Estimation of Hydraulic Conductivity Using the Slug Test Method in a Shallow Aquifer in the Venetian Plain (NE, Italy)

Paolo Fabbri, Mirta Ortombina and Leonardo Piccinini

Abstract: The slug test offers a fast and inexpensive field method of obtaining localized hydraulic conductivity values.

In this paper, we applied this procedure in a ‘fontanili’ zone located in the middle Venetian Plain (Villaverla, VI). In this site, 34 piezometers are present in a small area of 1.5 ha, which intercepts a shallow unconfined aquifer.

The experimental data, obtained by 59 slug tests, were processed with three different methods of analysis: Hvorslev, Bouwer-Rice and KGS, to obtain a permeability characterization of the area and identify the real differences between the considered solutions. Two slug tests were also analyzed using a three-dimensional finite difference groundwater flow model.

By comparing the different methods used in the same piezometer, we obtained highly similar values of permeability, while the numerical simulation of slug tests suggests that KGS is the best method for estimating hydraulic conductivity.

At the same time, we can identify a considerable heterogeneity in the area of investigation; indeed, the slug test estimates of hydraulic conductivity (K) range over three orders of magnitude (from 2.6E-06 to 3.8E-03 m/s).

This wide range of values confirms the high stratigraphic heterogeneity also observed during the coring.

Keywords: Venetian Plain, hydraulic conductivity, slug test, numerical simulation.

Riassunto: *Lo slug test è un metodo veloce ed economico che permette di stimare la conducibilità idraulica nell’intorno del pozzo o piezometro in cui viene realizzato.*

In questo articolo tale metodologia viene applicata per caratterizzare la conducibilità idraulica di un campo sperimentale ubicato in corrispondenza della fascia delle risorgive nella media pianura veneta (Villaverla, VI). Questo campo sperimentale, che si estende su un area di circa 1.5 ha, è costituito da 34 piezometri filtranti l’acquifero superficiale freatico.

I risultati di 59 slug tests sono stati analizzati secondo tre diversi modelli interpretativi: Hvorslev, Bouwer-Rice e KGS, al fine di caratterizzare la permeabilità dell’area oggetto di studio e di identificare le effettive differenze tra i metodi considerati. I risultati di due slug tests sono stati analizzati anche attraverso la modellazione numerica tridimensionale alle differenze finite del flusso sotterraneo.

La comparazione dei risultati derivati dall’applicazione dei diversi modelli interpretativi su uno stesso piezometro mostra valori di conducibilità idraulica molto simili, mentre i risultati della modellazione numerica suggeriscono che il metodo KGS è il più affidabile e preciso per la stima di tale parametro.

I risultati delle prove evidenziano un’estrema eterogeneità dell’area oggetto di studio con valori di conducibilità idraulica (K) che variano entro 3 ordini di grandezza (da 2.6E-06 a 3.8E-03 m/s). Questo ampio range di valori trova conferma nell’elevata eterogeneità stratigrafica osservata durante la realizzazione dei piezometri.

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Introduction

Permeability or hydraulic conductivity (K) is an essential parameter to understanding the movement of groundwater and pollution. The slug test is a fast and inexpensive technique for the determination of this fundamental value.

This method involves the instantaneous injection or withdrawal of a volume beneath the groundwater surface into a well. The volume can be water or a solid. The hydraulic conductivity in the immediate vicinity of the well can then be obtained by analyzing the change of water levels over time (Fig. 1).

Analysis of the data collected during a slug test is based on analytical solutions of mathematical models, which describe the groundwater flow toward a tested well. Over the last 60 years, many solutions have been developed for a number of test configurations commonly found in the field (Hyder et al., 1994). The slug test procedure in a confined aquifer was presented for the first time by Hvorslev (1951) and subsequently by many other authors. Cooper et al. (1967) derived a transient solution for the case of a slug test in a fully penetrated well in a confined aquifer; Dougherty and Babu (1984) derived a transient analytical solution for an overdamped slug test for fully and partially penetrated wells, including wellbore

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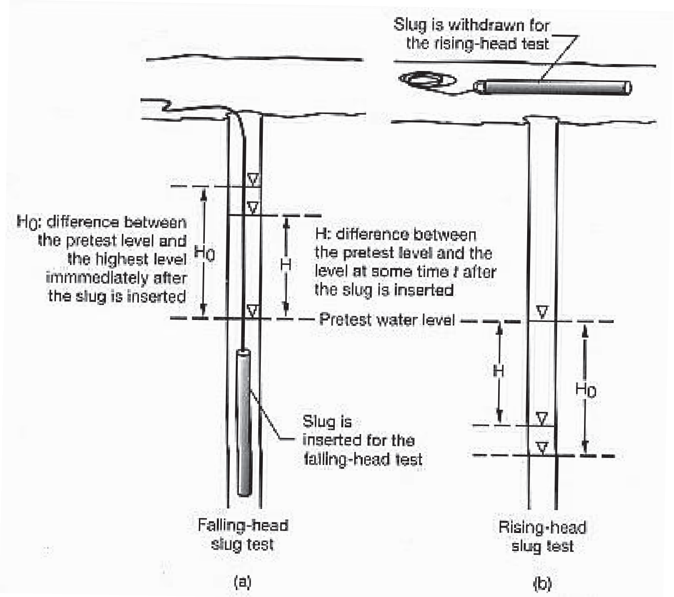

Fig. 1: *Slug test operative method (from Sanders, 1998): a) falling-head slug test and b) rising-head slug test; H_0 is the difference between the pre-test level and the highest level immediately after insertion of the slug, H is the difference between the pre-test level and the level at some time t after the insertion of the slug.*

skin, with "skin" referring to either mechanical damage or the enhancement of aquifer permeability by drilling (Maher and Donovan, 1997). Hyder et al. (1994) developed the KGS Model for confined and unconfined aquifers. This model includes a skin zone of finite thickness around the test well. McElwee and Zenner (1998) developed a model that involves various nonlinear mechanisms, including time-dependent water column length and turbulent flow in the well. Butler (1998) extended the Hvorslev (1951) solution to include inertial effects in the test well, which are established when there is an oscillatory water-level response, sometimes observed in aquifers of high hydraulic conductivity. Butler and Zhan (2004) derived an analytical solution for high-K aquifer that accounts for frictional loss in small-diameter wells and inertial effects.

