Determination of Flow Velocities in Groundwaters by the Aid of Tracer Techniques

C. Sebastián, J. Maguiña and G. Maghella

Industry and Hydrology Section, Technological Services Sub-Direction, Instituto Peruano de Energía Nuclear, Av. Canada 1470, Lima 41, PERU

Abstract: The present paper, which is part of the implementation of the Project "Evaluation of the Groundwater Resources of Peru", reports methodologies and techniques developed for on-site artificial tracer aided measurements of groundwater flow velocities. Horizontal flows are computed through labeling of the whole water column which is coated with a holed pipe in its entire length, below the piezometric level. Concentration monitoring inside the well, is performed prior to the experiment. The injection of a tracer in a borehole located in the influence area of the project, allowed the determination of velocity of ground water flow. The basis of the technique relates to the application of a relationship existing between the observed concentration decreases of a tracer solution released into the borehole. Changes in the position of the tracer as a function of time, allow us to draw some conclusions about the direction of flow as well. Satisfactory results show that techniques applied herein are cheap, simple and rapid methods for the determination of groundwater flow characteristics.

Key words: Unique well technique, artificial tracers, groundwater flow.

1. Introduction

Water resources of Ica Region in Peru, is being highly affected by the pressure of the economic activity of such a region, increasingly aggravating their availability, both in quantity and in quality as well. These pressure factors are fundamentally the overexploitation of aquifers, the shedding of some pollutants to water bodies, the changes in the use of the soil such as inappropriate agricultural practices, the increase in housing developments in water production areas, among other factors.

The decrease in water availability as well as the high rate of population growth generates conflicts and it is necessary to take decisions, such as the regulation of the use of water through mechanisms of planning, regulations and legal aspects which enable its protection and its distribution in a rational manner. This problem is also reflected in the overexploitation

of the groundwater of the region.

Groundwater flows through porous subsurface saturated layers to lower levels than the infiltration ones, and it can arise naturally as springs and rivers contributing flows. Groundwater can be found almost everywhere, either in mostuired, semi-arid or arid areas as it is the case of Ica Region. Ica groundwater is an important resource, but it is difficult to manage due to their sensitivity to pollution and overexploitation.

This study is related to the methodology of artificial tracers for determination of flow velocities of groundwater in unique well, having conducted experiments in the IRSH 64 well in the area of Los Aquijes-Ica Region. The experiment was performed in the framework of the project "Evaluation of the Groundwater Resources of Peru".

These techniques can be applied when we have wells, through which water can move more or less freely, when wells are not ducted, when the lithology of the ground permits the application, or in wells coated with grooved pipe throughout the section covered by the saturated zone (it is better to hole the all lengh). The

Corresponding author: Juan Julio Ordoñez Gálvez, Ph.D., research fields: Aguas Subterráneas, Acuíferos, Contribuyendo al desarrollo de una Cultura del Agua y la Gestión Integral de Recurso Hídrico.

number of holes must be such that the percentage of grooved surface is included between 0.5% and 3%, so that the permeability of coating pipe becomes high.

The characteristics of the aquifer and the objectives of the project, demanded a detailed study of the groundwater, so that the Nuclear Energy Peruvian Institute (IPEN) and the National Water Authority (ANA), initiated a series of hydrogeological research in order to take advantage of the groundwater as the main source of supply, in the most rational possible manner. As a part of this study, it was conducted works in recent months in a pilot well, to determine the velocity of groundwater flow, since this is an important parameter for complete evaluation of groundwater hydrology.

The inside diameter of the well under investigation was of the order of 20 inches. However, the technique deribed below can also be applied in wells with varied inside diameter.

2. Objective

To determine the velocity of water flow in the sector of Lanchas Valley of Ica Region, by the aid of tracer techniques, as applied to single wells, in order to contribute to the solution of the problem of the aquifer management.

3. Justification

Farmers in the lower part of Lanchas Valley in Ica-Peru, felt affected by the companies that exploited water resources of the aquifer. Conventional hydrology has failed so far, in determining velocities and directions of flow in order to prove or rule out claims of such farmers. The absence of multiple wells does not allow drawing up a map of isoipsas, which would give information on the groundwater flow directions.

By determining the parameters of groundwater transport such as the velocity and direction of flows, ANA can solve the problem of aquifer management, addressing the frequent complaints of farmers of the lower part of Lanchas Valley and contributing to the solution of the mentioned conflicts between such national authority and the farmers.

Figs. 1a and 1b show the scope of studies and the specific area of assessments, as a subject of the present report.

