

NEW TECHNOLOGY FOR THE MEASUREMENT OF FILTRATION VELOCITY AND OF VERTICAL FLOWS IN AQUIFERS

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1. INTRODUCTION

This paper illustrates the method developed by authors that can be used for the measurement of filtration velocity and of vertical flows in aquifers based on single well technique, using a new artificial saline tracer: potassium iodide (KI).

The determination of the hydrodynamic characteristics of groundwater is often difficult. The measurement of filtration velocity, in particular, is characterised by a series of problems arising essentially from the characteristics of the operating environment and, given that we are dealing with aquifers which are permeable through fissuring and karstification, to the heterogeneity of the environment.

The variable condition of fissuring and of karstification which characterises the hydrogeology of the environment in Apulia Region (Italy) poses serious limits on the significance of measurements. Therefore, the necessity of operating in such an environment, stimulated the authors to devise a methodology using a tracer which could be detected directly in the hole even at low concentrations, at considerable depths from ground level and which could also be used in waters with a high saline content.

The first step was, therefore, to identify artificial saline tracers with high solubility and, if possible, those naturally present in the considered groundwater system. This research led to the choice of potassium iodide. Simultaneously research was carried out to find solid state specific ion electrodes which could easily be adapted for use in immersion under a water head.

Tests in laboratory were carried out with the aim of determining the stability of the chemical/physical characteristics of the chosen tracer, as well as evaluating the response of the instrumentation employed. This was followed by experimentation in the field.

The methodology applied has been proved to be a valid alternative to all those techniques which use classical artificial tracers, as radioactive, dyes or saline.

2. HISTORICAL NOTES

By using the method of tracer dilution in a single well it is possible to measure filtration velocity or apparent velocity which exploits the relationship that exists between the velocity at which a tracer introduced into a well is diluted by the water threads which cross the section of well and the filtration velocity of the groundwater (Halevy et al.,1967).

Measurement is performed by determining the concentration of tracer over the whole depth marked and then calculating from the dilution curve against time, the integral calculus of tracer concentration relative to each single coring. By means of this method it is possible to measure velocity which are even lower than 1 cm per day.

At the same time it is possible to detect the presence of vertical flows. These flows are water movements through the column both upwards and downwards and are generally caused by differences in hydraulic load between two or more aquifer levels which are communicating as a result of drilling. Sometimes these movements are a result of temperature differences and/or density differences.

The determination of vertical flows in wells is performed by the punctual introduction of tracers at the depth at which it is presumed, on the basis of geological data, that the flow exist.

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Consequently, the movement of the tracer cloud through the vertical wall of the well is registered at given depths, thus determining the average velocity of the vertical flow between two successive points using the “double peak” method.

3. CHOICE OF TRACER

The first problem to solve was to find an artificial tracer with a concentration directly measurable in the hole even at low concentrations, and at considerable depths from ground surface and usable in coastal waters with high saline contents.

The substances that can be used as tracers are various and different in nature. In theory the “*perfect*” tracer must behave in an identical manner to that of the fluid particles into which it is introduced (Sauty, 1977), must be highly soluble, and transported by water without causing modifications or alterations to the host system. In practice the perfect tracer is a substance which does not modify the physical and chemical nature of the fluid into which it is introduced, does not interact chemically and/or physically with the medium within which it moves, does not degrade or pollute the water, and can be detected even at very low concentrations.

The main artificial tracers employed for the detection of filtration velocity and of vertical flow in karstic aquifers are: radioactive (iodine-131, bromine-82, chromium-51, sulphur-35 etc.), dyes (fluorescein, rhodamine, methyl blue, etc.), salts (sodium chloride, sodium iodide, sodium and potassium bromide, etc.) and, more recently, chlorophyll.