For an unconfined aquifer, Bouwer and Rice (1976) elaborated a semi-analytical method for the analysis of an overdamped slug test in a fully or partially penetrating well. This method employs a quasi-steady-state model that ignores elastic storage in the aquifer. Springer and Gelhar (1991) extended the method to include inertial effects. Dagan's (1978) method is used in wells screened across the water table in a homogeneous, anisotropic, unconfined aquifer.

Principal solutions have been modified and corrected by other authors for particular situations related to the geometry of the well: Ostendorf et al. (2009) developed a linear theory when an annular effect is present during the test, Butler (2002) introduced a correction for slug tests in small-diameter wells and Binkhorst and Robbins (1998) conducted slug test in wells with partially submerged screens.

The slug test presents numerous pros, but also some cons. Indeed, the reliability of a slug test is less than a pumping test that, when it is possible to use, undoubtedly more accurately estimates permeability. A slug test is simple, fast, inexpensive and does not require pumps or complex equipment.

The test indicates the permeability of the localized area near the testing site. The analysis of the data is often simple, and many software programs for data analysis are available. The slug test is also useful in the case of polluted aquifers because the extraction of water is not necessary.

However, the use of slug tests presents some limitations, as only the permeability near the tested piezometer can be evaluated, and this value cannot be representative of all aquifer.

Slug tests are extremely sensitive to near-well conditions, and low-K skins can produce slug-test estimates that may be orders of magnitude lower than the average hydraulic conductivity of the formation near the well screen (Butler and Healey, 1998). Furthermore, the specific storage (S_s) cannot be evaluated in most of the methods.

Theory

Usually, the Hvorslev method is used for confined aquifers. However, Bouwer (1989) observed that the water table boundary in an unconfined aquifer has little effect on slug test results unless the top of the well screen is positioned close to the boundary. Therefore, in many instances, we may apply the Hvorslev solution for confined aquifers to approximate unconfined conditions.

The basic Hvorslev (1951) equation, if the length of the piezometer is more than 8 times the radius of the well screen ($L_e/r_w > 8$), is the following:

$$K = \frac{r_c^2 \cdot \ln\left(\frac{L_e}{r_w}\right)}{2 \cdot L_e \cdot t_0} \qquad (1)$$

where r_c is the radius of the well casing (m), L_e is the length of the well screen (m), r_w is the radius of the well screen (m), t_0 (s) is the basic time lag and the time value (t) is derived from a plot of field data. Generally, t_{37} (s) is used, which is the time when the water level rises or falls to 37% of the initial hydraulic head H_0 (m), the maximum difference respect the static level (Fig. 1).

It is possible to introduce a correction at equation (*1*). Zlotnik (1994) proposed an equivalent well radius (R_{we}) for a partially penetrating well in an anisotropic aquifer:

$$R_{we} = r_w \sqrt{\frac{K_z}{K_r}} \qquad (2)$$

where K_r and K_z (m/s) are radial and vertical hydraulic conductivity, respectively.

The most widely used methodology for the analysis of slug tests in unconfined aquifers was presented by Bouwer and Rice (1976). Using the modified Thiem equation for unconfined and steady state conditions, they presented a relation for determining hydraulic conductivity:

$$K = \frac{r_c^2 \cdot \ln\left(\frac{R_e}{r_w}\right)}{2L_e} \cdot \frac{1}{t} \cdot \ln\left(\frac{H_0}{H}\right) \qquad (3)$$

where R_e is the radius of influence (m), and t is the time since $H=H_0$.

Using the results from an electric analog model, Bouwer and Rice obtained two empirical formulas relating $ln(R_e/r_w)$ to the geometry of an aquifer system, the first for $L_w>B$ and the second for $L_w<B$, where B is the formation thickness (m) and L_w is the static water column height (m).

The third and most recent method was developed by the Kansas Geological Survey (KGS; Hyder et al., 1994)**.** This method uses a semi-analytical solution incorporating the effects of partial penetration, anisotropy, the presence of variable conductivity, well skin and the storage property of the soil. This solution is more complex than the others presented above, which are based on the application of several simplifying assumptions, but it can determine more parameters of the aquifer in addition to K. However, the KGS solution requires some construction characteristics that are not always know.

The general equation representing the flow of groundwater in response to an instantaneous change in water level at a well in an unconfined homogeneous aquifer is:

$$\frac{H}{H_0} = f\left(K_r, K_z, S_s, K_{rsk}, K_{zsk}, S_{ssk}, L_e, d, B\right) \qquad (4)$$

Where S_s is the specific storage (1/m), t is the time (s), r is the radial direction (m), z is the vertical direction (m), the subscript sk refers to the well skin and d is distance from the water table to the top of the screen (m). For details of the solution derivation, see Hyder et al. (1994).

From this curve, we can determine K_r and S_s. However, when using this method for an unconfined aquifer, it is difficult to accurately assess the specific storage, especially if the test is conducted in wells with small values of L_e/r_w (Butler, 1998).

Test Site Characterization

The Venetian Plain is delimited on the north by the Prealps, on the east by the Livenza River, on the west by the Lessini Mountains and the Berici and Euganei hills, and on the south by the Adige River and the Adriatic Sea. The upper limit of the plain is 150-200 m a.s.l., diminishing toward the SSE until reaching the coast (Bortolami et al., 1979). From the west to the east, we can observe the hydrographical systems of Leogra-Timonchio, Astico-Bacchiglione, Brenta and Piave, whose alluvial deposits created the Venetian Plain.

