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Chapter - 24

**CHANGE IN FLOW VELOCITY AROUND A WELL IN A
POROUS AQUIFER AFTER PUMPING**

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ABSTRACT: This study compares the results of natural tracer tests before and after a pumping test in an alluvial aquifer. Changes in flow velocity demonstrate that intense well development (like that produced by an intense pumping test) can change natural aquifer properties around the well, which must be taken into account when designing and interpreting tracer tests to derive natural aquifer transport properties within 8-9 m of an injection well.

These hydrogeological changes occur because pumping tests (in this case, with a rate of 77 l/s) extract the finest part of the reservoir (i.e., silt and very fine sand) around the well, causing a negative skin effect.

An important groundwater reservoir is present in the alluvial plain of Treviso (Veneto region, NE Italy). Previous hydrogeological studies on the unconfined aquifer system have provided some qualitative and quantitative data for its hydrostructural and hydrodynamic assessment. In our study, tracer tests indicate that well development has increased local flow velocities 3.1 m from injection well B and that these changes are visible up to 8.4 m from the injection well.

KEYWORDS: Tracer Tests, Flow Velocities, Break Through Curves, Well Development, Gravel Aquifers, Alluvial Plain.

1. INTRODUCTION

Tracer tests can be used to derive flow and transport parameters, so it is important for these tests to represent natural conditions of the studied aquifer. However, drilling and developing water wells, particularly after an intense and long pumping test, can change the natural hydrogeological parameters of some aquifers up around the borehole. Field-scale tracer tests can be used not only to

calculate dispersivity values (Freyberg, 1986; Mallants *et al.*, 2000; Yang *et al.*, 2001) and flow velocities but also to evaluate both their variation near an injection well and the distance within which variations due to pumping are recognizable.

This paper presents the results of tracer tests, both before and after natural development and a pumping test. These results show that intense development of the aquifer can cause a significant change in flow velocities. This indicates that tracer tests must be used with caution, taking into account possible hydrogeological parameter changes, depending on the aquifer type and the distance from the injection site.

We conducted natural tracer tests in the Treviso area (Veneto region, NE Italy) (Figure 1), with the aim of studying this phenomenon.

The hydrogeology of the area is characterized in the north by an extensive unconfined alluvial aquifer some hundred metres thick. This area extends from the Pre-Alps to the “fontanili” line, where the water table intersects the topographic surface, creating plain springs called “fontanili” (Figure 1). During and after the Würm glacial period, the Piave streams formed large alluvial fans that were overlapped and laterally penetrated by fans from adjacent rivers. The entire plain from the pre-Alps to 15 km southward consists of an undifferentiated cover of gravel with sand and occasional interbedded clay layers (high Venetian plain) (Venzo, 1977).

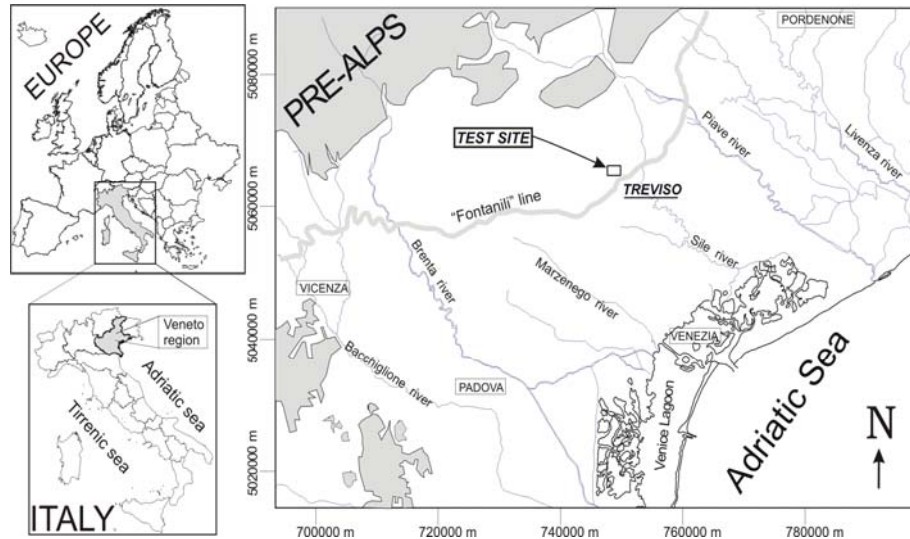


Figure 1. Map showing the studied area and location of the test site in the Treviso area (Veneto region, NE Italy).

