GROUNDWATER VELOCITY MEASUREMENTS WITH THE SINGLE POINT DILUTION METHOD (SPDM) IN A SAMPLE SITE OF THE HIGH VENETIAN PLAIN (GALLIERA V. - NORTHERN ITALY)

MISURE DI VELOCITA' DI DEFLUSSO DELLE ACQUE SOTTERRANEE CON IL METODO DELLA DILUIZIONE PUNTUALE IN UN SITO CAMPIONE DELL'ALTA PIANURA VENETA (GALLIERA V. - ITALIA SETTENTRIONALE)

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ABSTRACT - The following study forms part of a multidisciplinary program of research involving the groundwater pollution transfert in the high Venetian Plain. Some results concerning the application of an experimental methodology for the direct measurement of the groundwater filtration velocity and based on the use of artificial tracers in a single well are described. The area at issue is placed in the high Venetian Plain (Galliera Veneta, Padova). As regards the hydrogeological structure, the underground is composed of gravelly alluvial deposits (undifferentiated complex), where an unconfined aquifer is located; few kilometers southern permeable layers alternate with silt and clay beds generate a multistratum confined system typical of the middle plain. The method used consists in monitoring just in the injection well the dilution tracer caused by flow lines crossing the well-screen, until the tracer has totally disappeared. The variation of tracer concentration depends on an exponential law and it is related with the groundwater horizontal velocity of filtration in the porous medium. The field experiment, performed by a short tracer injection, was conducted by putting in the borehole a saturated salt-water solution (NaCl): this operation was carried out in order to guarantee a good mixing of the tracer in the well. The dilution log was obtained by measuring the electrical conductivity of the water; these measurements were repeated for every different depth level in accordance to an increasing time progression, until the initial situation was restored. The vertical distribution of filtration velocity (6-12 m/d) was calculated thanks to quantitative information obtained. The experimental data particularly show different filtration velocities inside the same gravelly aquifer. These variations in all probability depend on permeability vertical changes not visible by the boring lithostratigraphy. This paper describes an example of application of the point dilution method. In particular this technique allowed to improve the knowledge concerning some fundamental hydrogeological parameters in groundwater pollution transfert evaluation.

RIASSUNTO - Le indagini svolte rientrano nell'ambito di un programma di ricerca sul trasferimento degli inquinanti nelle acque sotterranee dell'alta Pianura Veneta. Vengono presentati alcuni risultati relativi all'applicazione di una metodologia sperimentale per la valutazione diretta della velocità di filtrazione delle acque sotterranee, basata sull'impiego di traccianti artificiali in pozzo singolo. La zona in studio è ubicata nell'alta Pianura Veneta in Comune di Galliera Veneta (provincia di Padova). Dal punto di vista idrogeologico il sottosuolo è costituito da depositi alluvionali prevalentemente ghiaiosi (complesso indifferenziato), in cui è alloggiata una falda a carattere freatico; pochi chilometri a valle la presenza di livelli permeabili alternati con letti di limi e argille dà origine al sistema multifalde ad

acquiferi sovrapposti in pressione, tipico della media pianura. La tecnica utilizzata consiste nel monitorare, nel punto stesso di immissione, la diluizione del tracciante, operata dai filetti liquidi che attraversano il pozzo, fino alla sua completa sparizione. La variazione di concentrazione del tracciante nel tempo segue una legge di tipo esponenziale ed è in relazione con la velocità orizzontale apparente del flusso idrico nel mezzo poroso. Il tracciamento, condotto secondo la pratica dell'immissione breve (modalità istantanea), è stato effettuato iniettando nel pozzo di misura una soluzione salina satura (NaCl): in questa fase si è operato in modo da garantire una buona omogeneizzazione del tracciante all'interno del tratto fenestrato. Il profilo di diluizione è stato ricavato da misure di conducibilità elettrica ripetute lungo la verticale del foro a intervalli di tempo crescente dalla perturbazione iniziale fino al ripristino della situazione naturale. Sulla base delle informazioni quantitative ottenute è stata ricostruita la distribuzione verticale della velocità di filtrazione nel sottosuolo, variabile tra 6 e 12 metri/giorno. Le prove hanno in particolare evidenziato velocità di filtrazione differenti entro il medesimo acquifero ghiaioso, legate a probabili variazioni verticali della permeabilità, non rilevabili dalla stratigrafia dedotta dai dati di perforazione. L'esperienza descritta rappresenta un esempio di applicazione di questo metodo di investigazione, che nel caso specifico ha consentito di approfondire la conoscenza di importanti parametri idrogeologici necessari nelle valutazioni delle modalità di trasferimento degli inquinanti in falda.