Therefore, the Venetian Plain consists of several large alluvial fans (megafans) whose widths (Plio-Quaternary deposits) increase toward the SSE (Bondesan and Meneghel, 2004; Fontana et al., 2008).

The hydrogeological features of the Venetian Plain depend principally on the depositional sequences of rivers and on the granulometric characteristics. In the upper part of the alluvial plain near the Prealps, where the subsoil is composed almost completely by gravels, there is a thick unconfined aquifer with high hydraulic conductivity.

Toward the south and closer to the Adriatic sea, the alluvial sediments change into a multi-layered system where alternate cohesive and incohesive sediments are present. Thus, the unconfined aquifer gradually evolves into a system of stratified, confined or semi-confined, often artesian, aquifers which represent the lower plain (Antonelli and Mari, 2007). Between the upper and lower plain is the middle plain, where a multi-layer system is present. This system is formed by gravelly and sandy horizons alternating with clayey and silty levels, the latest being more frequent from upstream to downstream (Fig. 3). This area is characterized by a high quantity of plain springs called 'fontanili', arising from the intersection between the topography surface and the water table.

Fig. 2**:** *Location of the test site.*

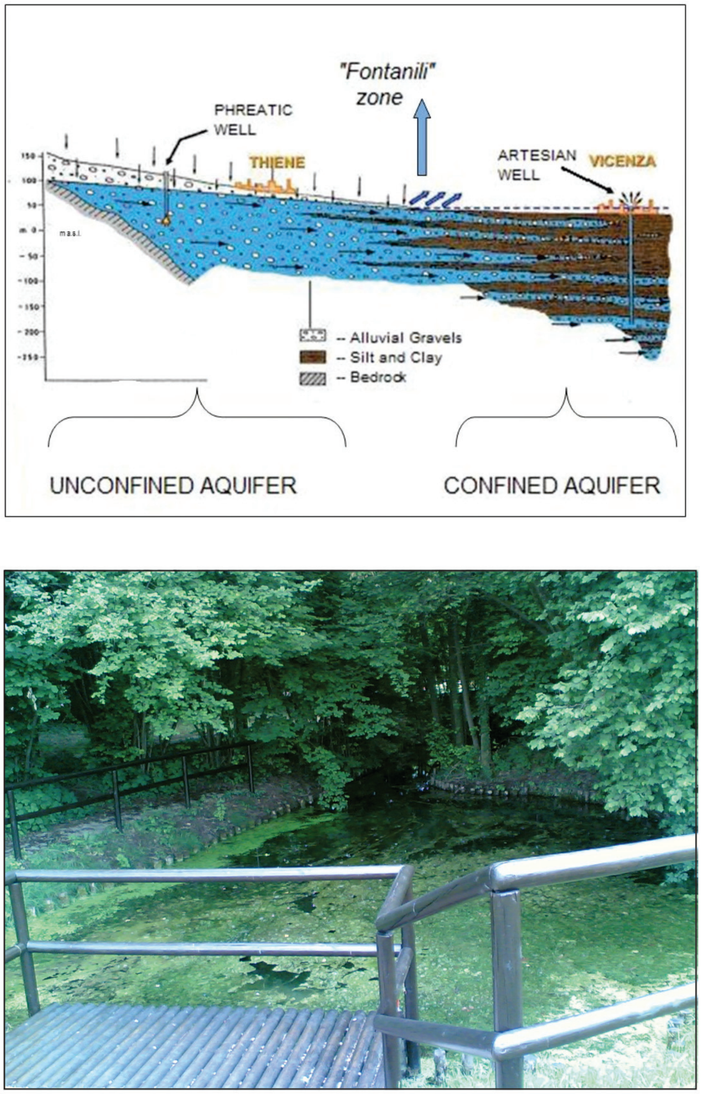

Fig. 3**:** *Schematic representation of high, middle and low plain and a resurgence ('fontanile') present in the test site.*

Geological and Hydrogeological setting of the test site

The analyses concern a hydrogeological study in an experimental site of 1.5 ha placed inside the drinking water supply area of ACEGAS-APS, which supplies the city of Padova.

This area is located in the middle Venetian Plain inside the 'fontanili' zone and the hydrogeological setting is characterized by impervious or semi-pervious layers interbedded with sand and gravel layers (Cambruzzi et al., 2010).

Topographically, the elevation of the area is between 56 and 50 m a.s.l., sloping from NW to SE. The local hydrography presents two plain springs named 'Boiona' (Fig. 3) and 'Beverara' and their drainage network (Fig. 4).

There are 34 piezometers in the study area, with a depth ranging from 1.6 to 22 m and a diameter ranging from 90 to 50 mm. Of these, 29 piezometers make the structural characteristics available, and for 14 of them, the stratigraphies are present. The subsoil composition and, consequently, the hydrogeological features, show high heterogeneity with gravel horizons alternating with sandy, silty and clayey levels (Figs. 4 and 5). In this area, we study the shallow unconfined aquifer (Ortombina and Fabbri, 2011; Monego et al., 2010).