The aforementioned “fontanili” line marks a plain band that is 2 to 5 km wide and several hundred kilometres long, which runs from the Piemonte region (NW, Italy) to the Friuli region (NE, Italy) and represents a boundary between

the high and low Padana Plain. This natural drainage system supplies a number of perennial streams, e.g., the Sile river ($5\text{--}6\text{ m}^3\text{ s}^{-1}$) (Antonelli *et al.*, 1980). South of the “fontanili” line, the unconfined aquifer changes into a multi-layered confined or semi-confined aquifer system. The hydrogeology is determined by impervious or semi-pervious layers interbedded with sand and gravel (middle Venetian plain). In the distal part of the fan, at various distances from the mountain region, the alluvial body is made up of alternating layers of gravel, sand, silt and clay that can be more than 10 m thick. The clay layers may be referred of lagoon or marine paleo-environment. The complete multi-layer aquifer can reach a thickness of up to 300 m and progressively increases near the Adriatic Sea (Figure 1) (Vorlicek *et al.*, 2004).

2. NATURAL-GRADIENT FIELD TRACER TESTS

A test site called “via Trieste” to the north of Treviso (NE, Italy) (Figure 1) was established with the goal of studying hydrogeological parameters of the aquifer. Contaminant transport parameters (longitudinal and transversal dispersivity, effective porosity and Darcy and flow velocities) were studied through the use of tracer tests and hydraulic conductivity, and storage were studied via pumping tests.

This test site has the hydrogeological characteristics of the high Padana plain.

The central borehole (B in Figure 2) was 20 m deep; the first 8 m had a steel casing, while the remaining 12 meters were screened. This borehole was drilled by a cable tool percussion method, and no completion method was executed in order to modify as few of the hydrogeological characteristics around the borehole as possible. All the other boreholes present at the site were drilled by direct rotary, had PVC casing between 0 and 8 m depth, and were screened between 8 to 22 m depth.

The test site stratigraphy is a homogeneous calcareous gravel of fluvial origin at depths up to 22 m (derived from borehole drilling log), with a maximum diameter of 10 cm. A silty sand matrix is also present, and there are limited thick sandy lenses. In this area, the gravel can be 30, 50 and sometimes even 80 m thick, and there is a clay horizon at about 50 m depth around the test site. The deposit indicates the existence of a palaeo-Piave river. Total porosity is about 27%. In this area, regional groundwater flows north–south with a hydraulic gradient of about 0.001– 0.0012 m/m; the water table is about 5 – 6 m below the ground surface (Antonelli *et al.*, 1999).

In order to evaluate the changes in flow velocity around a well, tracer tests were carried out before and after pumping. The tracer used was sodium chloride, which is easy to detect in situ, is harmless to health and has a low environmental impact. Chloride is a conservative ion, and sodium does not easily exchange or react with calcium carbonate, the predominant aquifer mineralogical component. Five of the six tests (T2, T3, T4, T5, T6) were carried out by injecting 15 litres of

this salt-saturated solution (272 g/l) into the central well (B) (in T1, 30 litres were injected) while monitoring the down-gradient wells. To minimize the influence of injection conditions, the instantaneous injection technique was used (Brouyère *et al.*, 2005). A packer was located at 9 m depth in injection well B, permitting tracing through one metre of the well screen. The injection lasted about 2-2.5 minutes, with an injection rate of ~ 0.1 l/s, after which no clean water was injected. Following injection, electrical conductivity (EC) was monitored in down-gradient wells in screened intervals of 0.5 m increments. Measurements continued until the initial EC conditions were reached. EC anomalies were detected along the flow direction in the wells nearest to the injection point, i.e., in S1 and S2b observation wells.