4. Theoretical and Methodological Considerations

Horizontal speed of the groundwater flow can be obtained from the decrease of the concentration of some injected tracer, a a function of time, in a given volume of a well, as a result of a perpendicular circutating flow. Let us suppose, that in a section of a well water column with height h and diameter d, defined by two perfect closing "packers", is injected a certain amount of tracer, giving an initial concentration C_0. It is assumed that the following conditions are met:

(a) That the waterflow circulating through the well has a steady state.

(b) That on the cylindrical volume $V = \pi d^2/4$ of the considered section, the distribution of the tracer is preserved homogeneous, i.e., at any time, the concentration in all points of this volume is the same. This implies that it is found the condition of good mix or instantaneous mixing of the water that enters the volume V.

(c) That the tracer output from volume V only takes place as a result of the horizontal flow of the aquifer.

The experimental technique for measurement of groundwater flow velocity is based on the method of labelling the entire column. This consists in injecting into the water column, a soluble and easily detectable tracer in water, and monitoring its movement in other nearby wells or the same injected well. The method assumes that the tracer velocity is equal or very similar to the speed of the water.

In case that the detection of the tracer takes too long, (which could occur in the event that the groundwater velocity is very low or when the flow lines do not link the points of injection and monitoring), the flow
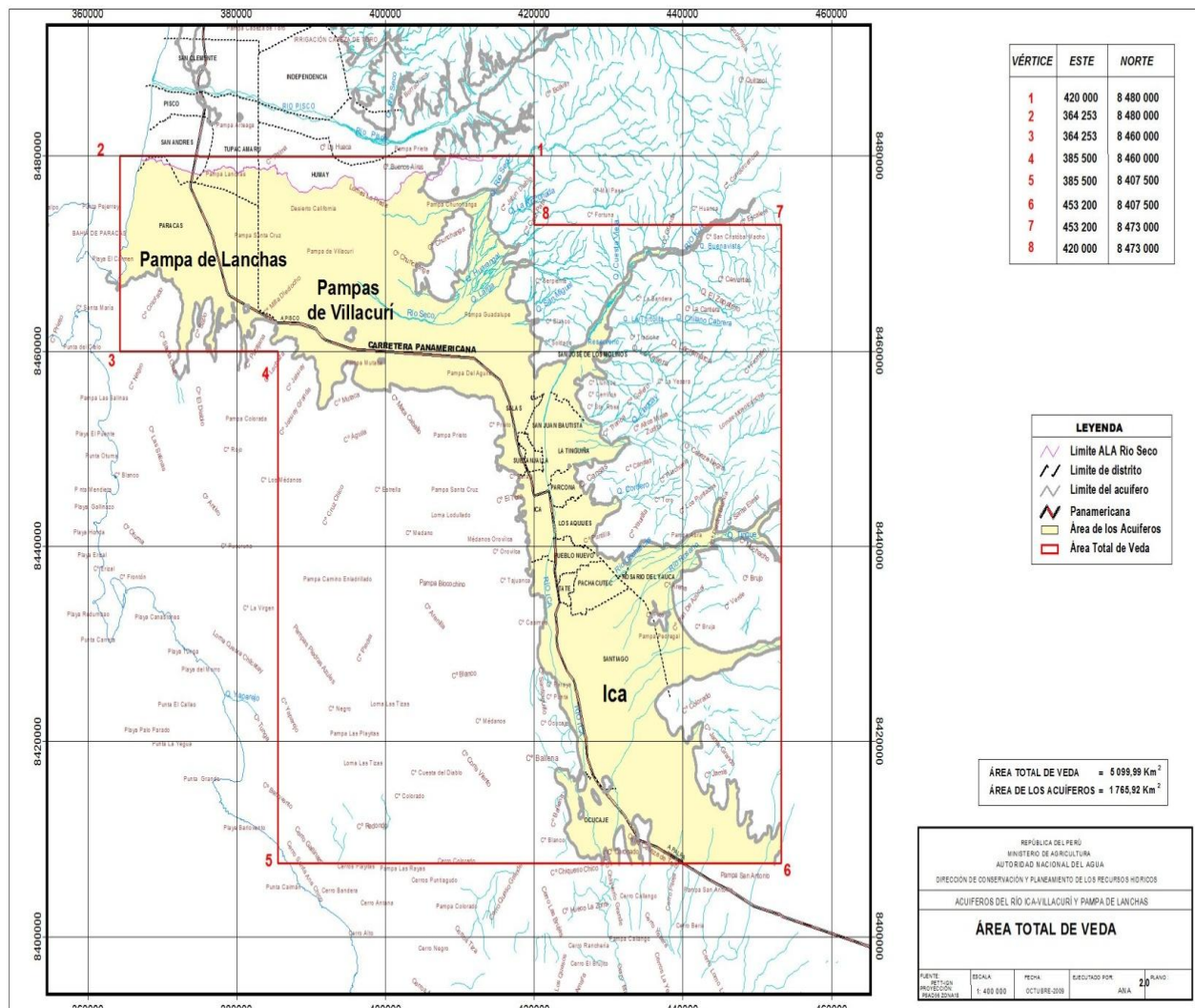
Fig. 1a   Area of the project studies, including the aquifers of Ica, Villacuri and Lanchas located on the central coast of the Peru, approx. between 239 and 340 km far from Lima city, by the South Pan-American Highway.
The aquifer Pampa Lanchas (where the experience was conducted), is located in the province of Pisco at Ica department, including Paracas and part of Humay, San Andrés and Túpac Amaru districts on the left side of Pisco River.