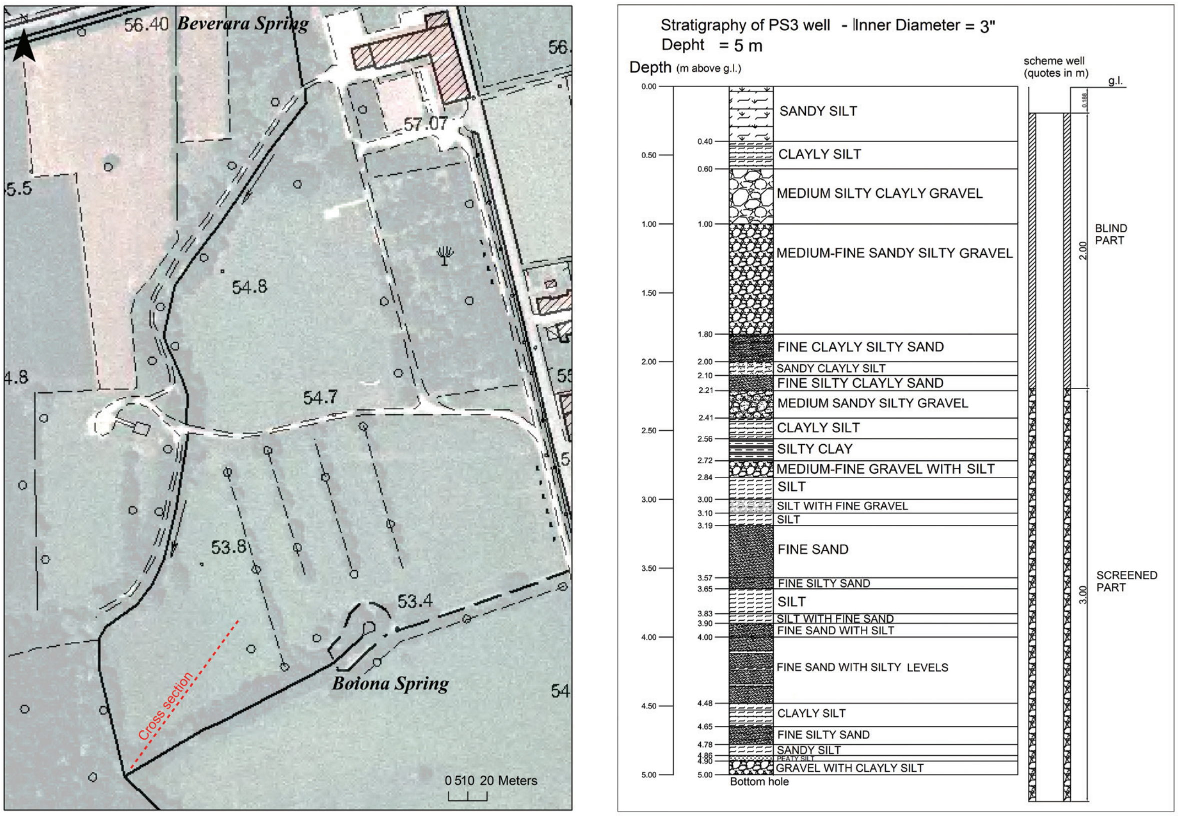

Fig. 4: *Plan view of the studied area and stratigraphy of the PS3 piezometer; the dashed red line represents the trace of the cross section of Figure 5.*

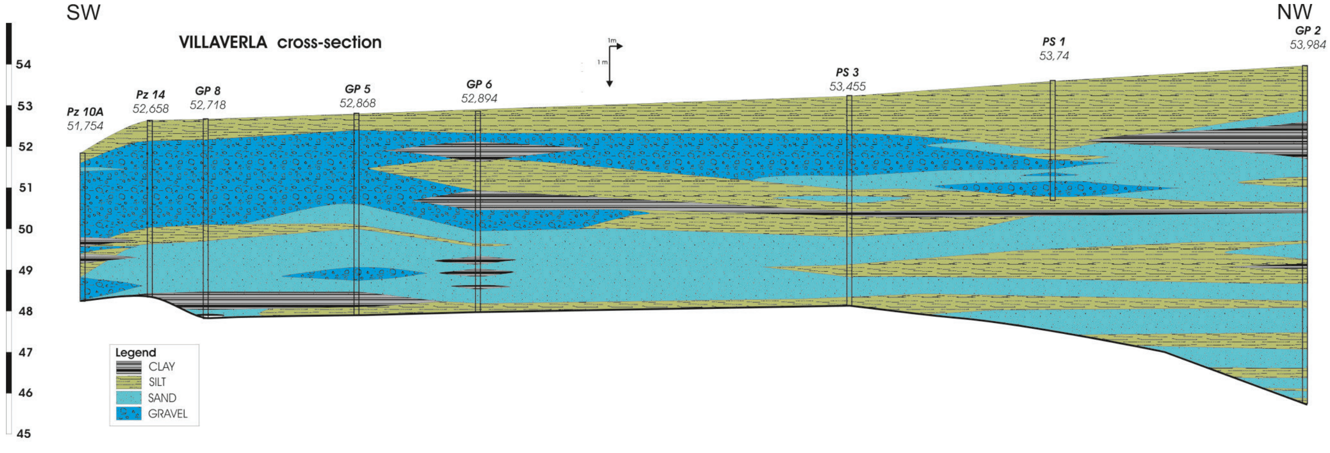

Fig. 5: *Cross section; the trace is present in Figure 4.*

Experimental Results of the Test Site

Fifty-nine falling head slug tests on 20 piezometers were carried out in the investigation area between 2010 and 2011, following the guidelines proposed by Butler et al. (1996).

The tested piezometers have a depth ranging between 8.5 and 1.6 m (partially penetrating wells) and a diameter ranging between 90 and 50 mm. Only nine piezometers (from GP1 to GP8 and PZ14) presented a gravel pack of some centimeters. Details of the construction parameters are presented in Table 1.

