DETERMINATION OF GROUNDWATER FLOW DIRECTION IN A SINGLE-WELL BY ELECTRICAL CONDUCTIVITY METHOD

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ABSTRACT

Among the currently and extensively used conventional methods that employ a single-well for the determination of groundwater flow vectors (the magnitude of underground flow velocity and flow direction) are those that utilize different radioactive tracers and a corresponding methodology for a particular selected tracer. There are also a few geophysical techniques, although less efficient, such as the SP method that traces spontaneous potentials both timely and spatially around a well for the determination of these parameters. The new technique suggested here requires only a few grams of common salt (NaCl) that is injected in the interested depth of the aquifer that is subject to the determination of groundwater flow vectors. Change of fluid conductivity of the affected water volume as a result of inflow of fresh water introduced to the well section causes current changes which are measured on the surface via a cable. This method has indicated similar results in the same wells when compared to groundwater flow vectors measured by the radioactive tracer method and was successfully applied in West Tirana city and Shkodra city wellfields (Albania) to substitute the conventional method of radioactive tracers. The most depicted benefits of the method are the safety of both operator and the environment, its low cost and rapid determination of the in situ groundwater flow vectors.

INTRODUCTION

Tracer substances that are applicable in hydrogeology for the determination of groundwater origin and flow vectors are versatile and are divided in two groups: 1) natural (for example hydrogen and oxygen radioisotopes, etc.) and 2) artificial tracers (dye stuff tracers, radioactive tracers and strong electrolyte compounds). Artificial tracers are further divided in radioactive and stable tracers. Natural tracers are mostly preferred for hydrogeological studies of groundwater origin because they are part of the water molecule, whereas artificial tracers are used in various applications and among those in the determination of flow vectors in a single-well.

The selection of the best single-well technique for determination of groundwater flow vectors is dictated by a series of variables where the most important are the health hazard imposed on the operator and the environment, technical project needs, timing and budget. For instance, for a regional hydrogeological study with roughly homogenous and isotropic hydro-parameters, a self-potential surface geophysical method would be adequate. Although this is an old method that is based on tracing of spontaneous potentials both timely and spatially according to circumferences of concentric radial-growing circles around a well that has a sack of a strong electrolyte salt in the subjected horizon, the flow vectors will represent a relatively larger area around the well under investigation. On the other hand, other single-well techniques extensively used are those of radio-tracers and recently the heat-flux method [Ballard, (1996)[1]] that usually determine the flow vectors that represent a small area around the subjected well and may be satisfactory for environmental studies and clean-up applications. Although the interpolation of flow vector measurements of single-well method in a wellfield would give a better picture for entire area under the investigation.

The new meter of a single-well technique for the determination of flux vectors with the conductivity method was widely used in West Tirana city and Shkodra city wellfields to substitute the tracer method (I-131 as tracer) due to safety and cost effectiveness issues of the latter. Both wellfields are located on confined (in most areas), heterogeneous alluvial aquifers with a clay top layer with a thickness ranging from 5m to 24m that overlies alluvium deposits with a thickness up to 32m. Below alluvium deposits, dense and plastic argillaceous sediments and shale formation continue to the hard-rock basement. This basement is composed of lignite bearing sandstone deposits in Tirana wellfield and limestone deposits (in fact, a half graben basin filled with marine deposits) in Shkodra wellfield. Conductivity meter was used in wells of both wellfields to assess flow vectors in different locations (well distance) from the river in discrete points in time (typically before and immediately after the rainfall) for the observation of river-aquifer interaction.

METHOD, EQUIPMENT AND MEASURING TECHNIQUE

The Method

Theoretically the method is based on the injection of a tracer into a well section and then following its concentration decrease (dilution) with time. The tracer dilution method is described in details by Drost (1968)[2], Haley (1967)[3] and IAEA (1968)[4]. For any tracer, the horizontal flow filtration (discharge) velocity V_f of groundwater is given by the following formula:

$$V_f = -\frac{V}{\alpha S t}\ln\frac{C}{C_0}$$

where:

V – is the measuring volume (the borehole volume in which dilution takes place);
S – is the cross-section of the measuring volume perpendicular to the direction of the groundwater flow;
C_0 – initial tracer concentration;
C - concentration of tracer in time t;
t – is the time interval between measurement of concentrations C_0 and C;
α – is a correction factor accounting for the distortion of flow lines due to the presence of the borehole

Drost (1968)[2] has demonstrated that this coefficient is a function of the well diameter, type of screen material, mesh configuration and dimension, screen wall thickness and permeability of both sand pack and aquifer. Many measurements conducted on hydraulic models for different production well diameters show that this coefficient varies between 1.5 and 4 [Drost (1968)[2], Haley (1967)[3], Hazzaa (1970)[4]]. For the calculation of discharge velocities in all field measurements performed in the above-mentioned wellfields this coefficient was considered equal to 2.