velocity with the single well technique can be determined indirectly.

The method consists in introducing a suitable tracer in a well or piezometer, and observing the decrease of its concentración as a function of time (Plata and Rodriguez, 1972). The variation of concentration depends mainly on any type of flow that exists inside the well and on a lower scale of dissemination of the tracer.

The decrease of homogeneously distributed tracer concentration in a well water column, as a function of time, is defined by the diferencia1 equation (in the absence of vertical flow and significant losses of tracer osmotic diffusion, i.e. by existing diffusion derived from an existing concentration gradient between the water from the well and the water from the aquifer):

$$\frac{dC}{dt} = -\frac{C}{V}\frac{dV}{dt} = Q\frac{C}{V} \tag{1}$$

The solution of Eq. (1) leads to the expression:

$$Q = \frac{V}{t}\ln\frac{C_0}{C_t} \tag{2}$$
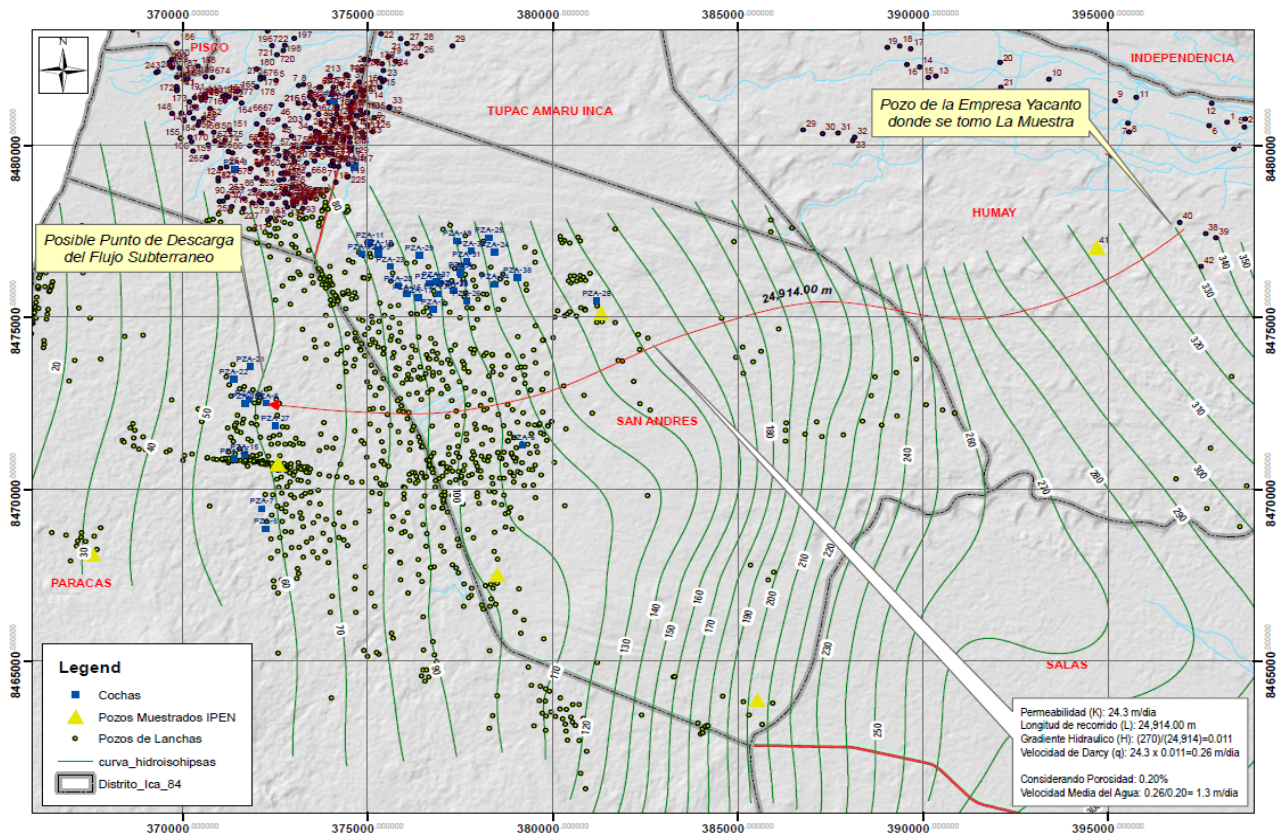
Fig. 1b   Specific area under project study in the Pampa de Lanchas aquifer.

where:

C = concentration of tracer.

t = time elapsed at the moment of measurement.

