to conduct controlled experiments. The field site can be used to install instruments that allow for high resolution monitoring of water movement through a deep vadose zone.

EQUIPMENT AND FIELD SETUP

One spread of electrodes (oriented N-S) was used that worked as receiver electrodes both for electrical resistance tomography and controlled source audio-frequency magneto-tellurics methods (Fig. 1). The CSAMT also used remote transmitter electrodes that are located at about 1 km from the recharge basin. Geonics EM31 and EM34 coils were used for the EMI and were set up on top of the recharge basin at its northeast corner.

GEOPHYSICAL TECHNIQUES

1. Gravitational Method

The gravitational attraction at a point on the surface of the Earth depends primarily on the density distribution of the materials in the subsurface. Gravity methods have long made use of spatial changes in the subsurface density distribution to define geologic structures. However, given that water is less dense than geologic materials and that the shape of the water table typically changes gradually with lateral distance (unless controlled by geology) gravity monitoring has limited use for subsurface water content mapping. Recently, however, the value of time-lapse gravity surveys has been recognized for inferring changes in subsurface water content distributions. The application of gravity method relies on the fact that, in most environments, changes in subsurface mass through time are dominated by changes in water storage. Therefore, after standard corrections are applied for tidal and instrument effects, the change in gravitational attraction at the ground surface can be related to the cumulative change in the water stored in the subsurface. Gravity-based water storage change monitoring has great promise for water balance applications because the method is portable, rapid, and requires far less infrastructure than monitoring wells. However, the method does not provide measurements of the subsurface water distribution. In fact, the method may be susceptible to errors if water accumulates at shallow depths above the water table, due to the inverse dependence of gravitational attraction on the distance to a body. Despite this potential error, gravity-based methods are uniquely capable of providing spatial estimates of water storage change over large areas. As a result, they will likely see expanded use both for direct estimation of water storage change and for calibration of saturated flow models (Pool and Eychaner, 1995).

Gravity measurements after 7 days from pumping the water into the basin showed a gravitational change of 31-38 microgal (Fig. 2) which can be explained by the distribution of mass in the surface basin (about 2 meters deep).

During transient infiltration, water replaces air in a previously unsaturated medium. As a result, the total mass of water and solids within the vadose zone increases during infiltration and decreases during subsequent drainage.

2. Electric and Electromagnetic Methods

The electric and electromagnetic geophysical methods show the most promise for application to recharge monitoring. Some of these methods (ERT, EMI and CSAMT) are used primarily to measure the electrical conductivity distribution of the subsurface. These methods can be divided into direct and inductive methods on the basis of how electrical energy is applied to the ground and how the electrical response of the subsurface is measured. Directly coupled methods require that electrodes be inserted into the ground to apply electrical current and to measure voltage (e.g. ERT). Inductively coupled methods eliminates the need to insert electrodes into the ground (e.g. EMI). CSAMT is a hybrid method in which a directly coupled source and both directly and inductively coupled receivers can be used. Electromagnetic methods for measuring the electrical conductivity distribution can be separated further into time domain methods, which measure the electrical conductivity over many frequencies simultaneously, and frequency domain methods, which measure at certain specific frequency. transient electromagnetic (TEM) is an example of a time domain method, while EMI and CSAMT are frequency domain methods (McNeill, 1990).

The following paragraphs discuss both of the electrical and electromagnetic methods used for monitoring water infiltration inside the recharge basin and their results:

Controlled Source Audio-frequency

1. Magnetotellurics (CSAMT)

CSAMT is a high resolution electromagnetic sounding technique which uses a fixed grounded dipole or horizontal loop as an artificial signal source. CSAMT is similar to the natural source magnetotellurics (MT) and audiofrequency magnetotellurics (AMT) techniques, with the main difference being the use of an artificial signal source for CSAMT. The source provides a stable signal, resulting in higher-precision and faster measurements than that are usually obtainable with natural source measurements in the same spectral band. However, the controlled source can also complicate interpretation by adding source effects, and by placing certain logistical restrictions on the survey. In most practical field situations, these drawbacks are not serious, and the method has proven particularly effective in mapping the earth's crust in the range of 20 to 2000 meters (Zonge, 1992).