The conductivity method of a single-well technique for the determination of flow vectors, represented here is based on water conductivity change caused by fresh water inflow that displaces a cloud of extremely diluted salt solution (NaCl as tracer) from a pre-selected interval of the well under investigation. Lab measurements show a linear relationship between salt concentration and conductivity of the water for relatively small amounts of salt concentrations far from achieving saturation point for a given temperature and the same quality of water. The schematic-diagram in Fig. 1 represents the principle of this method by the movement of the salt solution cloud through time in a well section. The flow direction in this figure is shown from north to south.

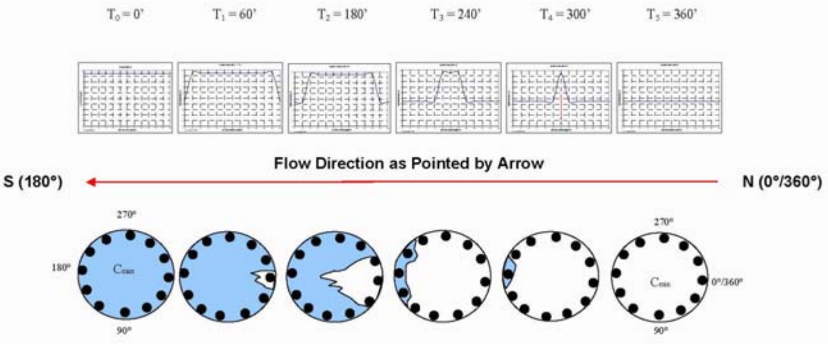

Figure 1. Cloud of Salt Solution Displacement through Time with Corresponding Graphs (Current Intensity vs. Azimuthal Direction)

It is preferred to first determine the discharge of flow velocity and then flow direction.

Equipment and Measurement Technique

An AC current generated by an oscillator at a frequency of about ~ 8 KHz (to prevent dissolving effect by a DC current) and a stable voltage, supplies a cylindrical wiring "cage" of vertical solid brass conductors (each is 2.5 mm in diameter) that is lowered down the well at a pre-selected depth utilizing a string of rigid rods (drill pipes) with diameter of about 5 cm (~2-inch). The vertical solid brass conductors, usually numbered 12 to 36 (depending on flow direction accuracy requirement, +/- 30^0 and +/-10^0 respectively) are installed around the circumference of the slabs and one is in the center of the cylindrical "cage" and inside the (plastic) injection tubing. They are evenly spaced from each other and are located about 5 mm from the edge of each of two fiberglass slabs. These two slabs, one at the bottom and one on the top of the cylindrical wiring "cage" have an equal diameter but slightly smaller than the inside diameter of the borehole or the screen pipe at the pre-selected section of the well. A simple diagram of cylindrical wiring "cage" is presented as Figure 2.

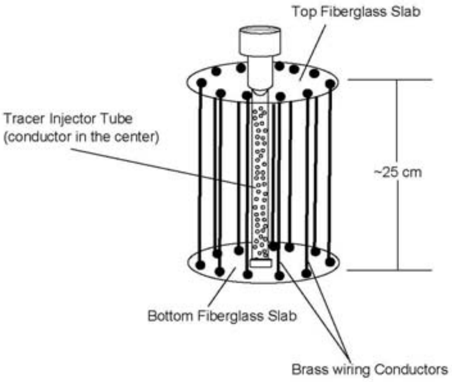

Figure 2. Cylindrical wiring "Cage" (Not to Scale)

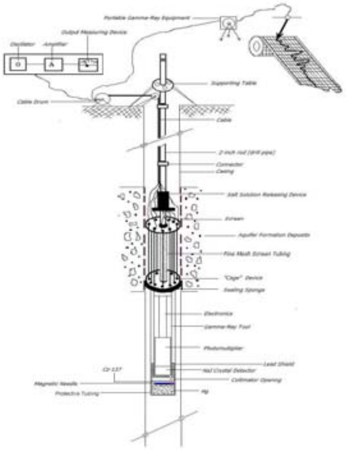

Figure 3. Conductivity Meter - Schematic Diagram

Each conductor is connected via a cable that terminates to the signal input slot of the above-ground measuring equipment. The above-ground measuring equipment houses the oscillator, an amplifier, a final measuring device that displays measured intensity current and the power supply (dry cell batteries of 12V x 3A). For data acquisition a data-logger may be used (emplaced in the above-ground equipment). Figure 3 shows a block-diagram of the conductivity equipment and the cylindrical wiring “cage” installed inside the well.