V = volume of the considered section.

Q = volume flow.

Eq. (2) can also be expressed as:

$$v = \frac{V}{S} \ln \frac{C_0}{C} \qquad (3)$$

where:

v = velocity of water flowing through the well.

V = Volumen of the considered section.

S = Section of the V volumen in the direction of the real flow.

C = Concentration of the tracer a1 after a time t.

C_0 = Inicia1 concentration of the tracer.

The velocity v is related to the speed of the water in the aquifer by the relationship:

$$v = \alpha v \qquad (4)$$

where α is a factor that represents the hydrodynamic perturbation caused by the well aquifer and v is the speed of the flow of water in the aquifer. The equation then takes the form:

$$v = \frac{V}{S\ \alpha} \ \ln \frac{C}{C_0} \qquad (5)$$

If the well diameter is d and the height of the water labeled column is h, V volume will be:

$$V = \pi \left(\frac{d}{2}\right)^2 h \qquad (6)$$

and: $\frac{C}{C_0} = e^{-\frac{sv\alpha}{V}}$

$$\frac{C}{C_0} = e^{-\frac{sv\alpha}{V}} \qquad (7)$$

From here it follows that $t_{1/10}$, time required for the concentration of the liner reduced to 10% of its initial value, is given by the expression:

$$t_{1/10} = \frac{1,81 d}{\alpha\ v} \qquad (8)$$

Then:

$$v = \frac{1{,}81\,d}{\alpha\, t_{1/10}} \tag{9}$$

where:

d = Inside diameter of the well.

A = Factor of hydrodynamic perturbation caused by the well in the aquifer, in relation to the natural flow pattern.

$t_{1/10}$ = Time required to reduce to 10%, the concentration of the tracer in the labelled volume.

v = Velocity of water in the aquifer.

Coefficient α depends mainly on the well coating conditions, casing and filter conditions, and can be evaluated if it is known or determined experimentally. α values varies between 1 and 4. Fig. 2 shows the types of profiles that are usually obtained with this technique. In the case of Fig. 2a, it is a horizontal flow in the intermediate section of the well. The successive concentration of the tracer profiles shows the decrease of the same within the indicated section. In the case of Fig. 2b, there is a downward vertical flow, with water inlet located along the stretch indicated with the letter I and the exit along the stretch indicated with the letter O.

Curves in Fig. 2 are used to identify the volumetric flow from the concentration profiles according to the time elapsed since injection of the tracer. The successive concentration profiles show how this diminishes gradually between both permeable sections. Losses of tracer that occur above the stage I and below the stretch O, are the result, primarily, of the turbulence created inside the well by the water flow. It must be remarked that, when common salt is used as a tracer, the salinity of the water in the well and, therefore, its density, increase as a result of the injection of such tracer.

Then, when water is renewed in the stretch between I and O, less salt water enters the well and an interphase between waters with different densities is created at the top O the stretch I.

The consequence is that the highest existing water density above this point, tends to get down due to density and the well is "clean" of tracer in this section, with speed less than the stretch affected by the vertical flow.