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2. Principles on which the method is based

The point dilution method consists of monitoring, from the point of injection, the course of a tracer in flows crossing a well until all signs of that tracer have completely disappeared.
This technique, amply discussed and tested, mainly in the sector of radioisotope hydrogeology (Drost et al., 1968 - Tazioli, 1973), provides a direct estimate of the velocity of filtration (*vf*) in groundwaters. More precisely, in cases of stationary regime and laminar flow, the time variations in tracer concentrations may be expressed by the following equation:

(1) $$\frac{dC}{dt} = -Av_a \frac{C}{V}$$

in which *C* is concentration, *t* time, *V* the volume in which dilution occurs, A the section of V orthogonal to the flow lines, and va the apparent velocity in the well.
In the case of instantaneous injection, the solution by integration of equation (1) becomes:

(2) $$v_a = -\frac{V}{At} \ln \frac{C_t}{C_0}$$

where C_0 is the concentration in the well at *t*=0 immediately after injection, and C_t the concentration at time *t*.

It may also be assumed that there is a relation between (*va)* and (*vf)* in the aquifer (Halevy et al., 1967), as follows:

(3) $$v_a = av_f + v_h + v_s + v_m + v_d$$

where *vh* is the apparent velocity deriving from convection due to density contrasts in the tracer, because of poor mixing or large vertical variations in temperature inside the tested stretch; vs the apparent velocity connected to the presence of natural vertical currents in the well generated, for example, by communications between various aquifers with different piezometric values (Tazioli, 1973); *vm* is the apparent velocity caused by artificial mixing; *vd* is the apparent velocity linked to the intrinsic diffusion of the tracer; and α is a coefficient to correct the inevitable distorsion of the flow net introduced by the physical structure of the well. In favourable experimental conditions, which may be optimized when operating in situ with due precautions, the disturbances caused by these factors may be reduced and thus reasonably neglected. In this way, if some terms are annulled, equation (3) becomes:

(4) $$v_a = av_f$$

so that (2) may be rewritten as:

(5) $$v_f = -\frac{V}{aAt}\ln\frac{C_t}{C_0}$$

This shows the analytical link between velocity of filtration (*vf)* and tracer dilution in time. The next passage, estimating the effective velocity of transit in the aquifer, (*vr)*, is obtained by dividing Darcy velocity vf by effective porosity (n_e*)*, according to the well-known equation:

(6) $$v_r = \frac{v_f}{n_e}$$

Without entering into details of other correction coefficients, which have to be considered in special operational situations (e.g., use of packers, very large probes in relation to well diameter), it must be stressed that parameter α may generically vary between 0 and 8 (Gaspar, 1987). In the specific case of wells in granular soils without prefilter, the value of à may easily be given by Ogilvi's (1958) formula:

(7) $$a = \frac{4}{1+\left(\frac{r_1}{r_2}\right)^2 + \frac{k}{k_1}\left[1-\left(\frac{r_1}{r_2}\right)^2\right]}$$

(in which *r1* and *r2* are the internal and external radii of the well, and *k* and *k1* are the coefficients of permeability of the aquifer and of the filter respectively), and tabulated by Klotz (1978) for various types of filter-tubes. Laboratory tests and many field investigations have in any case shown that, when *k1>>k*, α tends to be around 2 (Gaspar, 1987).

3. Study site

The area studied here lies in the high Venetian alluvial plain, at Galliera Veneta (province of Padova) (Fig. 1). In this part of the pedemontane belt, the subsoil is composed of a thick layer of incoherent gravelly-sandy materials belonging to the alluvial fans of the river Brenta. From the general hydrogeological viewpoint, the high plain is characterized by the presence of an unconfined aquifer. To the south, the alluvial cover begins to differentiate into permeable gravelly-sandy layers alternating with clay and silt, giving rise to a multi-layer system with overlapping confined aquifers. Figure 2 illustrates this hydrogeological model.
In this structural context, the experimental site of Galliera Veneta is located in the undifferentiated complex. The watertable lies at a depth varying between 6 and 9 m from ground level, according to the various phases of its regime. The piezometers (Fig.

3) were arranged according to a series of level measurements, with the aim of reconstructing the approximate direction of the local groundwater flow. The stratigraphic succession was reconstructed during continuous boring (Fig. 4). Lefranc tests supplied an initial assessment of the permeability of the alluvial deposits. Table 1 briefly lists the main data of the well field studied.