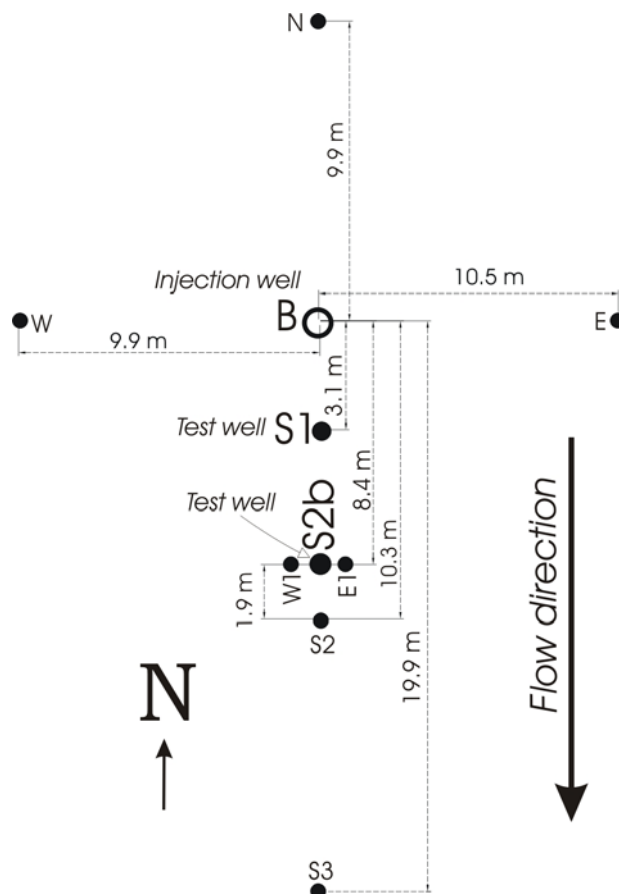


Figure 2. Sketch of “via Trieste” test site in the Treviso area (Veneto region, NE Italy).

3. RESULTS

Before pumping, two initial tests were carried out one month apart in late spring (T1, T2); only the S1 piezometer was monitored. Injection initially produced a perturbation in the flow field, but it quickly disappeared (Beinhorn *et al.*, 2005). The injection was at 9 m depth, and the tracer arrived at piezometer S1 at 13 m

depth; the tracer plume dropped about 52° relative to horizontal due to the density effect of the injected solution.

Figure 3 presents the breakthrough curves at 13 m. The curves at well S1 are generally log-normal. Barycentric time (t_b), calculated at the gravity centre of the surface delimited by the breakthrough curves, and peak time (t_p) of the same breakthrough curves were considered in calculating flow velocity. The results use the 13 m breakthrough curve in tracer test T1 (Figure 3.T1) and indicate flow velocities of 21.7 m/day (t_b) and 55.8 m/day (t_p) (Table 1). The hydraulic gradient measured during tracer tests T1 from wells N and S2 was 0.0019 m/m.

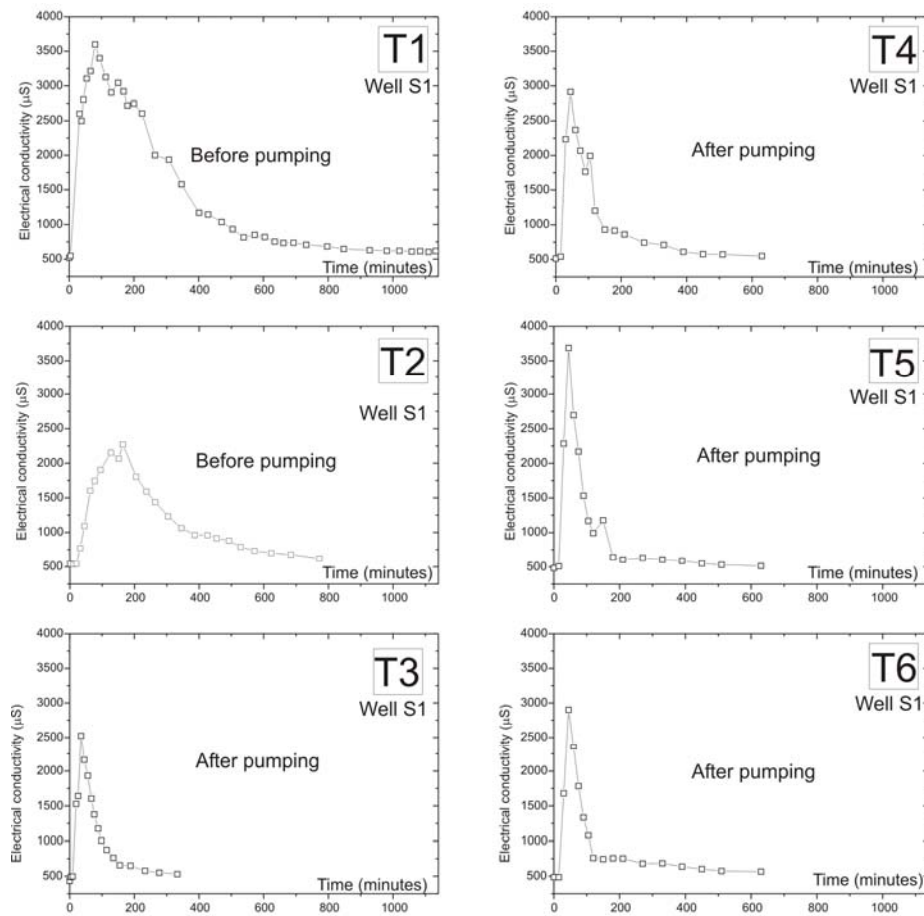


Figure 3. Observed tracer electrical conductivity (μS) in the S1 piezometer located at 3.1 m from the B injection well in the six tracer tests. The breakthrough continuous curves are relative at 13 m in depth.