Radioactive artificial tracers consist essentially of substances, soluble in water, the molecules of which contain a radioactive atom which emits beta or gamma radiation. The advantages of these are: high solubility; lack of chemical affinity with the elements which compose the rock; direct determination on site of the concentration by means of Geiger-Muller counters or scintillation detectors or counter impulse metres (Cotecchia, 1977, Tazioli, 1986). The use of these tracers, which is characterised by a certain risk level, requires personnel under medical surveillance and dosimetry, authorisations for use from the relative authorities and specific equipment. These facts may occasionally limit the use of the above mentioned substances.

With reference to the dye group, use is greatly limited when operating in an underground environment. The most used are the xanthenic dyes (rodamine and sulphurdamine group), the fluorescent molecules of which are particularly adapted to detection at very low concentrations by means of photometry (Benedini et al., 1992). Negative aspects are: interaction with the solid matrix (Benedini e Di Fazio, 1994); dangerousness; the need to take samples of water at predetermined depths on which to determine concentration with consequent disturbance throughout the water column; uncertainty as the sampling depths; high costs of the substances and instrumentation employed.

The saline tracers are the artificial substances which are most adapted to use in the study of aquifers as they are generally stable, i.e., they follow the flow and direction of the water without interacting with the solid matrix. They also have the advantage of being inexpensive, easy to find on the market and safe for man and for the environment. The measurement of the concentration of most of the saline tracers in question is effected on samples taken throughout the water column. Moreover, the detection of sodium chloride concentrations can be effected indirectly on site by measurement of the conductivity. Disadvantages include the necessity of taking samples of water from which to determine concentrations and by the limitations of use in coastal aquifers.

Finally we have chlorophyll, a natural pigment, which has the advantage of good fluid-dynamic characteristics, is not dangerous to man or to the environment, and can be detected at low concentrations by means of spectroscopy with visible light, fluorescence and phosphorescence (Di Fazio and Volterra, 1994). The main disadvantages regard the necessity to take samples and the high costs of the instrumentation used.

From this analysis it is apparent that the choice of an artificial tracer must take into account technological (high detection sensitivity and direct measurement of concentration), health (no dangers of transport and toxicity), and of an economic aspects (low costs of substances, easy to find on the market and low prices of detection apparatus).

The tracers usually used for the analyses in question are unlikely to respond at the same time to all of the requirements listed above. On the other hand, the proposed method using potassium iodide responds in all senses and can be used intensively.

Within the temperature range generally detected in the water in Puglia (10-20°C), potassium iodide is characterised by high solubility (The Merck index- tenth edition, 1983), is present in the underground waters in low concentrations, can be detected directly in the well with a specific ion sensor, has low costs, is easy to find and, above all, is not dangerous to man or to the environment.

4. DESCRIPTION OF THE TECHNICAL CHARACTERISTICS OF THE INSTRUMENTATION AND APPARATUS COMPOSING THE SYSTEM.

The following is a description of the principal technical characteristics of the apparatus used to effect the determination of filtration velocity and of vertical flows, as well as a description of all the equipment making up the system.

The determination of potassium iodide concentrations was carried out using the Idronaut Ocean Seven 901 probe (Fig.1) on which a specific ion sensor was installed for the detection of the iodine ion.

The sensor was adapted to make it usable up to a pressure of 50 bar. The probe itself is equipped with other five sensors: pressure, temperature, electrical conductivity, pH, dissolved oxygen (Fig.2); table 1 gives the principle characteristics of the above-mentioned sensors (Idronaut s.r.l., 1993).

