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Spatial characterization of hydraulic conductivity in alluvial gravel-and-sand aquifers: A comparison of methods

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Key Words: hydraulic conductivity, multilevel slug tests, flowmeter logs, sieve analyses, pumping test.

Abstract

For groundwater transport modeling on a scale of 10 – 100 m, detailed information about the spatial distribution of hydraulic conductivity is of great importance. At a test site (10 x 20 m) in the alluvial gravel-and-sand aquifer of the perialpine Thur valley (Switzerland), four different methods were applied on different scales. The comparison of the results showed that multilevel slug tests give the most reliable results at the required scale. For their analysis, a plausible value of the anisotropy ratio ($K_{vertical}/K_{horizontal}$) is needed. For alpine and perialpine aquifers, a range of 0.1 – 0.2 can be expected. Flowmeter logs are recommended, if the relative distribution of hydraulic conductivity is of primary importance. Sieve analyses should be used, if an accuracy of a factor of 3 is acceptable. Pumping test results indicate the upper boundary of the natural spectrum of hydraulic conductivity at the scale of the test site.

Zusammenfassung

Für die Modellierung des Stofftransportes im Grundwasser im Massstabsbereich von 10 – 100 m sind detaillierte Kenntnisse der räumlichen Verteilung der hydraulischen Leitfähigkeit unabdingbar. Bei einem Testfeld (10 x 20 m) im alluvialen Schotter-Grundwasserleiter des voralpinen Thurtals (Schweiz) wurden vier unterschiedliche Methoden, wirksam auf verschiedenen Messskalen, angewandt, um diesen Parameter zu bestimmen. Der Vergleich der Ergebnisse zeigte, dass tiefenaufgelöste Slugtests verlässliche Resultate für den gefragten Massstab liefern. Für deren Auswertung ist ein plausibler Wert für das Anisotropieverhältnis der hydraulischen Leitfähigkeit ($K_{vertikal}/K_{horizontal}$) nötig. Für alpine und voralpine Schotter-Grundwasserleiter kann ein Wertebereich von 0.1 – 0.2 erwartet werden. Flowmetermessungen sind zu empfehlen, wenn primär die relative Verteilung der hydraulischen Leitfähigkeit interessiert. Siebanalysen sollten verwendet werden, wenn eine grobe Abschätzung der hydraulischen Leitfähigkeit mit einer Genauigkeit eines Faktors 3 ausreicht. Die integralen Resultate von Pumpversuchen entsprechen tendenziell der oberen Grenze des natürlichen Spektrums der hydraulischen Leitfähigkeit auf dem Massstab des Testfeldes.

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1. Introduction

The heterogeneity of perialpine and alpine gravel-and-sand aquifers requires the knowledge of the three dimensional distribution of hydraulic conductivity for groundwater flow and transport modeling, especially on a scale of the order of 10 – 100 m. Various methods to assess the distribution of hydraulic conductivity have been compared for dominantly sandy aquifers (Bradbury & Muldoon 1990, Milham & Howes 1995, Niemann & Rovey 2000). One finding was the positive scale dependency of hydraulic conductivity. The latter was quantified by Schulze-Makuch et al. (1999) for predominantly fissured aquifers. For perialpine and alpine gravel-and-sand aquifers, a comparison of different methods seems to be lacking.

The aim of this work is to assess the distribution of hydraulic conductivity of the perialpine gravel-and-sand aquifer of the Thur valley using four different methods on different scales (Diem et al. 2010). The comparison of the results should lead to recommendations, which method to use in perialpine and alpine gravel-and-sand aquifers, depending on the purpose of an investigation.

The perialpine Thur valley is an east-west striking valley, situated in the northeastern part of Switzerland with an approximate length of 30 km. The shallow underground is composed by quaternary sediments of which the postglacial gravel-and-sand aquifer is of great importance, especially for drinking water supply.

For the investigations, a test site in the central part of the Thur valley (Widen) was equipped with a total of 18 fully screened wells of a diameter of 2" (14 wells) and 4.5" (4 wells). Fig. 1 shows the set-up of the site with an extent of about 10 × 20 m.