A CSAMT source used in this survey consists of a grounded electric dipole 670m in length, located at about one km from the area where the measurements are to be made. The frequency band for typical instruments is between 0.125 and 8,000 Hz, with measurements made in the 16 to 8,000 Hz range. Magnitude and phase are measured for 21 electric field (E) dipoles simultaneously with just one magnetic field (H) component (Fig. 3).

Grounded dipoles detect the electric field and magnetic coil antennas sense the magnetic field. The ratio of orthogonal, horizontal electric and magnetic field magnitudes (e.g. Ex and Hy) yields the apparent resistivity. This is usually referred to as the apparent resistivity after the French geophysicist who was instrumental in the development of the magnetotelluric (MT) method in the early 1950's (Zonge and Hughes, 1991).

Figure 4 shows the changes in resistivity distribution from CSAMT data reflecting the change in water content. The upper plot shows the pre-infiltration data (prior to water filling) while the lower plot shows the resistivity distribution after water infiltration into the ground. Dark areas (low resistivity) show the increase in water content while light areas (high resistivity) reflects low water content. There was a decrease in resistivity values in the upper 10m, but there is no change in the deeper layers which could be attributed to the lateral flow of water through a preferred path (possibly paleo-channel) rather than downward flow.

2. Electrical Resistance Tomography (ERT)

ERT is a method that calculates the subsurface distribution of electrical resistivity from a large number of resistance measurements made by electrodes. For in-situ applications, ERT uses electrodes on the ground surface or in boreholes. It is relatively new imaging tool in geophysics. The basic concept was first described as a marriage of traditional electrical probing and the new data inversion methods of tomography. Development of both the theory and practice of ERT was confined mostly