On the other hand, in interphase which is formed in the wall of the stage O, the water column is stable, because higher density water is found at the bottom. The case of Fig. 2c is the same as Fig. 2b, but with a vertical upflow. In both cases, the flowrate can be determined approximately.
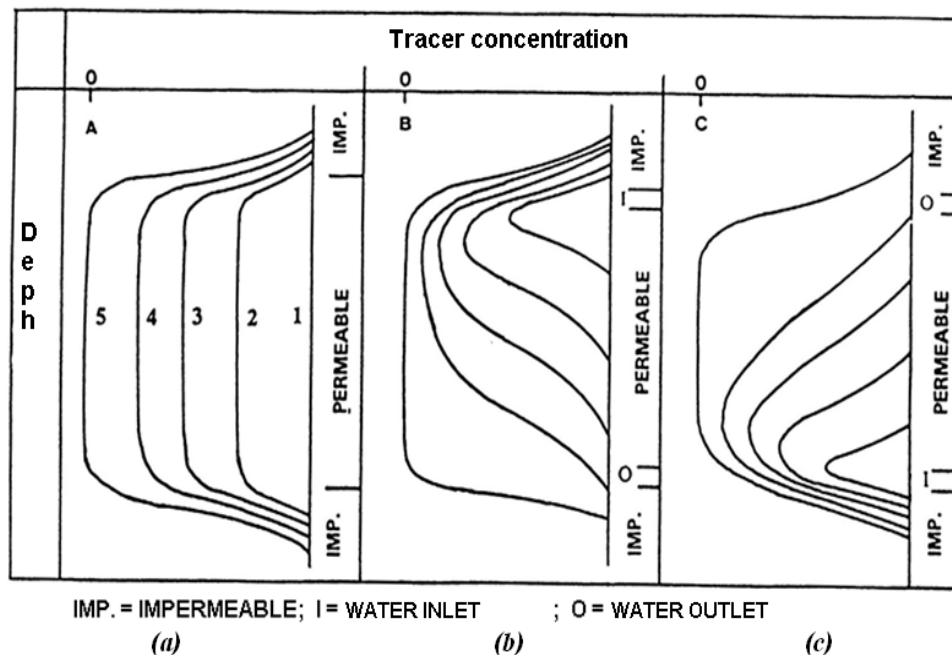
Fig. 2   Types of profiles that are obtained in the labelling of the entire water in wells; a = horizontal flow; b = vertical downflow; c = vertical upflow; I = water inlet; O = water outlet.

Fig. 3   View of the well used for the investigation of flow velocities in groundwaters.

These distances divided by the time interval elapsed between the measurements of the two profiles, provide the vertical flow velocity. Obviously, profiles of temperature and conductivity, measured before injecting the liner, are always helpful for interpreting the results of labelling throughout the water column.

Fig. 3 shows a view of the well in which the present investigation took place.

5. Equipment and Materials Used

Thermoconductivimeter.

Conductivity probe, with cable suitable for a maximum of 100 m depth.

Materials and basic tools for preparation and handling the tracer to inject. Tracer (saturated NaCl solution).

6. Operating Procedure

The applied technique of single well consisted of the injection of tracer in the well and monitoring conductivity for a period of 7 hours, time which depends on the hydrogeological characteristics of the aquifer. The procedure consisted of injecting certain amount of tracer along the entire column of the studied well, in such a way that its concentration becomes uniform (Fig. 4). Then conductivity was measured along the labelled column, at different heights. Measures were performed periodically in the same positions until the concentration is extinguished or reached sufficiently low value.

Labelling throughout the entire water column was realized introducing a plastic hose opened by both extreme and fitted with a ballast at its lower end, to facilitate the dive to the bottom. The solution of tracer consisting of a saturated solution of sodium chloride, equal to the internal volume of the hose (between the

bottom and the piezometric level) was then poured on top. This labelled volume completely displaces the water contained inside the hose. The hose was subsequently removed slowly and with constant speed, to allow the water column becomes labelled more or less uniform.

The measurement of the tracer was a thermoconductivimeter, connected through 100 m of cable, from the surface. Due to the flow of groundwater that passes through the well, the concentration of the tracer in the well decreases with time. The initial and final concentrations relationships, the elapsed time, and the the geometry of the well, allowed determining the flow velocity.