The general geologic profile shows a three

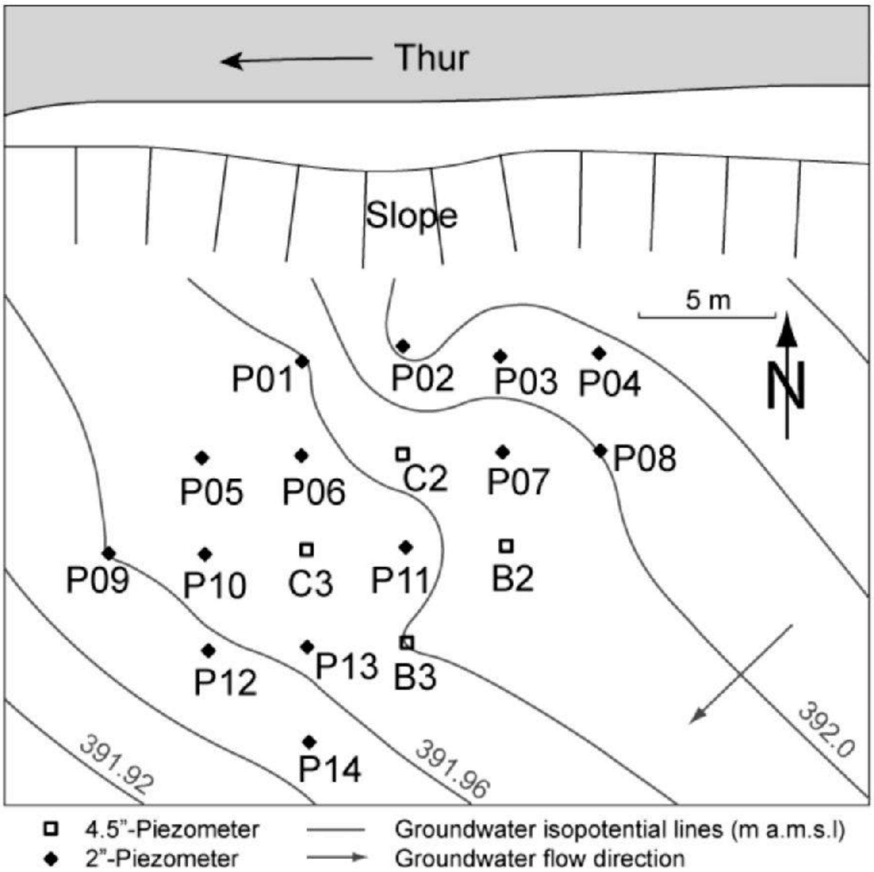

Fig. 1: Test site Widen: set-up of wells (modified after Diem et al. 2010).

meter thick cover layer of silty sand. Below follows the aquifer, composed of a slightly silty to silty gravel with sand of a thickness of about 7 m. The lower confining layer consists of clayey silt that can be interpreted as lake deposit.
The river Thur next to the test site (Fig. 1) is infiltrating into the groundwater, which is unconfined during average discharge conditions.

2. Methods used

The methods used to determine the distribution of hydraulic conductivity are acting on different scales. The measurement scale refers to the side length of a cube whose volume corresponds to the tested aquifer volume. This must be distinguished from the scale of investigation, which in this case lies in the order of 10 – 100 m.
Sieve analyses (measurement scale: decimeter) were conducted with the core material of the gravel of B2, B3, C2 and C3, separated into 0.5 m intervals. The calculation of hydraulic conductivity was done according to the following formula of Casati (1959), which is well adapted for the uniformity coefficients of typical perialpine sandy gravels ($d_{60}/d_{10} \sim 40$).

$$K = \frac{0.245}{16g_1+4g_2+2g_3+g_4+g_5} \tag{1}$$

$g_{1\text{-}5}$ [%]: weight proportion of grain size fractions 0-0.125, 0.125-0.25, 0.25-0.5, 0.5-1, 1-2 mm
K [m/s]: hydraulic conductivity