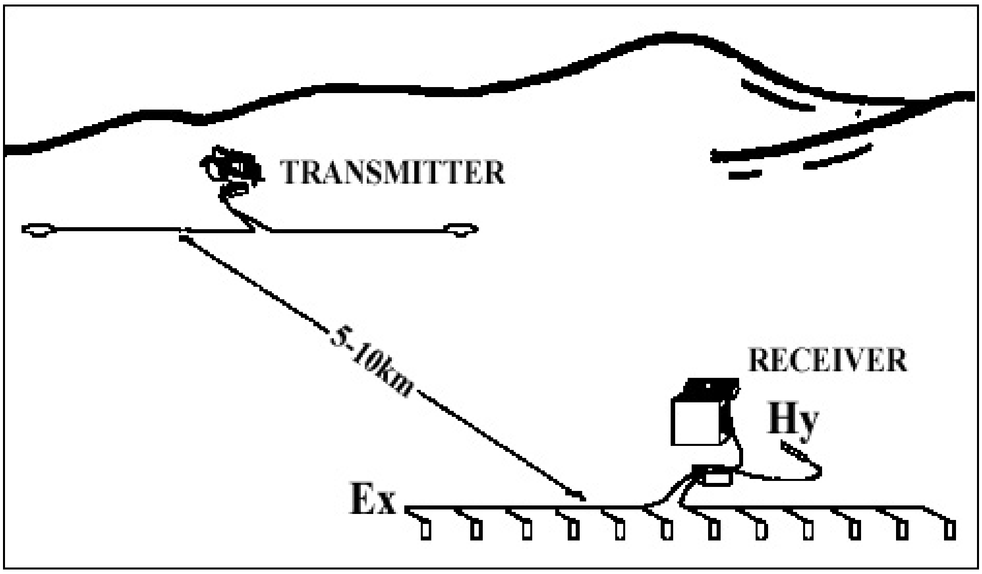

Fig. (3): CSAMT Field Setup

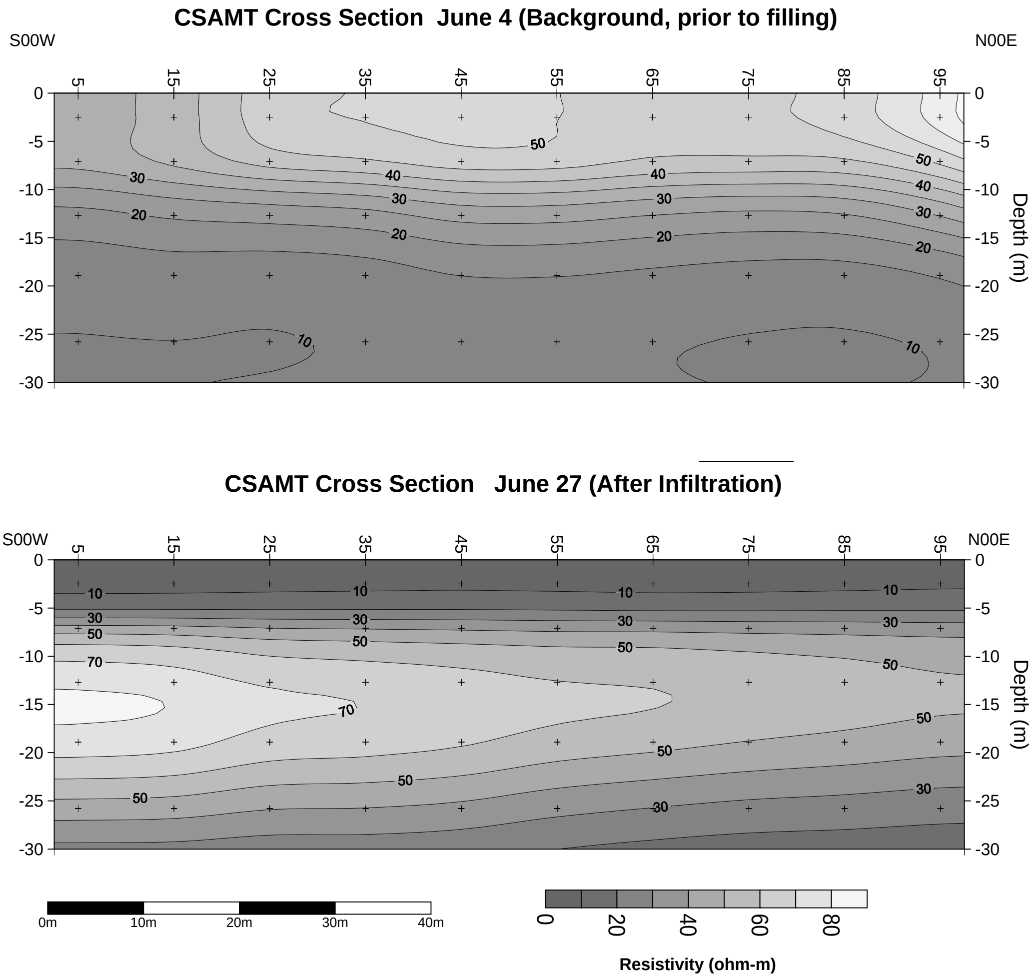

Fig. (4): CSAMT resistivity response with depth before and after infiltration.