Rapid qualitative and semiquantitative information about existing flows along the water column of the well was obtained.
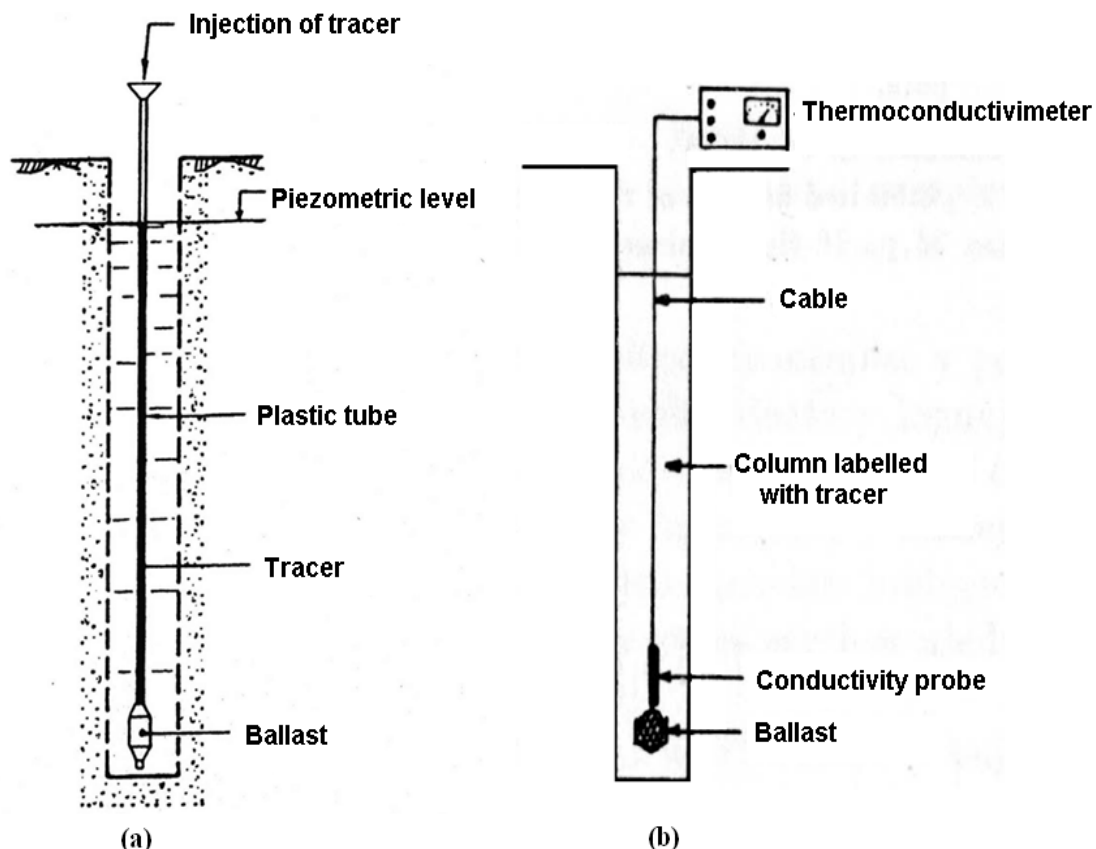

Fig. 4   (a) Method used for the labelling the entire column of water in the well, and (b) monitoring the tracer for obtaining the conductivity profiles

The labelling procedure is illustrated in Fig. 4a. A   10-mm diameter plastic hose was introduced to the

bottom well, by the aid of small ballast attached to its lower end. Later on, conductivity profiling was performed, displacing a cable of the conductivity probe and keeping the thermoconductivimeter in surface, as it is shown in Fig. 4b.

The hose was open at both ends. By the upper end of the hose, a volume of 6 L. solution of tracer was injected to fill the inside volume, measured from the piezometric level up to the bottom of the well. Then the hose was taken up slowly at an approximately constant speed, to allow the tracer to be distributed uniformly throughout the water column.

Tracer injection was made by gravity. A saturated solution of common salt was used as tracer, which solubility in water is about 350 g/L (*).

In this case, we first calculated the volume of solution of common salt required to be injected into the well to get a good distribution in the entire column, and to achieve the desired conductivity. This volume of solution was placed inside a suitable container and injected by moving the hose vertically up and down until the entire volume has been injected. Once the injection of the tracer was finished, it began the action to get successive concentration profiles sweeping the entire column with the probe, at different intervals, for example, 20 cm.

(*) Note: It was taken the following considerations for the calculation of tracer concentration to be used. The approximate conductivity of this solution must be in the order of 467 mS/cm. On the other hand, the internal section of the hose of 1 cm in diameter is 0.785 cm^2. Thus, if injection is carried out in a well of 6 cm diameter, whose section is 28.3 cm^2, the dilution that occurs amounts to 28.3/0.785 = 36. Therefore, the conductivity of the water from the well is increased by a value of 467/36 = 13 mS/cm. This increase in conductivity is sufficient to perform the test with ease if the initial conductivity of the water from the well is less than 5 mS/cm.

The frequency of the profiles was conducted in accordance with the rate of dilution of the tracer. It began with a higher frequency, for example, every 5 minutes, which was subsequently modified depending on the speed of the tracer dilution.

In this case, measurement probe and injection hose were a unique system by the aid of an adhesive paper. The lower end of the hose was located above the detector at a distance of 2.0 meters.

The hose was filled with solution of tracer in the same manner as indicated above. Then it was taken up the hose assembly and probe on a stretch of 5 meters. When this was done, a section of water column of the wellwas labelled just 5 meters, and probe was located approximately in the middle of the marked section.

Keeping fixed in this position the hose and the detector, the change in conductivity was measured as a function of time. Once the measure was over, we took up the hose assembly and conductivity probe, another 5 meters and repeated the measurement. The process continued in the same way to sweep all the stretch affected by the rapid flow.

7. Results

The collected data set allows us to identify the areas where there is horizontal flow in the well. In the section out of the stretch from 60.10 to 64.20 m., there was the area of blind pipe, where it can be seen that there is no loss of tracer since there is no flow. Table 1 shows the obtained data in the strecht of interest, while Figs. 5 and 6 show the curves registering by conductivity and the calculation of the groundwater velocity.