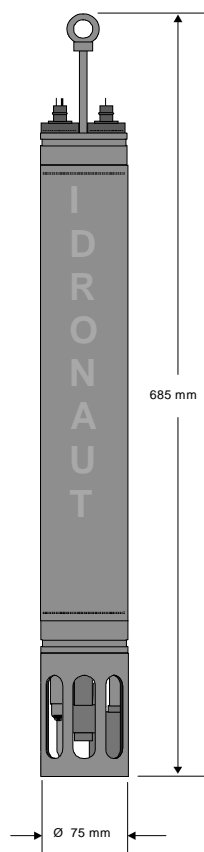


Fig.1 – Idronaut Ocean Seven 901

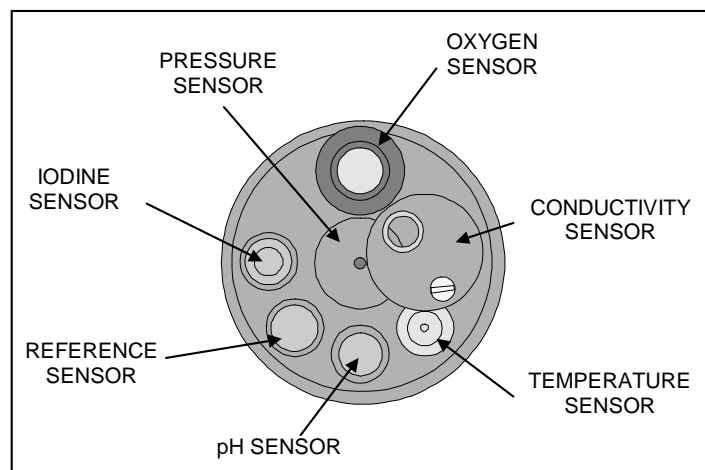


Fig.2 - Details of the sensors installed

In particular, the iodine sensor, which in the standard version of the probe substitutes the redox sensor, has an output in mV. Therefore, a calibration line, shown in Fig.3, was defined in the laboratory. From Fig.3 it is evident that the sensor response maintains an acceptable linearity, beyond the field indicated by the supplier (Orion, 1991), up to about 2300mg/l. In this field of measurement, sensitivity of values varies from 0,2 to 10mg/l, while average precision is $\pm 5\%$.

SENSOR	RANGE OF MEASUREMENT	PRECISION	SENSITIVITY
Pressure	0 ÷ 1500 bar	0.25% of max scale	0.1
Temperature	-1 ÷ +49 °C	0.1°C	0.01°C
Electrical conductivity	0 ÷ 62 mS/cm	± 5%	0.10 mS/cm
PH	0 ÷ 14	± 0.05	0.01
Dissolved oxygen	0 ÷ 50 mg/l	± 0.1 mg/l	0.01 mg/l
Iodine (*)	0.05 ÷ 127 mg/l	± 0.1 mg/l	0.01 mg/l
(**)	1 ÷ 500 mg/l		0.2 ÷ 10 mg/l

Table 1 - Characteristics of the sensors installed on the Idronaut Ocean Seven 901 probe.
 (*) Supplier data; (**) Experimental data.