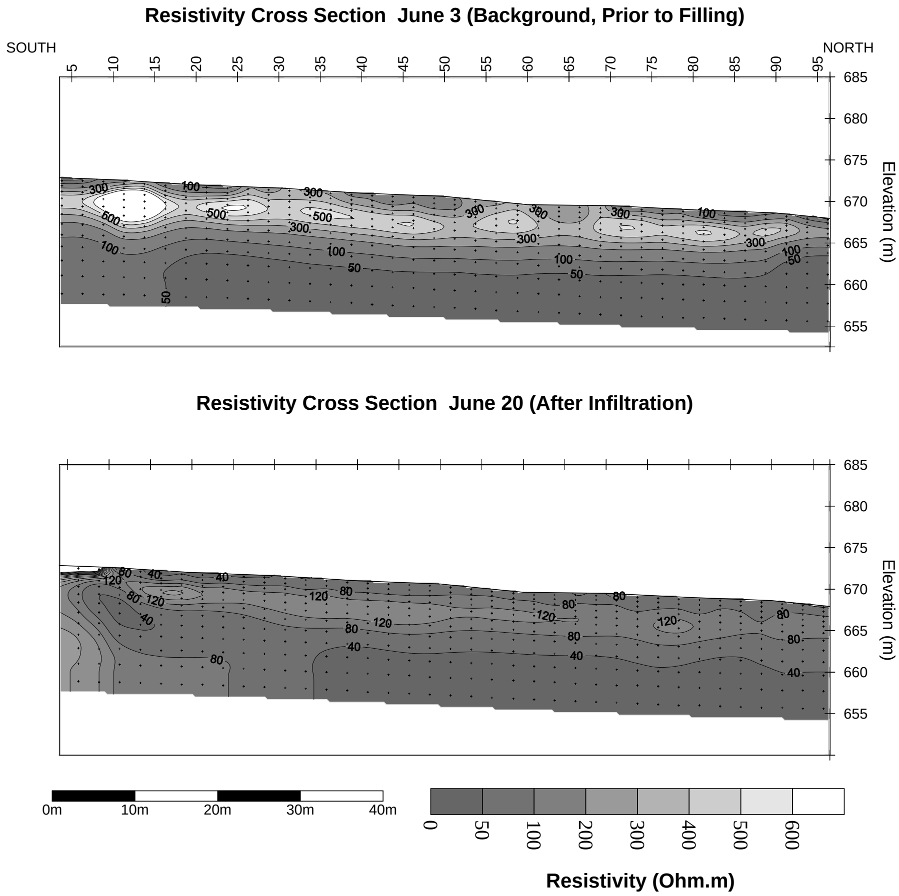

Fig. (5): ERT resistivity response with depth before and after infiltration.

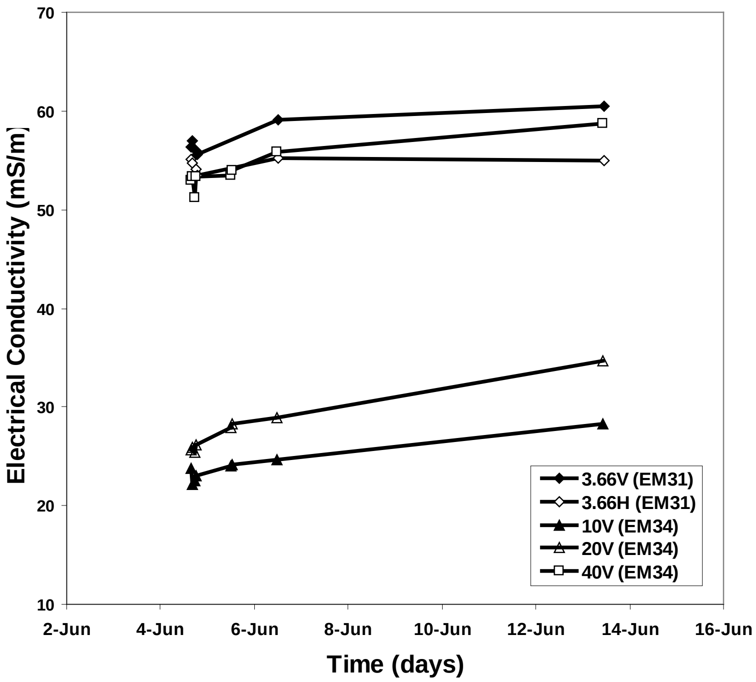

Fig. (6): EMI responses with the date of measurements before and after infiltration.

to the late 1980s and 1990s. Tomographic inversion added important new capabilities as it was more general, accurate, and rigorous at spatial imaging of geophysical electrical resistance data than earlier pesudosection or curve fitting methods (Daily et al. 2004).