The distance between two fiberglass slabs of the cylindrical wiring “cage” is about 25 cm. Underneath the bottom slab of the “cage” a sealing sponge as thick as 25 mm (~1-inch) and at a diameter that exceeds that of the slabs (approximately 50 mm higher [~2-inch]) is attached in a way that prevents the salt solution cloud from escaping out of the “cage”. This may happen due to vertical currents inside the well or borehole as well by gravitational forces, especially when discharge velocity V_f is very low (1 cm/day or less) and the salt solution cloud must remain inside the “cage” for a longer time to obtain accurate measurements.

A series of cylindrical “cages” may be prepared in advance (4-inch, 6-inch, 8-inch, 10-inch, 12-inch or higher diameters) for field works. The “cage” and surface measuring equipment are connected via a common logging cable. The injection tubing in the center of the cylindrical “cage” is of plastic material and evenly perforated (the same number of holes per unit of surface [holes/cm^2]). A brass conductor in the center of the tubing senses the decrease of concentration of salt solution (expressed in current intensity values) with time for flow velocity calculations. In the same way, the current intensity values are also recorded from each of the perimeter brass conductors that sense the fluid concentration change for the determination of flow direction. Both, the concentration of salt solution mixed in the water volume inside the “cage” and the conductivity values of this mixed water fluid have a linear relationship with the recorded current intensity values. The current intensity values are obtained by a series of measurements performed between each vertical brass conductor and a grounded electrode in the surface. A few series of measurements are necessary during the course of the test for discharge flow velocity determination.

Duration of the test for V_f determination depends on aquifer discharge flow velocity and the well diameter and may last from less than a hour (alluvial gravel deposits or karst environment) to a few days (for very low discharge velocity-fine clastic aquifer). However, the flow direction vector could be determined much faster, from less than one hour to a few hours (depending on flow velocity). After a little experience with field applications and the equipment, one can determine the flow direction as soon as one of the brass conductors is “cleaned” and the current intensity value returns to the same amplitude as it was before the injection of the tracer. Five to ten milligram of table salt (NaCl) dissolved in the same water of the well under investigation is sufficient for most flow vector determination tests. The conductivity meter can measure flow velocities in a range from 0.05 m/day (meters per day) to 4 m/day at a resolution of 0.01 m/day.

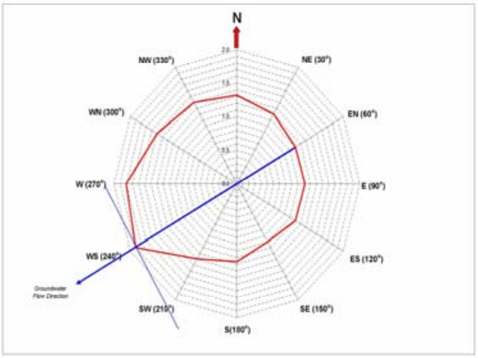

Figure 4a. Current Intensity (mA) on Major Azimuthal Directions 240 Minutes After the Injection of NaCl Solution (Well W18T)

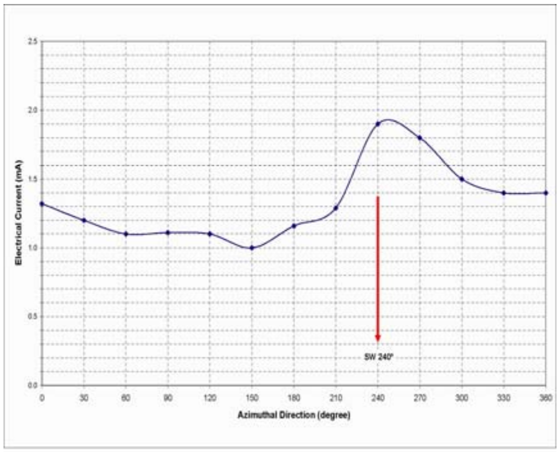

Figure 4b. Intensity of Electrical Current vs. Azimuthal Direction 240 Minutes After the Injection of NaCl Solution (Well W18T)

Figure 4a and 4b show the flow direction graph in planar and Cartesian coordinates respectively for a 6-inch diameter polyvinyl chloride (PVC) well (W18T) screened throughout the thickness of the aquifer (9 m to 21 m below the ground) in west Tirana wellfield utilizing the conductivity method.