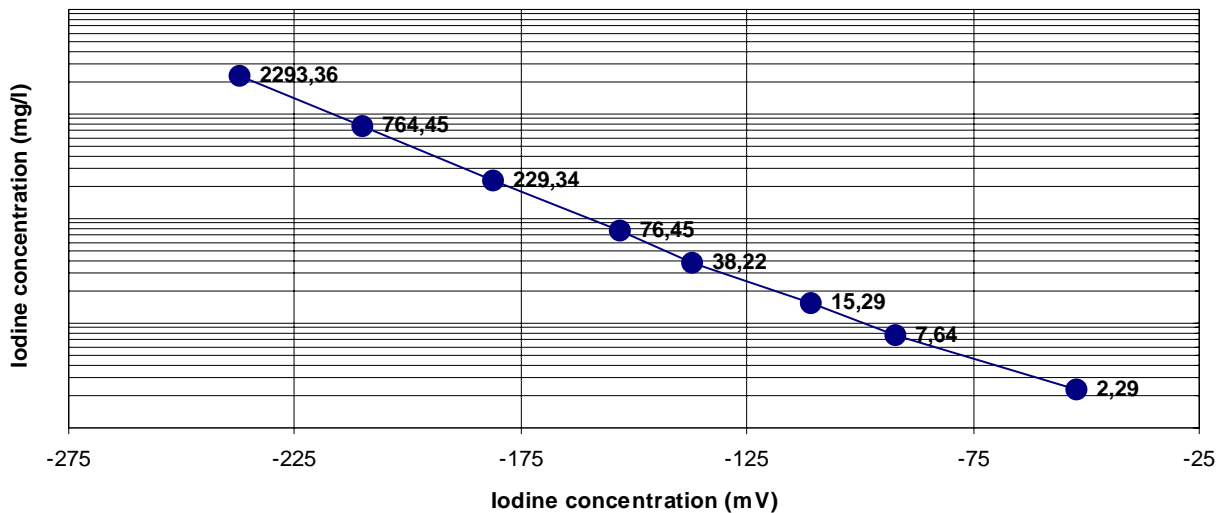


Fig.3 - Calibration line

In order to evaluate the response of the sensor to variations in the saline content of groundwater, calibration solutions were prepared using liquids of different salinity (from distilled water to sea water). The measurements performed in the solutions did not show evident variations in sensor response.

During on site experimentation, the calibration of the iodine sensor was monitored. As can be seen in Fig.4, this calibration is subject to a drift of the zero as a result of the progressive deterioration of the reference sensor. Therefore drift can easily be corrected by simple control measurements on a few calibration samples. This is reassuring when considering the repetitivity of determinations.

The measurement system mounted on an equipped vehicle including the Idronaut Ocean Seven 901 Probe, interfaced with portable personal computer equipped with printer and relative software which permits the on site visualisation and printing of the various concentration profiles detected in time.

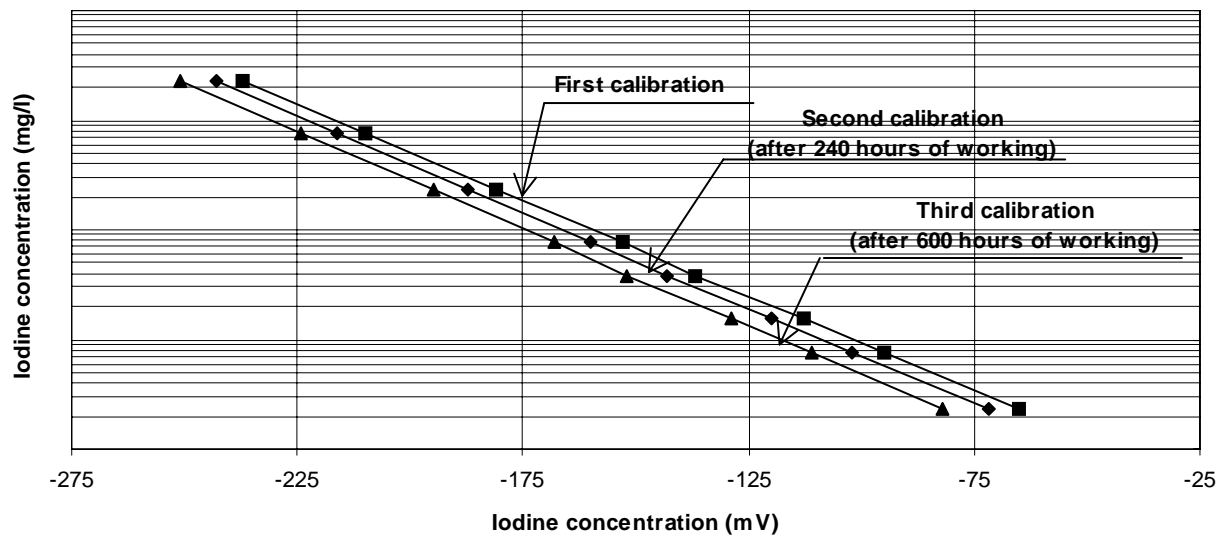


Fig.4 - Zero drift of the iodine sensor related to the progressive deterioration of the reference sensor.

