# Using borehole flowmeter data to optimize hydraulic conductivity characterization in heterogeneous unconsolidated aquifers

Daniel Paradis[1]
*1: Natural Resources Canada, Geological Survey of Canada, Québec, Canada*
René Lefebvre[2], Roger H. Morin[3] & Erwan Gloaguen[2]
*2: INRS-Eau Terre Environnement, Québec, Canada / 3: U.S. Geological Survey, Denver, Colorado, USA*

ABSTRACT
Borehole flowmeter measurements obtained during pumping can be effective in determining profiles of hydraulic conductivity (*K*). Few tests have been reported on flowmeter in full-screened wells that penetrate unconsolidated aquifers. In this paper, we demonstrate the utility of the flowmeter technique in quantifying the spatial variability of *K* and in distinguishing hydrofacies in an unconsolidated heterogeneous aquifer that exhibits low to moderate *K*. Results indicate that: (1) comparison of *K* values obtained from flowmeter measurements and multilevel slug tests shows differences consistently below 10%, and (2) individual hydrofacies can be delineated based upon *K* contrasts.

RÉSUMÉ
Le débitmètre dans un puits en pompage peut efficacement définir des profils de conductivité hydraulique (*K*). Peu d'essais ont été faits avec le débitmètre dans des puits crépinés dans les dépôts meubles. Dans cet article, nous démontrons l'applicabilité du débitmètre pour quantifier la variabilité spatiale de *K* et identifier les hydrofaciès dans un aquifère granulaire hétérogène avec des valeurs de *K* faibles à moyennes. Les résultats montrent que : (1) les différences de *K* obtenues par débitmètre et essais de perméabilité multi-niveaux sont inférieures à 10% et (2) les hydrofaciès peuvent être identifiés sur la base des contrastes de *K* mesurés.

## 1 INTRODUCTION

It is generally recognized that the hydraulic-conductivity (*K*) heterogeneity of an aquifer controls groundwater flow and solute transport. In heterogeneous aquifers, the spatial distribution of hydraulic properties may be complex and numerous measurements may be required to develop a realistic understanding of the hydrologic system. Therefore, a means of adequately quantifying the spatial distribution of hydraulic properties for a reasonable investment of time and money is essential for practical aquifer characterization.

Borehole flowmeter measurements during pumping can efficiently determine the vertical distribution of *K* in fractured rocks (Morin et al., 1988; Molz et al., 1989; Paillet, 1998). However, relatively few studies have used the borehole flowmeter in fully-screened wells penetrating unconsolidated aquifers. Drilling operations or well construction can disturb the aquifer fabric and cause either a reduction or an increase in *K* near a well. For example, Boman et al. (1997) showed that flowmeter measurements conducted in gravel-packed wells could yield misleading results due to an annulus of high-permeability material surrounding the screen that allows flow to bypass the meter. Conversely, Young (1998) suggested that gravel packs be used for well installation in heterogeneous granular aquifers to reduce the formation of a reduced *K* zone around the well. Consequently, the use of the borehole flowmeter in unconsolidated aquifers has been restricted primarily to the characterization of dominant flow pathways (Young, 1995) or specifically to coarse-grained materials (i.e. Li et al., 2008; Morin, 2006; Hess et al., 1992).

In this paper, we demonstrate the practical utility of the borehole flowmeter in quantifying the spatial variability of *K* and distinguishing hydrofacies in an unconsolidated heterogeneous aquifer that exhibits low to moderate *K* ($10^{-6}$ to $10^{-4}$ m/s). The field investigation consists of tests conducted in five wells located in the study area of St-Lambert, Quebec, Canada (Paradis et al., 2008). The wells and their tested intervals were chosen to provide a broad sampling of *K*. First, we compare high-resolution profiles of *K* obtained from borehole flowmeter tests with corresponding profiles obtained from multilevel slug tests in packers. We then propose a graphical procedure for distinguishing hydrofacies (material of distinct *K*) from the cumulative curve of transmissivity (or *K*) constructed from borehole flowmeter measurements. Before presenting results, background information is presented regarding 1) the direct-push technique used to install fully-screened wells in unconsolidated deposits, 2) the implementation of borehole flowmeter and multilevel slug tests and 3) the hydrogeology of the St-Lambert test site.

## 2 METHODS

### 2.1 Well Installation and Development

The wells used for *K* measurements were installed with a direct-push rig (Geotech 605D) (Figure 1). A 76-mm OD metal casing equipped with an expendable point was first pushed into the ground to the desired depth. Then a 52-mm ID (60-mm OD) fully-screened PVC tubing was inserted inside the metal casing before this outer casing was withdrawn.