Tab. 1**:** *Construction parameters of the field piezometers; L_e = length of well screen; r_c = radius of the well casing; r_w = radius of the well screen.*

Well	**Depth** (m)	**L_e** (m)	**r_c** (mm)	**r_w** (mm)	**Elevation** (m asl)
GP1	5.47	3.00	25	41	54.53
GP2	8.55	7.00	25	41	53.93
GP3	3.97	3.00	25	41	52.97
GP4	3.93	3.00	25	41	52.96
GP5	3.96	3.00	25	41	52.82
GP6	3.97	3.00	25	41	52.82
GP7	3.96	3.00	25	41	52.76
GP8	4.56	3.00	25	41	53.30
PZ1	1.86	0.60	30	30	52.60
PZ4	2.53	0.60	30	30	52.80
PZ5	2.40	0.60	30	30	52.69
PZ6	1.62	0.60	30	30	52.61
PZ7	1.62	0.60	30	30	52.52
PZ8	2.20	0.60	30	30	52.42
PZ9	2.82	0.60	30	30	52.13
PZ14	4.25	3.00	38	45	53.30
PS1	3.02	2.00	38	38	53.59
PS2	4.97	3.00	38	38	53.33
PS3	4.98	3.00	38	38	53.27
PS4	4.95	3.00	38	38	53.02

Before the tests, we carried out a well development in every piezometer; this operation allowed the removal of fine materials usually present near the screens. The times and the water levels were recorded until they reached the initial static head.

The slug test data through the Hvorslev, Bower-Rice and KGS methods were processed by obtaining permeability values ranging from 2.6E-06 m/s for the upstream piezometer (GP2) to 3.8E-03 m/s for the downstream piezometer (PZ14; Fig. 6 and Tab. 2).

In all cases, we assigned an anisotropy permeability of K_z/K_r =0.1, while the well skin effect was not considered because it is impossible to distinguish well skin from heterogeneity effects using only the slug test response.

Tab. 2: *Hydraulic conductivity values; K_H, Hvorslev method; K_{BR}, Bouwer and Rice method; K_{KGS}, KGS method; and geometric average.*

Well	**K_H** (m/s)	**K_{BR}** (m/s)	**K_{KGS}** (m/s)	**AVERAGE** (m/s)
GP1	8.1E-05	6.0E-05	6.6E-05	6.8E-05
GP2	2.9E-06	2.2E-06	2.7E-06	2.6E-06
GP3	4.7E-05	3.3E-05	3.6E-05	3.8E-05
GP4	1.6E-04	1.2E-04	1.4E-04	1.4E-04
GP5	9.3E-05	6.9E-05	7.4E-05	7.8E-05
GP6	1.9E-04	1.3E-04	1.4E-04	1.5E-04
GP7	2.1E-05	1.7E-05	1.7E-05	1.8E-05
GP8	3.5E-04	2.4E-04	2.3E-04	2.7E-04
PS1	1.6E-04	1.2E-04	1.6E-04	1.5E-04
PS2	3.1E-05	2.4E-05	2.4E-05	2.6E-05
PS3	1.8E-05	1.4E-05	1.4E-05	1.5E-05
PS4	6.1E-06	4.1E-06	4.6E-06	4.8E-06
PZ1	4.5E-04	3.6E-04	5.5E-04	4.5E-04
PZ4	3.7E-06	4.0E-06	5.0E-06	4.2E-06
PZ5	1.8E-05	1.3E-05	1.4E-05	1.5E-05
PZ6	8.4E-05	6.0E-05	7.1E-05	7.1E-05
PZ7	6.0E-04	4.6E-04	5.5E-04	5.3E-04
PZ8	8.2E-04	6.7E-04	9.1E-04	7.9E-04
PZ9	9.7E-05	7.6E-05	9.4E-05	8.8E-05
PZ14	5.2E-03	3.6E-03	2.9E-03	3.8E-03
AVERAGE	7.9E-05	5.9E-05	6.7E-05	6.8E-05

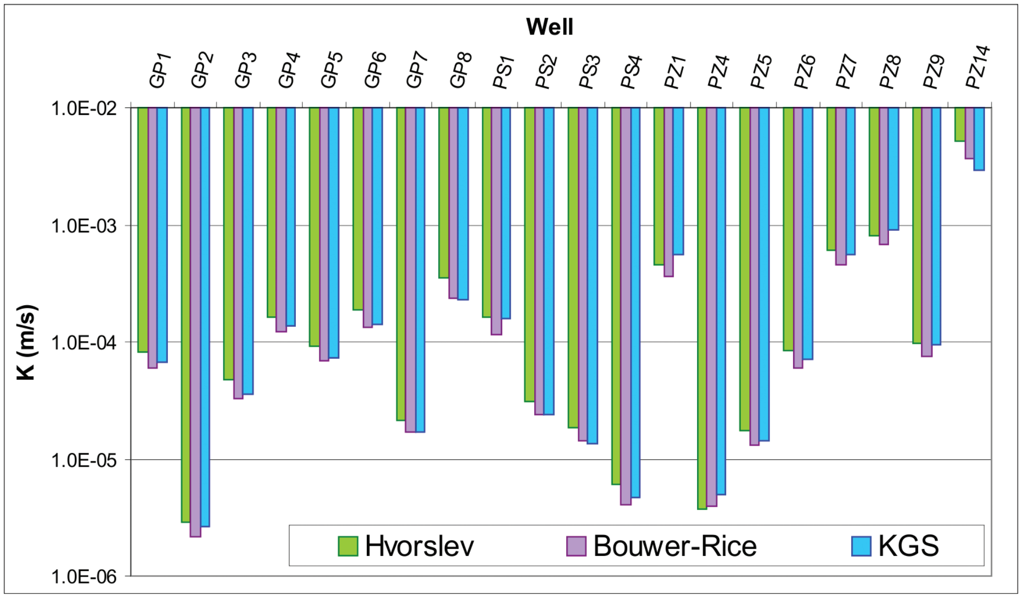

Fig. 6: *Summary of slug tests with three different methods of data analysis.*

The wide range of hydraulic conductivity found is supported by the high stratigraphical heterogeneity also observed during the coring. Observing the slug test data, we see an overdamped behavior of the aquifer without the oscillatory effects typical of high permeability aquifers.

In Figure 7, the average values of hydraulic conductivity are shown. Generally, we can observe an increase of permeability to SW.