A marker bottle has been designed and realised for the introduction of the tracer. This bottle is introduced closed into the well and then opened at the desired depth by means of commands sent from the surface and transmitted along the suspension cable. Emission of the tracer occurs through a series of openings situated in the base which permit the tracer itself to be diffused in the heart of the water column. Further openings in the top of the bottle allows groundwater to flow into the bottle substituting the solution within.

In this way it was possible to avoid (especially in fresh waters) the high initial concentration of the tracer in the marking bottle causing the unexpected outflow of the tracer itself. The high solubility of the tracer also gives the possibility to mark significant lengths of the water column, from a minimum of 10m to a maximum of 50m depending on the diameter of the perforation. The velocity with which the tracer flow out of the bottle can be adjusted by varying the number of openings in the base and top.

A motorised winch on the vehicle is used to assist in the above-mentioned measurements. The winch is equipped with a steel cable to which the marking bottle is connected and an electric cable to which the Idronaut Ocean Seven 901 probe is connected. The linear velocity of the winch can be varied by means of an inverter from a few cm/s to about 70cm/s. The length of the cable is controlled by a metre counter through which the cable itself is threaded .

5. OPERATING MODES

Before performing the analyses of filtration velocity and vertical flows, a multiparameter test is always performed through the entire water column of the well, analysing the principle chemical and physical parameters of the groundwaters and the initial iodine concentration (Cotecchia et al., 1999).

Apart from giving useful information on the chemical and physical characteristics of the waters, this prospecting permits important evaluations of marking depths and especially of the most suitable concentrations and temperatures for the tracer to be introduced. These concentrations and temperatures must not trigger modifications to the natural stratification of the underground waters or density flow along the water column with consequent alteration of measurement results.

Execution of the operation itself is performed by marking the water column along its most significant lengths. In particular, the solution which contains potassium iodide is distributed, using the special dispenser bottle, along the length to be marked from the bottom upwards and is then homogenised by means of alternating movements of the bottle.

Following the introduction of the tracer, a series of analyses of iodine concentration are performed, measuring the iodine along the entire water column at depth intervals which vary from 20cm to 50cm, starting from well water table at the bottom of the hole. The time intervals between one analysis and the next vary considerably from one well to another and are, therefore, directly evaluated in the field by means of observation of the dilution velocity of the tracer. In any case the duration of analyses was never less than 24 hours and rarely more than 72hours.

6. EXAMPLES OF APPLICATION

The system developed has been applied in about 70 drilled wells essentially in calcareous aquifers, permeable through fissuring and karstification which are typical of the Apulia region, reaching maximum depths of 700m with maximum water heads of 500m.

Fig.5 shows the test performed in the P1 well, situated in the area of Casamassima (province of Bari) whose depth is 600m (lined and unslot screen from 0 to 300m and unlined from 300 to 600m). The water table is located at about 168m from the ground surface. Consequently the usable water column is 432m high.