One pumping test (measurement scale: decameter) was carried out in the well C2 while the drawdown of the groundwater table was measured in nine surrounding observation wells. The analysis after Neuman (1972) was conducted in such a way that the entity of observed drawdown data was explained the best. The result is one optimal parameter set consisting of the transmissivity (hydraulic conductivity respectively), storativity, specific yield and anisotropy ratio ($K_{vertical}/K_{horizontal}$).
Flowmeter measurements (measurement scale: meter) were taken in B2, B3, C2 and C3 at intervals of 0.5 m. The flow rate profiles were analyzed according to Molz (1989). The resulting profiles of relative hydraulic conductivity (K/K_{mean}) were calibrated to absolute values, assuming that K_{mean} corresponds to the hydraulic conductivity result of the pumping test as suggested by Molz (1989).
Multilevel slug tests (measurement scale: meter) were conducted at intervals of 0.5 m in all 14 2"-wells. The tests were initialized pneumatically and the resulting data were analyzed using the methods of Springer & Gelhar 1991 for the underdamped response data and of Bouwer & Rice 1976 for the overdamped response data. Both methods can account for the anisotropy of the aquifer, for which the anisotropy ratio of the pumping test was used.
The measurement intervals of the sieve analyses, the flowmeter logs and the slug tests were chosen in a way that the limits were falling on the same absolute height (e.g. 391.0 – 391.5 m a.m.s.l.).
The distribution of hydraulic conductivity can be represented by a log-normal probability density function (Gelhar & Axness 1983). The statistical moments (mean, variance) are therefore indicated in $\log_{10}$ form.

3. Results and comparison

The results of sieve analyses show a quite narrow hydraulic conductivity distribution, compared to the resulting distribution of the flowmeter logs and the slug tests, expressed in the small logarithmic variance of 0.01 (Fig. 2). The absolute values of the distribution are reasonable and lie within the scatter of the other two distributions; the logarithmic geometric mean (– 2.73) forms the lower boundary though. The analysis of the entity of drawdown data of the pumping test resulted in a logarithmic hydraulic conductivity of – 1.83 and an anisotropy ratio of 0.16. These values describe integral values for the volume between the pumping well and all used observation wells. Flowmeter measurements show a geometric mean of – 1.9 and an arithmetic mean of – 1.83, which, as expected, corresponds exactly to the value of the pumping test as it was used for calibration of the flowmeter results (Fig. 2). The slug tests show a distribution of hydraulic conductivity that covers a spectrum of about two orders of magnitude and the variance (0.11) is similar to the one of the flowmeter results (0.14). The geometric mean (– 2.38) lies between the ones of the other two distributions. The experimental standard deviation of one slug test measurement was determined to be 10% of the value of hydraulic conductivity, corresponding to about 0.04 logarithmic units.

4. Discussion

Theoretically one could expect the distributions of the slug test and the flowmeter results to show absolute values in the same range, as they are acting on similar measurement scales. As mentioned, flowmeter results were calibrated with the pumping test result, which is the reason for the systematic offset between the two distributions. The higher hydraulic conductivity of the pumping test, which involves a much larger volume, reflects the positive scale dependency described in literature (Bradbury & Muldoon 1990, Niemann & Rovey 2000). Fig. 2 illustrates where this scale dependency originates from. The highest values measured by slug tests correspond exactly to the value of the pumping test.