Table 1   Collected data for registering profiles of conductivity as a function of well deph at different time intervals (data for the strecht of interest).

Profundidad (m)	Conductividad (µS/cm)								
	$t = 0$	$t = 25$ a 35 min	$t = 120$ a 130 min	$t = 160$ a 170 min	$t = 200$ a 210 min	$t = 250$ a 260 min	$t = 310$ a 320 min	$t = 370$ a 380 min	$t = 420$ a 430 min
60.10	*	*	*	*	*	*	*	*	*

60.40	3,450	900	850	842	849	842	848	833	843
60.60	3,530	901	853	843	855	844	848	833	843
60.80	3,510	903	855	850	856	842	854	844	850
61.00	3,480	911	859	848	865	853	870	847	860
61.20	3,510	912	887	853	898	855	876	850	879
61.40	3,500	921	905	910	964	860	964	856	940
61.60	3,340	1,101	1,070	965	1055	940	1000	940	1,027
61.80	3,350	1,700	1,200	1,130	1,200	962	1,180	1,100	1,172
62.00	3,350	2,100	2,400	1,820	1,705	1,600	1,700	1,426	1,404
62.20	3,350	3,006	2,580	2,450	2,150	1,900	1,727	1,480	1,480
62.40	3,350	3,800	2,540	1,770	1,708	1,740	1,726	1,490	1,583
62.60	3,360	3,120	2,550	1,800	1,710	1,720	1,726	1,500	1,583
62.80	3,360	3,080	2,560	1,790	1,710	1,720	1,726	1,497	1,580
63.00	3,350	3,000	2,560	1,800	1,715	1,740	1,726	1,497	1,583
63.20	3,540	3,160	2,570	1,800	1,718	1,740	1,727	1,502	1,583
63.40	3,450	3,200	2,580	1,800	1,718	1,750	1,727	1,506	1,577
63.60	3,530	3,230	2,580	1,790	1,718	1,755	1,727	1,511	1,583
63.80	3,510	3,100	2,610	1,790	1,716	1,756	1,729	1,513	1,583
64.00	3,480	3,050	2,610	1,800	1,700	1,760	1,729	1,515	1,583
64.20	3,510	2,980	2,600	1,790	1,714	1,767	1,733	1,515	1,582

(*) Out of the wáter level.
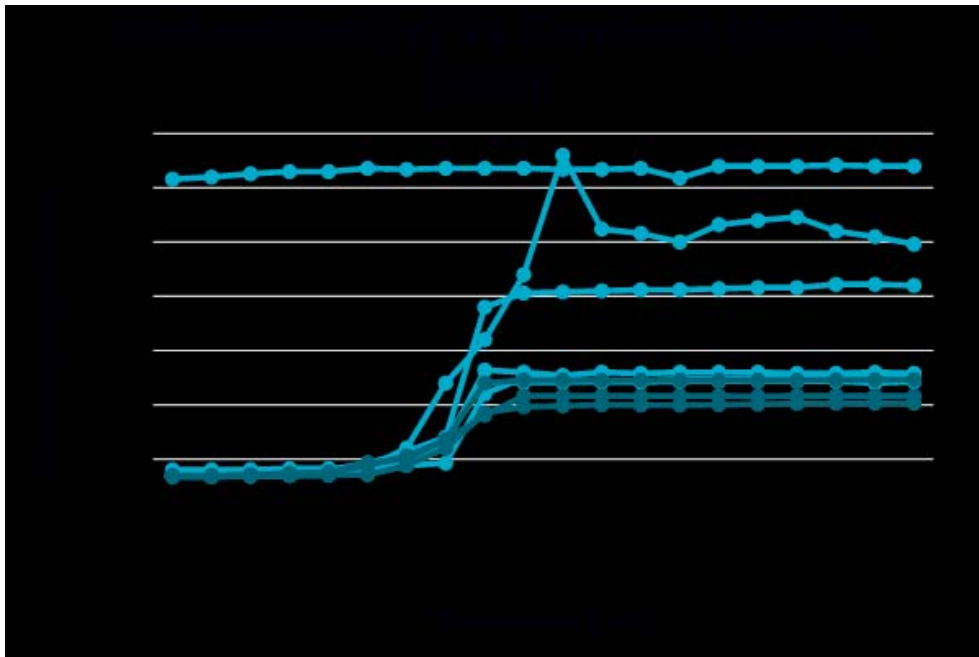
Fig. 5 Conductivity profiles as a function of the depth of the well. In most of the cases, it was observed maximum conductivity values at an average depth of 62.20 m.