One month later, another tracer test (T2) was carried out under the same conditions and with the same gradient. The t_p calculated for the 13 m breakthrough curve at S1 (Figure 3.T2) produced a flow velocity of 27.2 m/day, while t_b at 13 m indicated 21.9 m/day. The barycentric flow velocities for T1 and T2 were very similar; the different peak flow velocities were probably due to the 30

litre injection in T1 and to an unclear peak arrival time in T2, as visible in Figure 3.T2.

A month after the second injection test (T2), borehole B was naturally developed (F.G. Discroll 1986) by 24 hours of pumping. Three days later, a pumping test was carried out, in which well B was used as the pumping well, and the other wells were monitored. Well B was pumped for 24 hours at a rate of 77 l/s, and the pumping test results were analysed in unsteady state conditions. Unfortunately, the very high aquifer specific capacity did not permit adequate testing. Moreover, indicative hydraulic conductivity was about 2×10^{-2} m/s, typical in this area.

Using the measured hydraulic gradient, the hydraulic conductivity and a plausible effective porosity (n_e) of 0.15, the obtained flow velocity is similar to those experimentally calculated in T1 and T2.

Table 1. Flow velocities calculated at S1 and S2b piezometers.

Tracer Test	Barycentric Time (t_b) (min)	Flow velocity (t_b) (S1) (m/day)	Peak Time (t_p) (min)	Flow velocity (t_p) (S1) (m/day)	Barycentric Time (t_b) (min)	Flow velocity (t_b) (S2b) (m/day)	Peak Time (t_p) (min)	Flow velocity (t_p) (S2b) (m/day)
T1	206	21.7	80	55.8				
T2	203	21.9	164	27.2				
T3	65	68.7	35	127.5				
T4	93	48.0	45	99.2	325	37.2	275	44.0
T5	73	61.1	45	99.2	322	37.6	275	44.0
T6	97	46.0	45	99.2	315	38.4	245	49.4

After the pumping test, pumping at well B stopped, and the pump was extracted. Two weeks later, a new tracer test (T3) was carried out between wells B and S1 under the same conditions as in T2. The results obtained were very different from those of T2 and T1. The flow velocities at 13 m (Figure 3.T3) were 68.7 m/day (t_b) and 127.5 m/day (t_p), respectively, referring to a hydraulic gradient of 0.0017 m/m.

Tracer tests were repeated three times two years later. The first test was carried out in autumn (T4) (Figure 3.T4), and the barycentric flow velocity was 48.0 m/day; the second (T5) (Figure 3.T5) was in winter with a result of 61.2 m/day (t_b) given a gradient of 0.0021 m/m. Fifteen days later, the last test (T6) (Figure 3.T6) was done, and the flow velocity calculated was 45.9 m/day (t_b) in the presence of the same gradient. Table 1 shows that the peak velocity was 99.2 m/day, which was the same in all three tests (T4, T5, T6).

Tracer tests pre- and post-pumping were carried out in the same experimental conditions. No consistent variations in velocity were measured during the different seasons in this aquifer (there were certainly no variations between T2 and T3).

The breakthrough curve shapes before and after the pumping tests also emphasize the changes of natural hydrogeological parameters of the aquifer. For example, the tail is clearly longer before the pumping test (T1, T2) than after it (T3, T4, T5, T6). Moreover, the peak concentration after pumping is generally higher, except for in T1 where 30 litres were injected into well B. Vertical profiles of the different tracer tests before and after pumping present a slightly narrower zone of tracer breakthrough after pumping, but this does not indicate preferred pathways for groundwater circulation.