To analyze the slug test data with the KGS method, we used the automatic nonlinear least squares procedure to match a type curve to our data. Through a sequence of iterations, the procedure systematically adjusts the values of hydraulic properties to achieve the best statistical match between a theoretical solution (type curve) and the experimental data. Each iteration seeks to minimize the sum of squared residuals (Duffield, 2000).

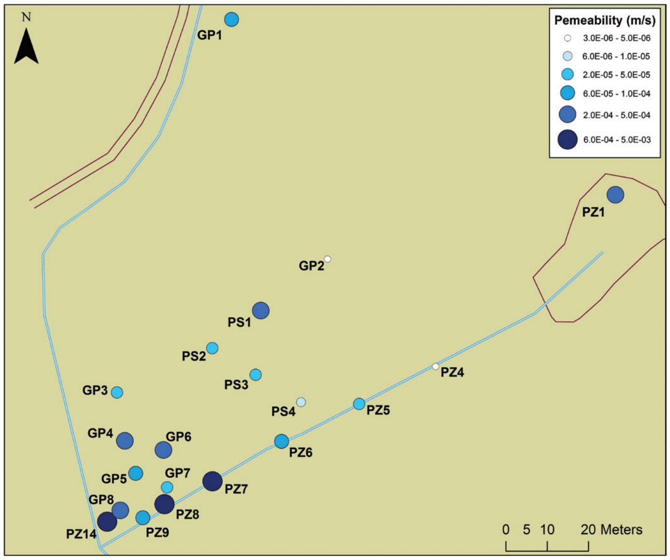

Fig. 7: *Maps summarizing the results of the slug tests.*

Comparison of Methods

Overall, the permeability ranged from 2.2E-06 to 5.2E-03 m/s, and the geometric mean value is 6.8E-05 m/s.

The calculated values by the three considered methods are comparable, as we can see from Figure 8. Indeed, the variability of the permeability values obtained with the different solutions does not exceed 34%. The largest differences between the methods are in the piezometers that have a value of K greater than the others (PS1, GP8, PZ1, PZ14); in these cases, we have a greater uncertainty due to the minor number of data recorded and due to possible turbulence around the well associated with relatively high groundwater velocity caused by the imposed hydraulic gradient in the very permeable soil.

The hydraulic conductivity calculated by Hvorslev is always greater than that derived from the Bouwer and Rice method, with the exception of the PZ4 borehole. This phenomenon could be caused by the proximity of the water table to the screened section; this can invalidate the K calculated by the Hvorslev solution because one of the assumptions imposed on the validity of the method in an unconfined aquifer is that the top of the well screen is positioned far from the boundary.

The permeability values calculated with KGS are often included between the Hvorslev and Bouwer-Rice results.

On average, the K values calculated with the Hvorslev method are underestimated by 14.8% KGS, and the K values calculated by the Bouwer-Rice method are overestimated by 11.5% KGS. Finally, the K values calculated with the Hvorslev method exceed that of Bouwer-Rice by 24.6%.

However, despite the different underlying assumptions, all three methods yield very similar estimates of K for all slug tests carried out at the Villaverla site. Additionally, the Hvorslev solution, which is commonly used with confined aquifers, produces a K estimate that is similar to the values computed with the more rigorous KGS model and the Bouwer-Rice solutions, which are typically associated with unconfined aquifers.

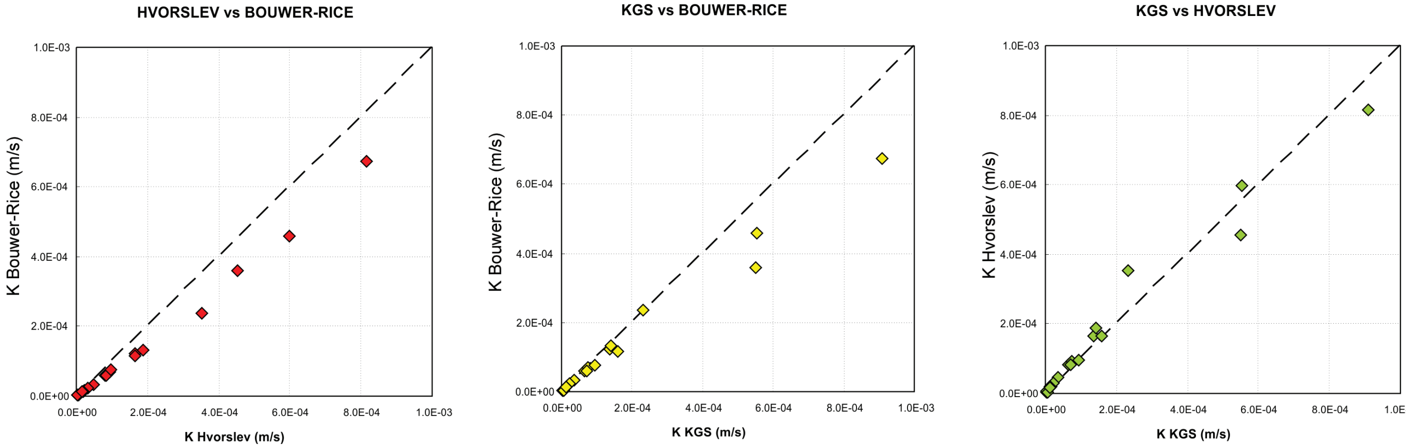

Fig. 8: *Comparison of the three solutions used.*

Numerical Simulation of Slug Tests

Finally, the results of some slug tests were simulated numerically because the models offer an ideal tool to reproduce well-aquifer interaction and then to verify the results of analytical solutions. The numerical model was applied at the southwestern portion of the study site, where the subsoil is composed mainly of gravel and sand with less heterogeneity.