Using the same technique (conductivity meter), the horizontal discharge flow velocity for this well was determined at 0.29 m/day (~1.2 cm/hr). The cylindrical "cage" was lowered in the middle of the aquifer layer (~15 m below the ground surface).

For the same well, both horizontal flow velocity and flow direction vectors were determined utilizing radioactive tracer method by injecting in the same horizon an assay of I-131 with an activity of 0.56 milliCurie (mCi), IAEA (1968 and 1972)[5] and Tazioli (1973)[6]. Radiotracer method confirmed the exact flow direction as it was determined by conductivity meter and the horizontal discharge flow velocity was determined at 0.26 m/day (~1.1 cm/hr). Flow direction in well W18T determined by radioactive method in planar and Cartesian graphs is shown in Figures 5a and 5b respectively.

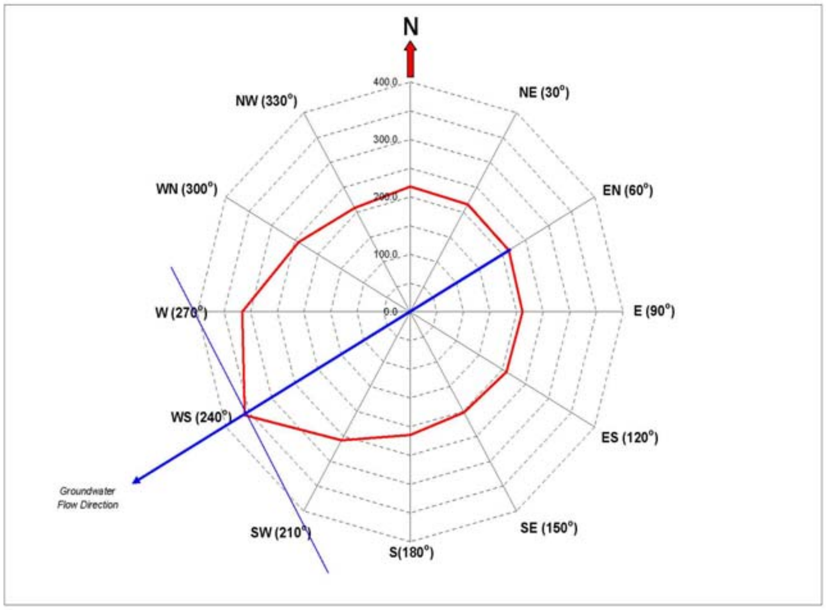

Figure 5a. Gamma Intensity Radiation (API) on Major Azimuthal Direction 240 Minutes After the Injection of I-131 (Well W18T)

The orientation of the cylindrical "cage" toward north direction is achieved by a "floating" compass and a gamma detector. The compass has a small grain of Cs-137 with an activity of approximately 100 µCi glued in the end of the north arrow needle. The magnetic arrow moves freely over a small volume of Mercury that is contained in a plastic bottle (~ 4-inch diameter) and is located below a gamma ray detector tool.

A lead shield as thick as 4 mm separates the plastic bottle (that contains the Mercury and magnetic arrow with Cz-137) and the gamma ray tool. This shield has a collimated hole that corresponds with the vertical direction of one of the brass conductors (typically Conductor No. 1). Gamma ray intensity would be the highest when the collimator's hole corresponds and is positioned above the north tip (Cz-137) of the magnetic needle.