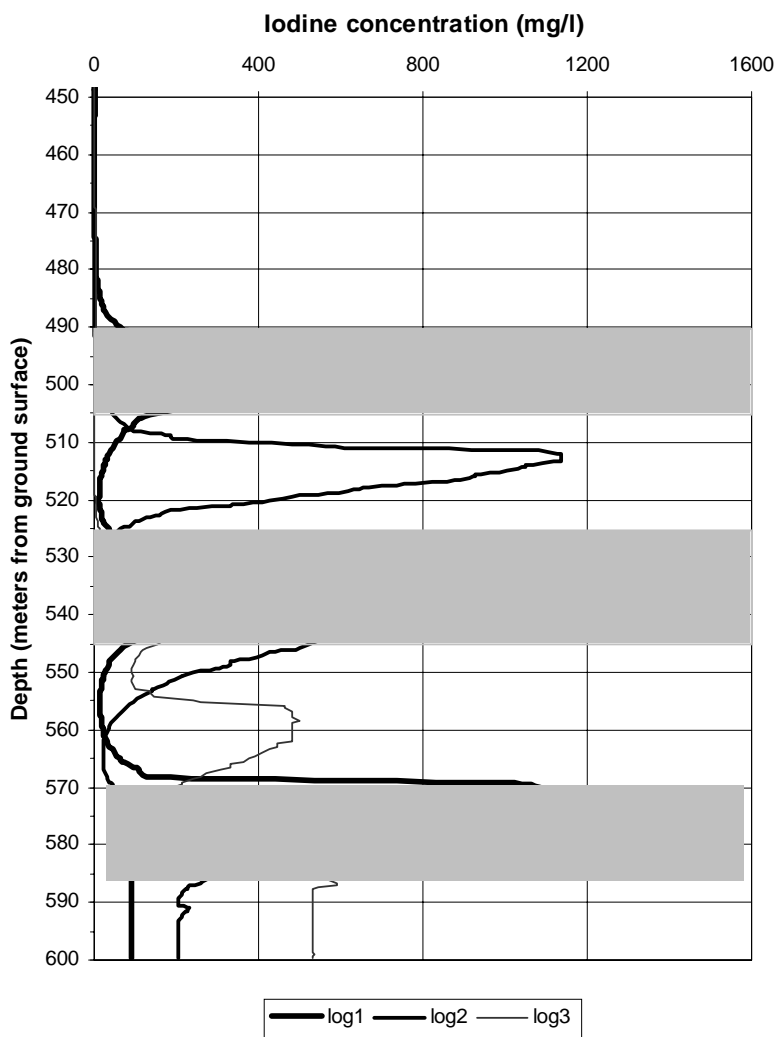


Fig.5 - Log plots following marking of the P1 well.

Three markings were carried out in consider well along the water column at the following depths: from 490 to 510m, from 525 to 545m and from 570 to 585m. As can be seen from Fig.5, which shows the profiles of the iodine concentrations (log0, log1, log2) performed through the water column at progressive time intervals, a descending vertical flow of 0.7cm/s is detected. This flow prevails over the horizontal flow which velocity was not possible to quantify. On the other hand it can be observed that no appreciable mixing of tracer clouds are registered in time during their movements downwards.

Fig.6 shows the test performed in a spy well of the Irrigation Agency, located in S.Vito dei Normanni (province of Brindisi), whose depth is 300m (lined and windowed throughout its entire length). The water table is located at about 68m from the

ground surface, therefore 232m from the bottom of the wells. Three markings were carried out along the water column at the following depths: from 95m to 127m, from 155m to 173m and from 250m to 292m.

As can be seen from the diagram of filtration velocity calculated in the marked lengths, the presence of an upper zone is detected characterised by a filtration velocity over 10 cm/d and two lower zones with filtration velocities lower than 5cm/d. No upward or downward movements were detected. It is important to note that during the tests at several depths the tracer concentration remained practically unchanged, confirming the reproducibility of the measurements.