The results of two slug tests conducted in the GP5 borehole were analyzed using a three-dimensional finite difference groundwater flow model. The applied code was MODFLOW 2000, developed by the U.S. Geological Survey (Harbaugh et al., 2000), and is an updated version of the original MODFLOW (McDonald and Harbaugh, 1988). Rovey (1998) verified the ability of MODFLOW to reproduce wellbore tests with reasonable accuracy, although it is not possible to simulate radial symmetry flow around a line source with this code.

To analyze the slug test data, four simulations were implemented and calibrated. Two steady-state simulations reproduced the groundwater head distribution prior to the tests, and therefore, two transient simulations reproduced the falling level during the slug tests performed in June 2010 and July 2011. The model domain is a 18 x 20 m rectangle centered on a GP5 borehole and oriented with an inclination of 50° from the north direction according to the mean groundwater flow direction (Fig. 9).

A high-spatial-resolution, non-uniform grid with cell dimensions ranging from 1 cm to 42 cm resulted in 140 columns (X-dimension) by 150 rows (Y-dimension). The minimum 1 cm horizontal grid spacing was designed to represent the nominal diameter of the GP5 borehole (2 in) and, separately, the 2-cm-thick gravel-pack surrounding the screen (Maher and Donovan, 1997; Shafer et al., 2010). The horizontal cell dimension expansion factor for telescoping cell widths to the model boundaries was 1.17, less than 1.5. Along vertical axes, 22 variables thickness layers were represented, starting from the topographical surface. Layers 1-13 represent the upper gravel, on average, from 52.38 m a.s.l. to 49.97 m a.s.l., and layers 13-22 correspond to lower sands, from the bottom of the gravels to 48.61 m a.s.l.

The vertical discretization was designed to break the screen interval into segments so that the model results would be directly comparable to the elevation of the pressure transducer in the well. In other words, the model setup was structured so that the simulation of the slug test was representative of the well configuration and the elevation of the level probe.

Five zones were distinguished in the model domain: three of hydraulic conductivity (K_x, K_y and K_z) and two of storage (S_s, specific storage and S_y, specific yield), which correspond, respectively to wellbore, gravel-pack surrounding the screen, gravel aquifer (two

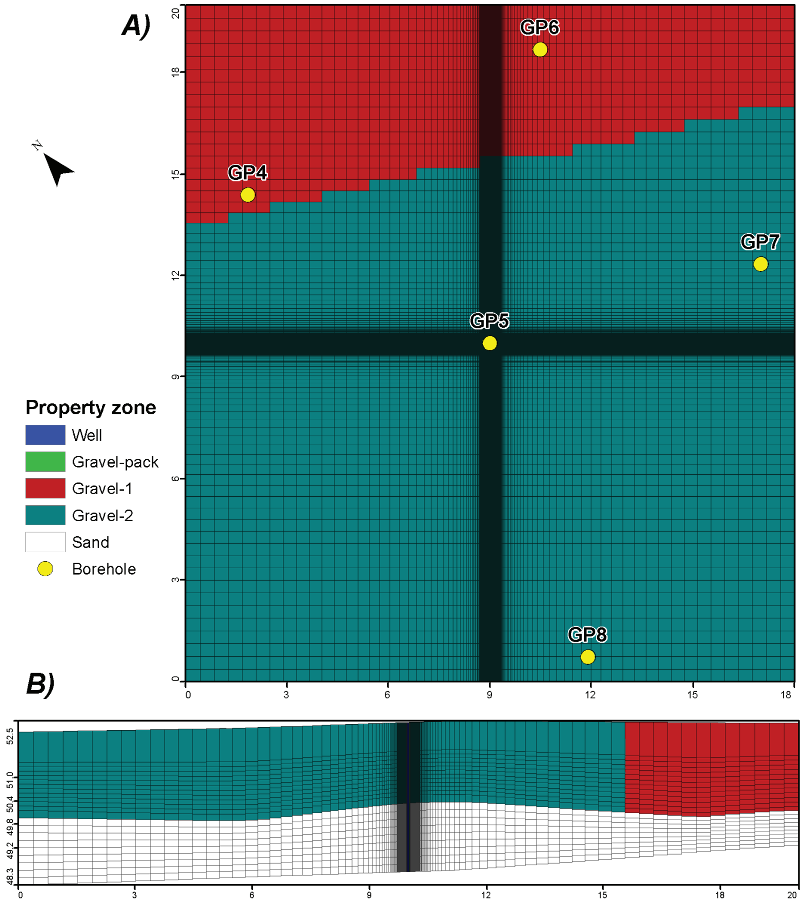

Fig. 9: *Property zones of slug test models: A) plan view at layer 1 and B) SW-NE section at column 69.*

zones) and sand aquifer (Fig. 9). The values assigned at the wellbore itself are as follows:

$K_{x\text{-well}}$, $K_{y\text{-well}}$ = 1.0E-03 m/s
$S_{s\text{-well}}$ = 0.25 1/m
$S_{y\text{-well}}$ = 1

These parameters ensure there is no flow resistance within the well (Rovey, 1998; Shafer et al., 2010). Permeability is always assigned as isotropic proprieties (K_x/K_z = 1 and K_y/k_z = 1), except for the wellbore zone, where an anisotropy factor of 0.01 is used. During the calibration process, the wellbore parameters were fixed, while the gravel-pack and aquifer parameters were allowed to vary.

The upgradient and dowgradient constant heads (1st type boundary conditions) were established at the northeastern and southwestern sides of the domain so that the field-measured hydraulic heads in the boreholes at the beginning of the tests were reproduced (steady state simulations) and then used as initial heads in the transient simulations.

The instantaneous rising level in the transient simulations (t_0) were reproduced by modifying the initial heads on the cells corresponding to the wellbore as a function of maximum level recorded at the beginning of every slug test.

In the transient models, a total simulation time of 100 s was divided in 20 time steps with an increment ratio of 1.2.