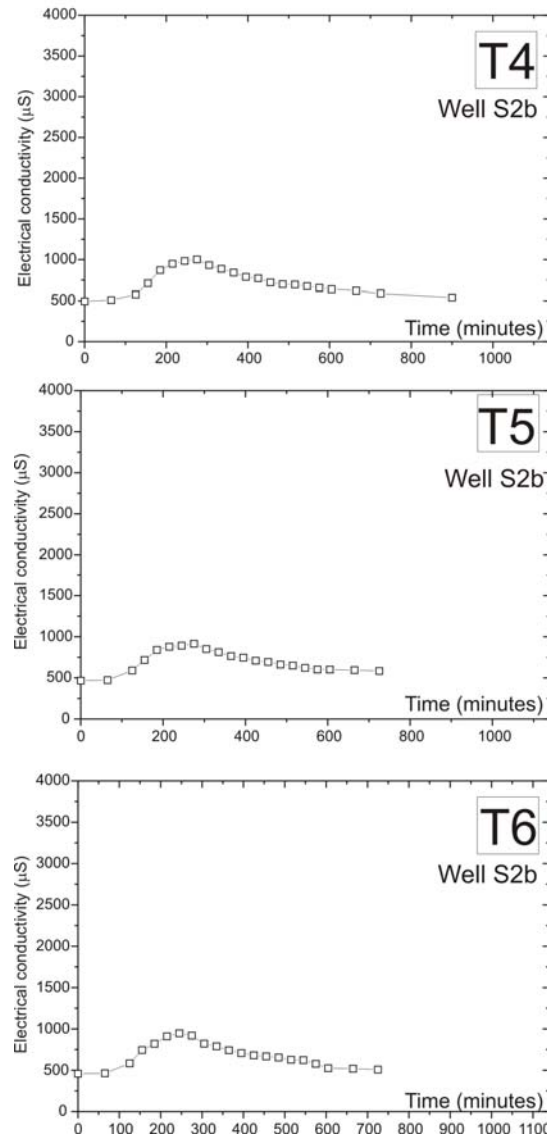


Figure 4. Observed tracer electrical conductivity (μS) in the S2b piezometer located at 8.4 m from the B injection well (T4, T5, T6). The breakthrough continuous curves are relative at 21 m in depth in the S2b piezometer.

During tracer tests T4, T5 and T6, the S2b piezometer was also monitored. The experimental results indicate that, at this piezometer located 8.4 m from the injection well, the tracer arrives at piezometer S2b at 21 m depth. The calculated barycentric flow velocities indicate values between 35–40 m/day, lower than those in S1 post-pumping but higher than those calculated in S1 pre-pumping. Breakthrough curves (T4, T5, T6) at well S2b (Figure 4) after pumping show very long tails compared to those in T1 and T2 pre-pumping at well S1 (Figure 3); these are also very different from those curves obtained after pumping in T3, T4, T5 and T6 (Figure 3). This comparison of Figures 3 and 4 suggests that the hydrogeological changes produced by pumping are reduced 8.4 m from injection well B.

All flow velocity results calculated at S1 and S2b are summarized in Table 1.

4. CONCLUSIONS

Comparing the flow velocities in monitoring wells S1 and S2b, respectively located 3.1 m and 8.4 m from the injection well, before and after a natural development, indicated changes in velocity around the injection well. In particular, by analysing the breakthrough curves and flow velocities the following conclusions are evident:

- Comparison among breakthrough curves at well S1 (Figure 3) clearly shows shape changes: the long tails evident before pumping (T1, T2) turn into short tails after pumping (T3, T4, T5, T6).
- In pre-pumping conditions, flow velocities measured 3.1 m from the injection well were about 20 m/day, while the flow velocities were 50 – 60 m/day after pumping under the same experimental conditions.
- Breakthrough curves (Figure 4) 8.4 m (S2b) from the injection well had tails more similar to those visible in Figure 3 from pre-pumping than those visible in the same figure post-pumping.
- Post-pumping flow velocities calculated 8.4 m from the injection well were higher than pre-pumping velocities calculated in S1 3.1 m from the injection well, but lower than those calculated post-pumping in S1.

The change of natural hydrogeological parameters is very high 3.1 m from the pumped well, as in Figure 3, and tends to decrease outward, so that at 8.4 m, the flow velocities are half-way between those obtained pre- and post-pumping 3.1 m from the pumped well.

These hydrogeological changes are due to extraction of the finest part of the reservoir (i.e., silt and very fine sand) around the pumped well, which increases hydraulic conductivity around the well and produces a negative skin effect.

The results obtained demonstrate that a strong well development can change natural aquifer characteristics around a well and, even, the hydrogeological transport properties of an alluvial aquifer similar to the one studied here. Thus, if

natural hydrogeological parameters are to be measured in an aquifer as the one studied here, well development and eventual pumping tests must be kept to a minimum before tracer tests, especially when the measured well is less than 8-9 m from the injection developed well.

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