Obviously, there are too many measurements to be acquired manually. To efficiently measure all the desired transmitter receiver electrode combinations requires a computerized acquisition system that automatically switches both transmitter and receiver electrodes and has multi-channel measurement capabilities. Such data sets are required to generate conductivity images using inversion software. These capabilities greatly improve the usefulness of resistivity measurement for problems wherein the resistivity method is traditionally applied. Moreover, the capability of ERT to generate "images" of conductivity distribution greatly expands the applicability of the electrical resistivity method to many problems in engineering and hazardous waste site characterization and monitoring, and in geophysical and groundwater exploration as well (Yeh, et al, 2002).

Figure 5 shows the change in resistivity distribution from ERT data reflecting the change in water content. The upper plot shows the background resistivity before water filling and the lower one shows the resistivity distribution after water infiltration. Similar to the CSAMT results, there is a decrease in resistivity (dark areas) in the upper 10m compared to the high resistivity (light areas) before infiltration. There is a clear path (possibly paleo-channel) that extends laterally and could be a preferred path for water flow which explains why water did not move downward.

Electromagnetic Induction (EMI)

EMI profiling is a surface geophysical technique used to measure terrain conductivity, a term which refers to the bulk electrical conductivity of subsurface materials. EM conductivity surveying is primarily a tool for rapid lateral mapping of variations in soil conductivity. These EM instruments do not require any ground contact or surface disturbance. Therefore, they are rapid and relatively inexpensive.

The basic principle of operation of the EMI method is that it radiates an electromagnetic field using a transmitter coil which induces electrical currents (termed eddy currents) in the earth below the coil. These eddy currents in turn generate a secondary magnetic field. The receiver coil detects and measures this secondary field. The instrument output, calibrated to read in units of terrain conductivity (apparent conductivity), is obtained by comparing the strength of the quadrature phase component of the secondary field to the strength of the primary field. The apparent conductivity measurement represents a weighted average of subsurface conductivity from the ground surface to the effective depth of exploration of the instrument. The depth of exploration depends on the separation between the transmitter and the receiver coils, as well as on the coil orientation, coil axis/dipole horizontal (H) or vertical (V), (McNeill, 1990).

In these measurements, Geonics EM31 and EM34 were used. EM31 has a fixed coil spacing of 3.66m and one frequency (9800 Hz) while EM34 has 3 coil spacing: 10, 20, 40m. Each coil spacing is associated with different transmitter frequencies, 10m (6400 Hz), 20m (1600 Hz) and 40 m (400 Hz). The lower the frequency and larger coil separation, the deeper the penetration depth of exploration. The coils were installed on top of the recharge basin about 50 meters west of the northeast corner.

Figure 6 shows the change of conductivity with the time of measurements. It can be noticed that all the EM34 measurements changed over time, but the EM31 (shallow measurements) did not increase much. It is possible that these increases were related to increases in water content with depth and that those areas (shallow layer) that did not exhibit large change did not experience a sufficient change in water content to be detected.

It can noticed that the EM34 40V has higher conductivity than the others. It is possible that it senses more deeply, encountering a zone that has a higher saturation or salt content.

CONCLUSION

Electrical and Electromagnetic geophysical methods proved to be successful monitoring techniques for water infiltration. Time-lapse gravity method is capable of providing qualitative spatial estimates of water storage change over large areas.

CSAMT and ERT methods as well as monitoring wells detected lateral flow for the infiltrated water. It is believed that water flow traveled through a preferred path (paleo-channel) to the western side of the basin.

Future forward modeling (simulation) is required to find relations relating geophysical response with hydrological parameters.

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