4. Test methodology

The test described here follows a series of experimental calibrations, during which some technical and methodological aspects are progressively improved.The tracer solution was composed of about 100 litres of a saturated solution of sodium chloride. The mixture was taken to the same temperature as that of the groundwater. Before the test, at each piezometer, equipped with phreatimeter and conductivity recorder, the depth of the watertable was measured (6.9 m from ground level), and thermometric and conductivity logs were measured, as references. Injection into piezometer A lasted about 7 minutes, at a constant flow rate of 0.2 l/s. During this period, the injection tube, the last 4 m of which was densely perforated and sealed at the tip, was repeatedly withdrawn and then reinserted to the bottom of the well at a very slow constant speed, for good homogenization of the salt solution. In this initial phase, however, disturbance of the initial hydraulic conditions was noted, due to the anomalous lowering of the groundwater level in the injection well, as a result of the increased density of the fluid (Bernardi et al., 1995). This phenomenon lasted about 30 minutes, and was probably accentuated by the watertable depth, which was about 2 m higher than that of the filters. However, it was very small ($\Delta h<3$ cm) with respect to the values measured during previous experiments, in which mixing along the column was less effective ($\Delta h=20$ cm). Dilution in the well was observed by measuring the values of rising electrical conductivity, samplings being recorded approximately every 60 cm (2 feet). Measurements were taken at increasing intervals of time from the end of injection, and lasted about 30 hours. During this period, the downstream piezometers were constantly checked, although no variations in electrical conductivity due to the perturbation caused by the tracer passing through the aquifer were noted.
The probe used for measuring electrical conductivity ($\phi=2.5$ cm) supplies automatically compensated values at 20°C over a range from 0 to 20,000 μS/cm, with 2% precision .

5. Results and calculation of velocity of filtration

The point dilution method, being rapid and simple, gives interesting results as regards rapid determination of groundwater flow velocities. Although it has the disadvantages and approximations which are inevitable when using a tracer of electrolytic type, the point dilution method does identify variations in the velocity of filtration at various depths due to different permeabilities which cannot be appreciated during boring. The overall results are shown in Fig. 5 and are briefly summarized below.

- Layers between depths of 7 and 21 m were subdivided into 4 zones.

- The upper portion of zone A lies at a depth of 6-8 m and coincides with that part of the piezometer without filters. In this stretch, although the velocity of horizontal filtration is of course nil, the fall in electrical conductivity in time is slow because, although indirectly caused by the dilution in the lower stretch, it mainly occurs by diffusion. Between depths of 8 and 9.5 m, there is a layer with a slower speed than that of the underlying zone B, linked to the layer of coarse sand (7-9 m).
- The trend of the dilution profile in zone B shows that this layer has the highest velocity of filtration. Unlike the situation in the other zones, the electrical conductivity in the well had returned to normal values only 3 h after injection. The tracer is rapidly and uniformly evacuated and shows a peak velocity value at depths of 11-13 m.
- Zone C has filtration speeds which are than lower those of zone B and decrease with depth, to the lowest values recorded in zone D. In more detail, at 14-16 m, dilution velocity continues to be quite high, but between 16-18 m it rapidly falls. This behaviour, revealed by the changing response to flow, is definitely due to reduced permeability.
- Zone D has a very low, uniform velocity of filtration, very probably due to still further reduced permeability inside the gravels not identified by the boring stratigraphy. Conductivity in the column 27 hours after tracer injection was still quite high - twice as high as the initial value.

Processing of experimental data to estimate the velocity of filtration inside the porous medium was carried out starting from equation (5), linking it to the asymptotic decrease in tracer concentration. It should be stressed that passage from in situ conductivity values to concentration values (C) was made possible thanks to a laboratory test simulating dilution of the tracer on a sample of NaCl-saturated groundwater (C_0=350 g/l at 15°C).
During the calibration test, the conductivity meter first went off-scale up to the threshold of C/C_0=0.05 (conductivity=15.2 *m*S/cm). As dilution proceeded, the measurements began to follow a regular trend, which was accurately interpolated by a third-order polynomial correlation function (Fig. 6).
In order to calculate the velocity of filtration, equation (5) was thus rewritten in the following form:

(8) $$\ln\frac{C_t}{C_0} = -\left(\frac{aAv_f}{V}\right)t$$

which is the equation of a straight line with an angular coefficient:

(9) $$m = \frac{aAv_f}{V} = kost \cdot v_f$$

The data were plotted in semi-logarithmic form. The experimental points over a time interval of C/C_0=0.1 (Halevy et al., 1967) were subjected to linear regression analysis.

This procedure gave a value for *m* for each depth sampled, from which the corresponding value of *vf* was derived. Table 2 shows the values of real velocity (*vr*), calculated by assuming α=2 and n_e=0.10-0.15-0.20.