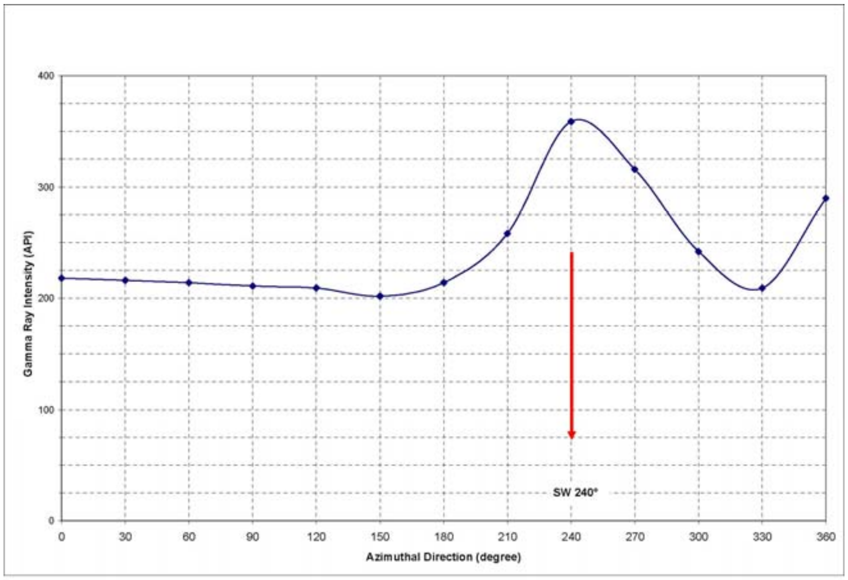

Figure 5b. Gamma Intensity Radiation (API) vs. Azimuthal Direction 240 Minutes After the Injection of I-131 (Well W18T)

A full circle rotation of the entire string of rods (360^0) will result in two high spikes on a gamma ray intensity plot that indicates the north azimuthal direction and is recorded by a portable gamma ray above-ground equipment. For shallow depths (less than 10 m) the orientation of the cylindrical “cage” may be done directly with the string of rigid rods by carefully lowering them toward a known azimuthal direction. The “floating” magnetic device for cylindrical “cage” orientation performs satisfactory in uncased or PVC cased wells. For testing in wells of metallic screen, other alternatives must be found; for example employing a small gyroscope that fits in casing diameter of the well under the investigation could be an appropriate measure. The conductivity meter has performed flawlessly up to a depth of 100 m. The magnetic floating device is presented as Figure 6.

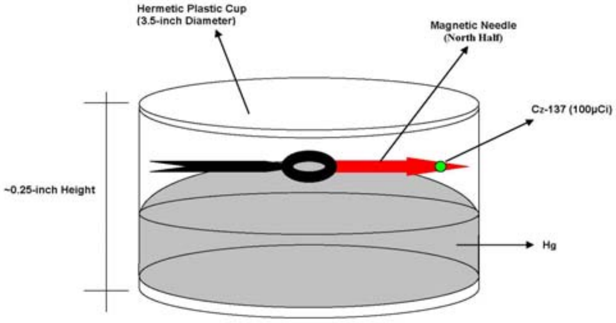

Figure 6. Floating Compass Device
(Not to Scale)

COMPARISON WITH OTHER METHODS

The results of most single-well methods utilized for groundwater flow vector measurements characterize only a local pattern of flow vectors around the well under the investigation (with the exception of electrical surface geophysical methods). Each method is a valuable tool for the hydrogeologist when it is utilized for an appropriate application.

Single-well technique of conductivity method could be utilized in almost every type of aquifer matrix. A drilled well is needed for the application of this method. However, for very low velocities usually less than 0.05 m/day, diffusion effect could compromise the application of the method.

On the other hand, heat-flux method is superior in applications for fine and/or middle grain size unconsolidated sediment deposits, but it is not that effective in alluvial deposits or fissured rock applications. It may require a homogenous aquifer strata matrix for an evenly and good contact of temperature probe (thermistors) with the section of the aquifer under the investigation. Flux results may also be affected by thermal variations of the upper portion of the aquifer when water table is close to ground surface. A hollow-stem auger flight is also needed for the installation of flow sensors for the application of this method.

Currently radioactive tracer applications are mostly limited to the detection of flow behind the casing and/or of the leakance determination between aquifers. In these instances they may be the best or least expensive method of obtaining the desired information. Nevertheless potential hazard for the operator and environment is a limiting factor in general applications of radio-tracers in hydrogeology.

CONCLUSIONS

Measurements of flow vectors utilizing conductivity meter method had proven to be safe for both the operator and the environment. No special handling, transportation or mean of injection in the well is required. Flow vector data measurement results obtained with conductivity meter are the same with those obtained by other methods. The application of conductivity meter method requires inexpensive above-ground and down-hole equipment. Down-hole tool could be easily replaced and no maintenance is needed. Although in most cases of karst environments, groundwater flow direction could be determined accurately and in agreement with other methods, the flow velocity has a broad range of values (for the same well) and the measurement of this parameter in most cases is inconclusive.

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