Figure 10 shows the results of the trial and error calibration process for both falling-head slug tests. The transient simulation obtained a nearly one-to-one match of calculated heads to observed heads in the GP5 borehole. The quantitative calibration reaches a good level, expressed by a normalized root mean square (RMS%) ranging from 1.46% to 3.33% (Tab. 3). The parameter values that produce this match are shown in Table 4.

The modeled hydraulic conductivity of the gravel is half an order of magnitude higher than the mean hydraulic conductivity calculated with the analytical solutions, while that of the sand is an order of magnitude lower (Tab. 2). The geometric mean of model permeability values is equal to 3.5E-05 m/s, while the weighted mean based on the length of the filtered lithology is 7.3E-05 m/s. This last value in particular is reasonably close to the mean value calculated with analytical solutions and with the KGS method (7.8E-05 m/s and 7.4E-05 m/s, respectively). Additionally, the final storage values are consistent with the hydrodynamic properties of a gravel-sand aquifer.

Tab. 3**:** *Calibration statistical data of slug test models.*

	June 2010	**July 2011**
Num. of data Point	101	101
Max. Residual (m)	0.064	-0.046
Min. Residual (m)	-0.006	0
Residual Mean (m)	-0.023	-0.002
Abs. Residual Mean (m)	0.025	0.008
Root Mean Squared (m)	0.027	0.012
Normalized RMS (%)	3.329	1.459

Tab. 4**:** *Estimated values of Hydraulic conductivity (K_x, K_y e K_z) and storage (S_s and S_y).*

	Zone	***K_x (m/s)***	***K_y (m/s)***	***K_z (m/s)***	***S_s (1/m)***	***S_y ( )***
🟩	Gravel-pack	1.0E-03	1.0E-03	1.0E-03	1.0E-06	0.3
🟦	Gravel-1	1.8E-04	1.8E-04	1.8E-04	1.0E-06	0.23
🟥	Gravel-2	3.0E-04	3.0E-04	3.0E-04	1.0E-06	0.23
⬜	Sand	6.8E-06	6.8E-06	6.8E-06	1.0E-06	0.16

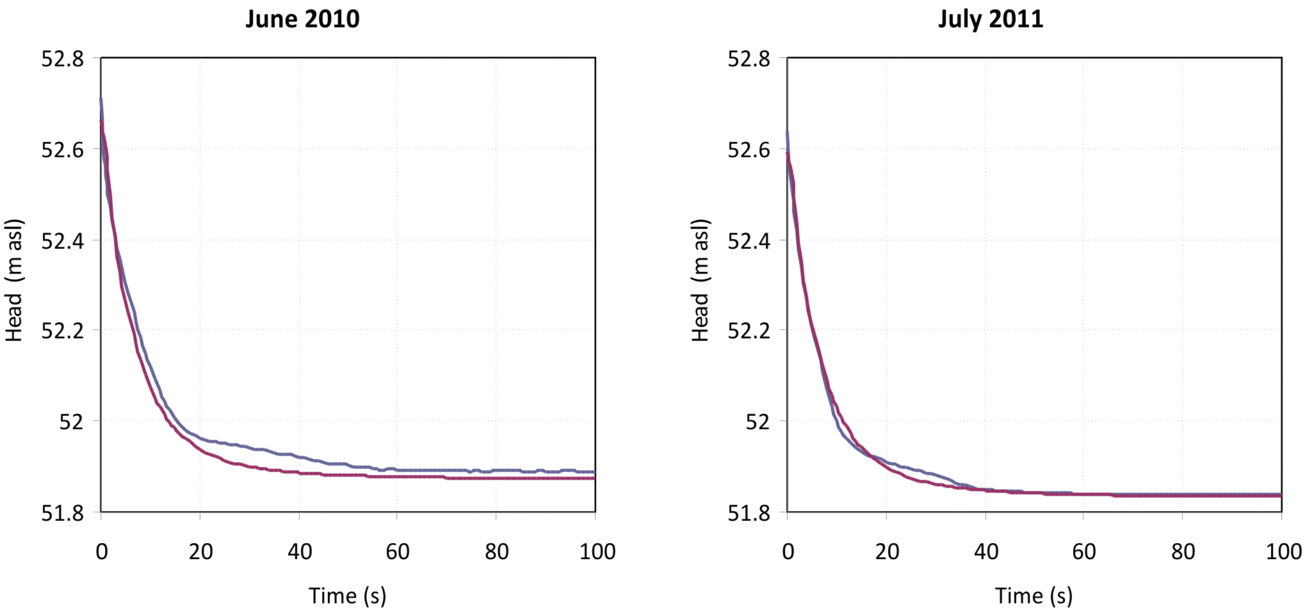

Fig. 10**:** *Calibration graphs of slug test models: observed (blue) vs. calculated (red) head values.*

Conclusion

The slug test is a fast and inexpensive method to calculating hydraulic conductivity (K). The method was applied to 20 piezometers located in the middle Venetian Plain (Villaverla, VI).

The slug-test data were analyzed with three different methods (Hvorslev, Bouwer-Rice and KGS). These solutions generate nearly identical values of K for a given piezometer, with a variation of less than half an order of magnitude and with clear behavioral trends.

At the study site, the slug test results show large differences of hydraulic conductivity between piezometers, with values ranging over three orders of magnitude. This occurrence is confirmed by the naturally high stratigraphic heterogeneity present in the test site.

The results of the numerical model suggest that KGS is the best method for estimating hydraulic conductivity. The KGS model rigorously accounts for elastic storage in the aquifer, while the Bouwer-Rice and Hvorslev methods both use the quasi-steady-state approximation of slug-induced flow.

Nevertheless, the KGS method, even though it is more rigorous, requires a large number of data on the construction parameters of the well, which are often difficult to find. For this reason, in some cases, a good alternative for the calculation of permeability could be the Bouwer-Rice solution.

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