6. Conclusions

The point dilution method was tested in a single well in the well field of Galliera Veneta (N. Italy). It revealed that velocities vary significantly with depth, and that groundwater flow reaches maximum velocities of 6-12 m/day. In more detail, the test revealed considerable differences in velocities within the same gravelly aquifer. This behaviour, very probably due to small-scale vertical variations in permeability, was not detected by the stratigraphic reconstruction of the subsoil desumed from data collected during mechanical boring. The current research program involves further tests using other methods, to confirm these preliminary results. In studying the propagation of polluting phenomena, therefore, careful attention must be paid when comparing data from various monitoring wells and positions of well-screens: although inserted into an apparently homogeneous aquifer, measurement devices may intercept flows with very different velocities.

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Tab.1 - Technical data about the piezometers.

Nome	Diam. (f)	Tipo	Prof. (m)	Spessore Filtri (m)	Perforazione		Test
					Metodo	Fluido	
Pz A	3"	PVC	21.0	8-21	Distruz. nucleo	Acqua	--
Pz B	3"	PVC	20.5	8-21	Distruz. nucleo	Acqua	--
Pz C	3"	PVC	24.0	9-21	Carotaggio cont.	Acqua	Lefranc
Pz D	3"	PVC	20.5	8.5-21.5	Distruz. nucleo	Acqua	--
NOTE: I piezometri sono chiusi al fondo con tappo filettato in PVC							

Tab.2 - Filtration and flow velocities obtained in the site of Galliera V.

ZONE	A		B						C					D			
P	**8.5**	**9.1**	**10.4**	**11.0**	**11.6**	**12.2**	**12.8**	**13.4**	**14.6**	**15.2**	**15.8**	**16.5**	**17.1**	**18.3**	**18.9**	**19.5**	**20.1**
v_f	0.4	0.4	1.3	1.3	1.2	1.2	1.1	1.0	1.0	0.9	0.9	1.0	1.1	0.3	0.3	0.4	0.4
$v_{r\,1}$	3.9	3.9	13.4	12.5	12.0	11.5	10.7	9.7	9.9	8.8	8.7	9.6	10.8	2.7	2.8	3.9	3.8
$v_{r\,2}$	2.6	2.6	8.9	8.4	8.0	7.7	7.1	6.4	6.6	5.9	5.8	6.4	7.2	1.8	1.8	2.6	2.5
$v_{r\,3}$	2.0	1.9	6.7	6.3	6.0	5.8	5.3	4.8	5.0	4.4	4.4	4.8	5.4	1.3	1.4	2.0	1.9

P= profondità delle misure (metri); v_f=velocità di filtrazione (metri/giorno, α = 2);
v_r 1= velocità di deflusso (metri/giorno) per porosità efficace (n_e) = 10 %;
v_r 2= velocità di deflusso (metri/giorno) per porosità efficace (n_e) = 15 %;
v_r 3= velocità di deflusso (metri/giorno) per porosità efficace (n_e) = 20 %;

Fig. 1 – Location of studied area

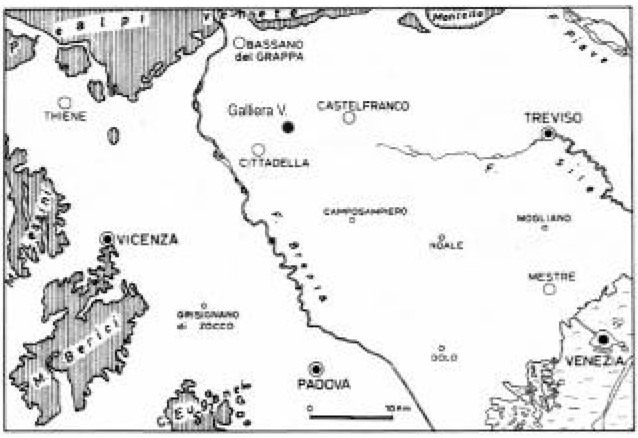

Fig. 2 – Hydrogeological model of high and middle Venetian Plain

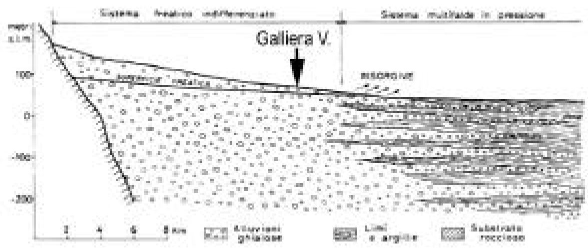

Fig. 3 - Geometry of the well field.