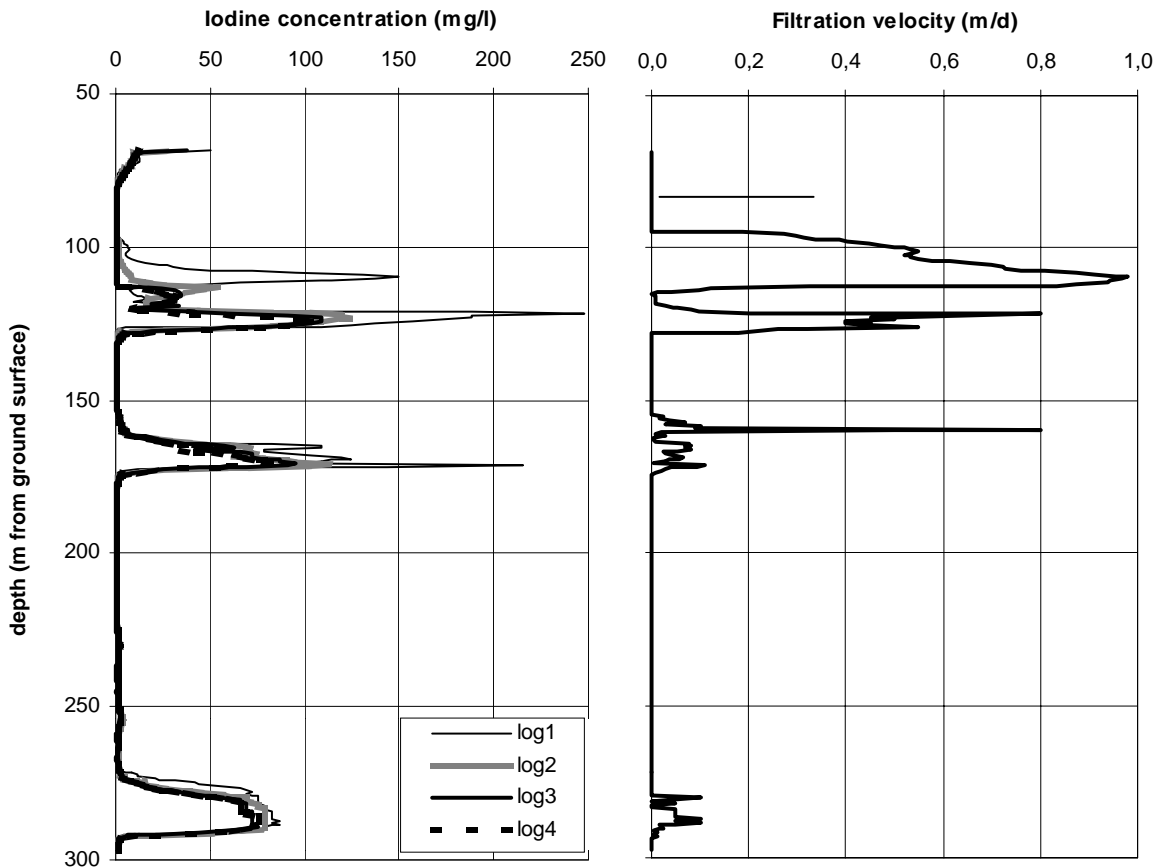


Fig.6 - Log plots and filtration speed calculated in the marked lengths of the P2 well.

7. Conclusions

The methodology developed and refined, presents a number of advantages in the study of aquifers which permits its extensive application over wide areas and, above all, groundwater with different chemical and physical characteristics. It should also be underlined that the application is not conditioned by all those limitations characterizing the usual techniques for the determination of filtration velocities and vertical flows.

In particular, it should be noted that the tracer concentration data are immediately available, as it is not necessary sample water and analyse it. Moreover, the complications resulting from the use of radioactive substances are avoided. This also results in a considerable decrease in error related with the sampling procedures i.e. the lack of precision of sampling quotas.

The possibility of performing marking along wide stretches of the water column without limits of depth, the direct acquisition of concentration data, the limited cost of the tracer used, as well as the danger-free nature of the tracer make this technique particularly advantageous also from an economic point of view.

In particular, the most interesting advantages of the method are represented by the velocity of intervention, by operational velocity resulting from the high solubility of the tracer and therefore the possibility of marking wide stretches of water columns; by the immediate detection of the tracer; by the possibility of investigating with a greater resolution (every 20cm) the portion of aquifer to be examined without added burdens; by the possibility of calibrating the programme of analysis while performing measurements, giving, therefore, greater significance to the investigation.

All the above leads evidently to direct time and cost saving to which can be added the additional information, useful in the phase of interpretation resulting from the zero cost analysis of chemical and physical parameters as well as the practical absence of limits of use both with concern to the depth at which the investigation is performed and to the chemical and physical characteristics of the waters concerned in the analyses.

The probe with which detection of the tracer is performed merits a paragraph of its own. It provides notable resolution and representativity of measurements, an aspect of fundamental importance to the correctness and precision of data.

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