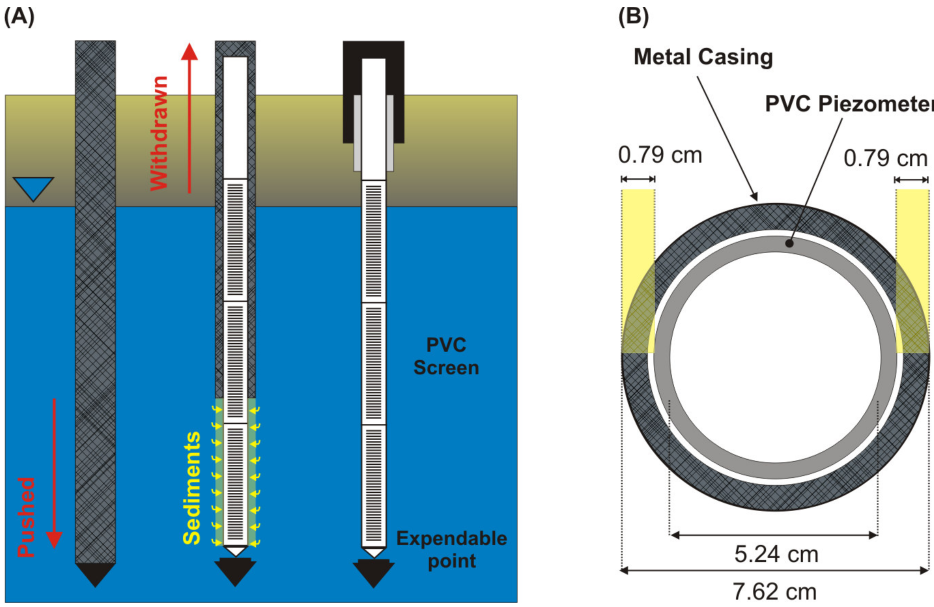


Figure 1. Direct-push well installation. (a) General methodology: a metal casing with an expendable point is first pushed into the ground. Then a fully-screened PVC tubing is inserted inside the casing before it is withdrawn. (b) Hole and tubing dimensions: the annulus between the OD of the metal casing and the OD of the PVC tubing is 8 mm wide.

The thickness of the annulus between the OD of the metal casing and the OD of the PVC well is 8 mm. Slots in the PVC screen were 0.024 mm (0.001 inch) wide, in accordance with the average particle-size distribution of the sediments. With this type of installation procedure, sediments are maintained in direct contact with the screen, there is minimal disturbance to the surrounding aquifer, and gravel packing is avoided.

In addition to proper well installation, it is critical that wells be developed thoroughly in order to obtain accurate information regarding hydraulic properties (Butler, 1998). For example, an undeveloped well can underestimate *K* because of the presence of fine sediments that clog the screen or the formation. Consequently, an aggressive development program is necessary to correct for the disturbance that occurs during the installation process.

In this study, several pumping-surging configurations were tested to insure adequate well development. A well was considered developed when its global *K* was no longer affected by development operations. The pumping-surging operations were performed with an inertial pump equipped with a foot valve and a surge block having a diameter slightly smaller than the inside diameter of the screen tubing. Well development configurations tested were: (1) with the foot valve at the bottom of the well only ("Bottom" on Fig. 2), (2) at three locations along the screen (bottom-middle-top; "3-pts" on Fig. 2)), and (3) at 0.5 m intervals ("0.5 m" on Fig. 2). For each configuration, the interval was pumped until no turbidity was observed in the discharged water. Before and after each tested configuration, slug tests were conducted over the fully-screened interval. Comparison of configurations indicates that pumping-surging development at 0.5 m intervals was the most effective configuration. Figure 2 provides an example of the change in *K* related to well development.

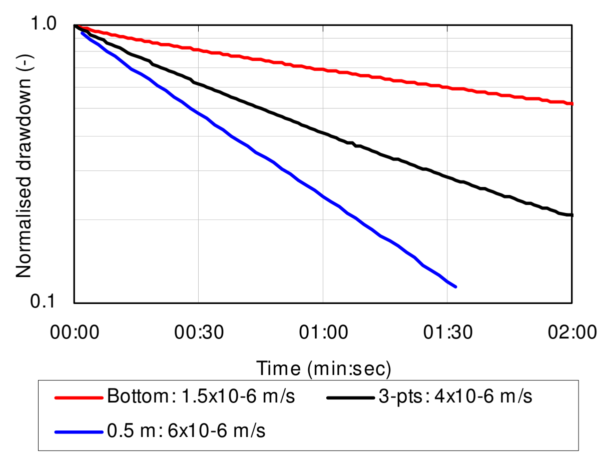


Figure 2. Normalised drawdown as a function of time at observation well P6-362P for different pumping-surging well development configurations. Hydraulic conductivity is proportional to the slope of the time-drawdown curve. For the 0.5-m configuration, over-pumping did not change the slope of the time-drawdown curve (not shown).