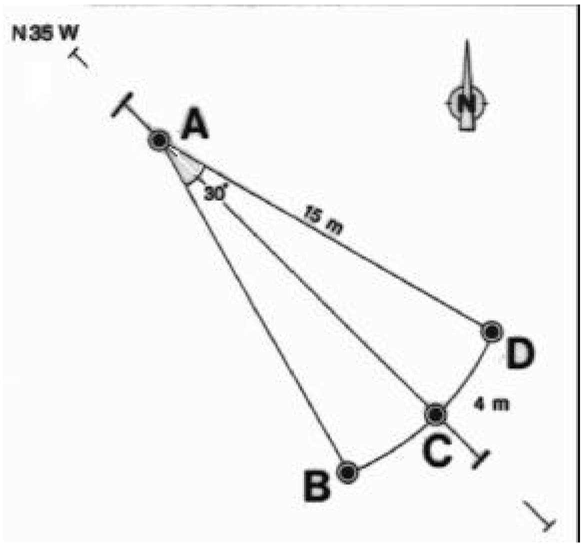

Fig. 4 - Piezometer C lithostratigraphy

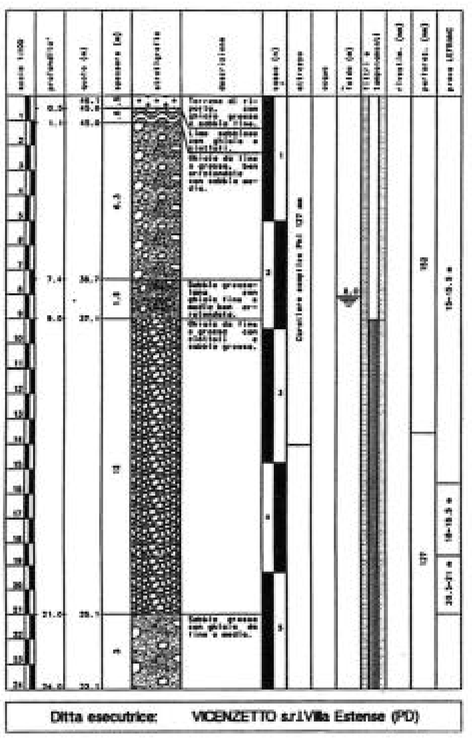

Fig. 5 - Dilution log

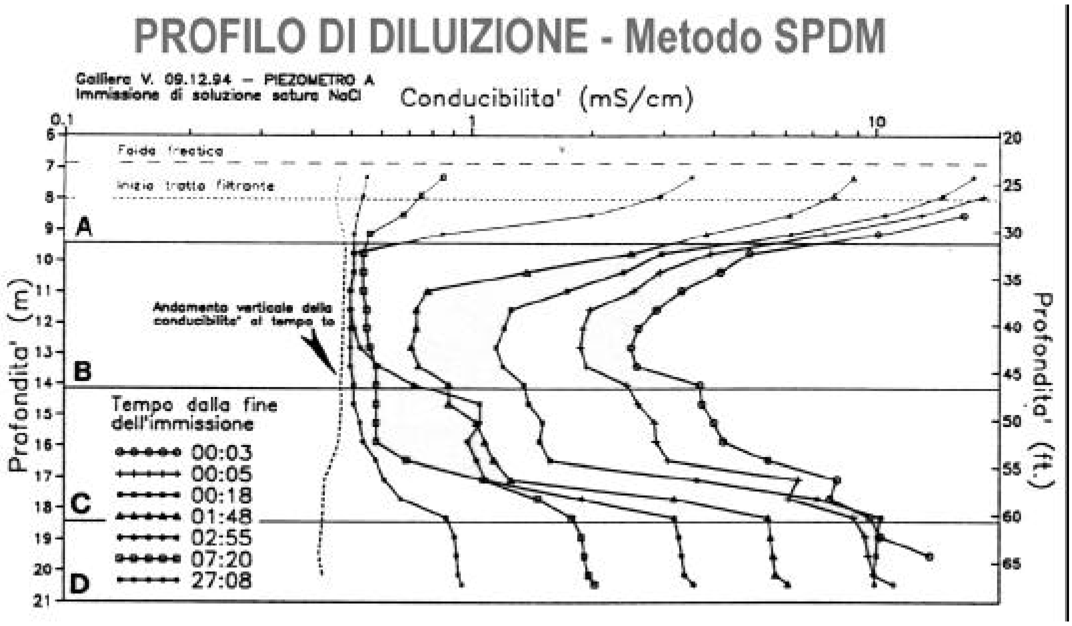

Fig. 6 - Instrumental correlation between concentration and electrical conductivity