Serie 1: Registro a $t = 0$ (start of meassurements)
Serie 2: Registro a $t = 30$ minutes (0.5 h)
Serie 3: Registro a $t = 125$ minutes (2.08 h)
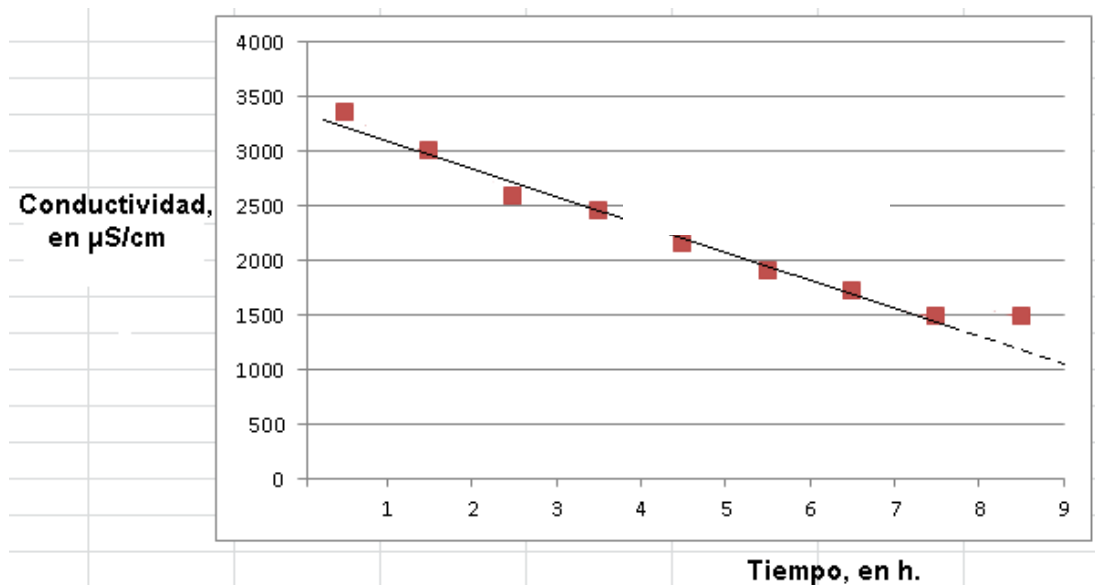Serie 4: Registro a $t = 165$ minutes (2.75 h)
Serie 5: Registro a $t = 205$ minutes (3.42 h)
Serie 6: Registro a $t = 255$ minutes (4.25 h)
Serie 7: Registro a $t = 315$ minutes (5.25 h)
Serie 8: Registro a $t = 375$ minutes (6.25 h)
Serie 9: Registro a $t = 425$ minutes (7.08 h)

Fig. 6   Conductivity declining curve as a function of time, at the level of horizontal water flow (62.20 m).
This information is also used to calculate the flow velocity of the groundwater.

Using the equation:

$$v = \frac{1,81\,d}{\alpha\ t_{1/10}}$$

We finally obtain:

$$v = \frac{1,81\ x\ 20\ x\ 0,0254\,m.}{1\ x\,\dfrac{10,25}{24}\,day} = 3,44\,m/day$$

8. Conclusions and Recommendations

(1) It was not observed the presence of vertical flows. The technique provided the horizontal speed of the underground flow fairly accurately, without making any adjustment to the methodology.

(2) Horizontal velocity found in the studied well is 3.44 m per day. The static level was 25 meters of depth during the measurements.

(3) To interpret the results correctly, it was necessary to have information on the constructive aspects of the well. The basic parameters needed are the inside diameter of the well, the characteristics of groove made in the pipe coating and data about possible external filling with gravel.

(4) The low variability of the values of the horizontal velocity and the absence of vertical flows, corroborates the affirmation that the aquifer is homogeneous and that there are flows concentrated through fractures.

(5) Given the importance which means the proper utilization and management of water resources of the area, it is recommended that higher speed levels require a detailed study and adequate management of the aquifer, taking into account the dangers of biological contamination of groundwater, which may result from septic tanks or surroundings to the recharge area.

(6) Once known the values of the speed of infiltration and under field conditions, one can get parameters such as hydraulic conductivity and transmissibility.

(7) It has been established the mainly benefits provided by the use of tracer techniques, including the following:

• The speed can be determined without knowing the porosity of the aquifer.

• Only one well is needed to perform the measurements.

• The speed of the ground water at any depth in the profile of the well is obtained independently. Speeds from few centimeters per day up to several tens of meters per day can be measured inside the well.

(8) Measurements in single wells represent a timely data, which may not be representative of the study area. However, this can be overcome if we carried out measurements in a sufficient number of carefully selected wells.

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