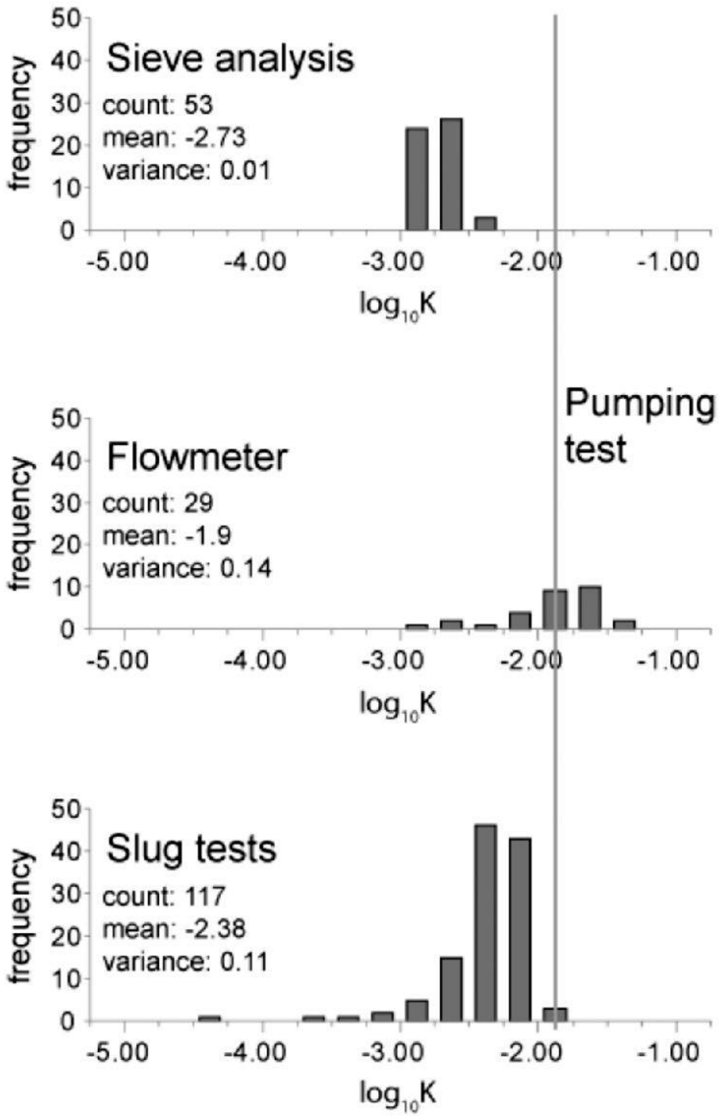

Fig. 2: Histograms of logarithmic hydraulic conductivity with indicated number of datapoints (count), logarithmic geometric mean and logarithmic variance (modified after Diem et al. 2010).

This means that the pumping test is non-sensitive to zones of smaller hydraulic conductivity and the result is dominated by zones of high hydraulic conductivity. In this regard the hydraulic conductivity of a pumping test is not appropriate for calibration of the flowmeter data. A better approach could be a slug test over the whole saturated thickness of the aquifer. After Butler (1998), in aquifers of high hydraulic conductivity the pneumatic approach of slug test initiation should be used, which is nearly impossible to realize in a fully screened well.

In contrast to the flowmeter measurements, the slug test results do not have to be calibrated by another method. Thus they give direct absolute values of hydraulic conductivity with an accuracy of about 10%. In this case, slug tests covered a wide spectrum of hydraulic conductivity values, where the variability (standard deviation: 0.33) exceeds the accuracy with about a factor of 10. A sensitivity analysis has shown, that the hydraulic conductivity determined by slug tests increases by about 40% if the anisotropy ratio decreases by a factor of 10. To get accurate values of hydraulic conductivity, $K_{vertical}/K_{horizontal}$ must be known by using an additional method or an educated guess.

The small variability of hydraulic conductivity from sieve analyses can mostly be assigned to the approach of Casati (1959) which uses five grain size fractions to calculate hydraulic conductivity (equation 1). Assuming a true geometric mean for the test site of 2.38 from the slug test results, sieve analyses underestimate it by a factor of 2.2.

5. Conclusions

Sieve analyses and the calculation of hydraulic conductivity after Casati (1959) can be used, if an estimate with an accuracy of a factor of about 3 is acceptable. To resolve the vertical variability of hydraulic conductivity, sieve analyses are not well suited as the variability will probably be underestimated. So for each well only single samples of each lithologic unit should be sieved and analyzed after Casati (1959) to get an estimate of hydraulic conductivity.

Flowmeter logs should be used, if the relative distribution of hydraulic conductivity is of primary importance. As it can be seen in Fig. 2, the variability is well represented by the flowmeter results. For the calibration to absolute values a slug test over the whole saturated thickness of the aquifer would probably be the best approach, which is nearly impossible to realize in high permeable aquifers.

Multilevel slug tests should be used if detailed information on the absolute values of hydraulic conductivity and their distribution is required. The pneumatic slug test initiation must be used to guarantee a good data quality and the frequency of measurement of the water table movement should be 5–10 Hz to avoid aliasing of data. The anisotropy ratio can be expected to lie between 0.1 and 0.2 for perialpine and alpine gravel-and-sand aquifers, assuming a similar mode of deposition of the alluvial material as for the one of the Thur valley.

In contrast to the other three methods, the pumping test gives an integral parameter set. The resulting hydraulic conductivity corresponds to the upper limit of the natural spectrum. This value can be assumed for investigations where a conservative result is desired. Furthermore, the pumping test is one option to assess the anisotropy ratio.

To reduce the amount of work needed e. g. for multilevel slug tests, direct push methods or the combination of hydraulic with geophysical methods could be suggested.

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