## 2.2 Electromagnetic Borehole Flowmeter

The borehole flowmeter has been used in numerous studies to measure the vertical variation of horizontal *K* surrounding a well (Morin et al., 1988; Molz et al., 1989; Paillet, 1998). The borehole flowmeter measures vertical flow in a pumping well at various depths and results are used to determine the inflow to the well across specific intervals. Data analysis presumes the aquifer to be perfectly layered so that the *K* of each tested interval is proportional to the measured flow from that interval and is a fraction of the average transmissivity of the entire well (Molz et al., 1989).

For this study, the vertical flow measurements at each interval were made with an electromagnetic (EM) flowmeter. During testing, the perturbation created by the fluid passing across a magnetic field generated inside the probe is proportional to the average velocity of the water (Young and Pearson, 1995). The EM flowmeter was chosen for its low detection limit and its large dynamic range of operation (0.5 to 20 L/min).

Flowmeter measurements were made every 15.24 cm (6 inches). Pumping operations were performed with a centrifugal pump at pumping rates between 4 to 19 L/min. The testing strategy involved using a pumping rate sufficient to produce a measureable flow above the detection limit of the tool while also minimizing drawdown in the well to preserve a saturated upper section of the aquifer to allow additional flowmeter measurements. Pumping rate and hydraulic head were continuously monitored to ensure stable conditions throughout the entire operation. The average *K* used in the data analysis was the average value obtained across each individual interval as determined from the multilevel slug tests (see below). The total screened section used for this average consisted of the same sections tested by the flowmeter. For intervals where the flow fell below the tool's detection limit (null measurement), the corresponding intervals tested by means of slug tests were nevertheless included in the average. A total of 141 estimates of *K* were obtained from EM flowmeter measurements.

### 2.3 Multilevel Slug Tests

When a slug test is conducted between packers that isolate (or straddle) a particular screened interval of a well, it is usually referred to as multilevel slug test. Multilevel slug tests used to construct a vertical profile of *K* along a well have been previously reported (Melville et al., 1991; Sellwood et al., 2005; Zemansky and McElwee, 2005; Ross and McElwee, 2007).

For this study, inflatable packers were fabricated over 2.54 cm ID PVC tubing. Threads on the PVC tubing allowed variable screen lengths between packers. An air line was attached to the packers and connected at the surface to an air compressor to inflate the packers to the desired pressure. The dual-packer assembly was also connected by a 2.54 cm ID PVC riser pipe to the surface, and a rigid tape was attached near the top to accurately locate the position of the straddled interval.

Slug tests were carried out using a pneumatic method to induce an initial lowering of the water level (Levy and Pannell, 1991). For this purpose, a wellhead assembly was attached to the top of the riser pipe that contained an airtight adapter that allowed a transducer cable to pass and a ball valve for rapid release of pressure. An air compressor was also connected to the wellhead assembly to increase air pressure in the riser. A precision digital air-pressure gauge was used to accurately set the desired initial hydraulic head for the slug test and to ensure air pressure stabilization before initiating the test.

Slug test measurements were made every 15.24 cm coincident with the same intervals tested by the EM flowmeter. Varying and repeated head changes were imposed at some intervals for quality control and to verify repeatability (Butler et al., 1996). Since tested wells were extensively developed, intervals were randomly selected for quality control. The *K* values were estimated from slug tests using the interpretation method of Bouwer and Rice (1976). A total of 227 *K* estimates were obtained from these multilevel slug tests.

## 3 HYDROGEOLOGICAL SETTING

### 3.1 Saint-Lambert Site Description

The study area is located 40 km south of Quebec City (Canada) and encompasses an area of about 12 km$^2$. The aquifer is composed primarily of 10 m of surficial Quaternary-age sediments that were deposited and reworked during the presence of the Champlain Sea (Bolduc, 2003). These sediments are mainly fine-to-medium sand but range from coarse sand to clayey silt. Based on regional geological data and site cone penetrometer soundings, the hydrostratigraphy of the aquifer follows the distinctive structure of a spit that was produced in a littoral environment. This feature is defined as a narrow fingerlike ridge of sand formed by the longshore movement of sediment at the mouths of estuaries and extending from land into open water.

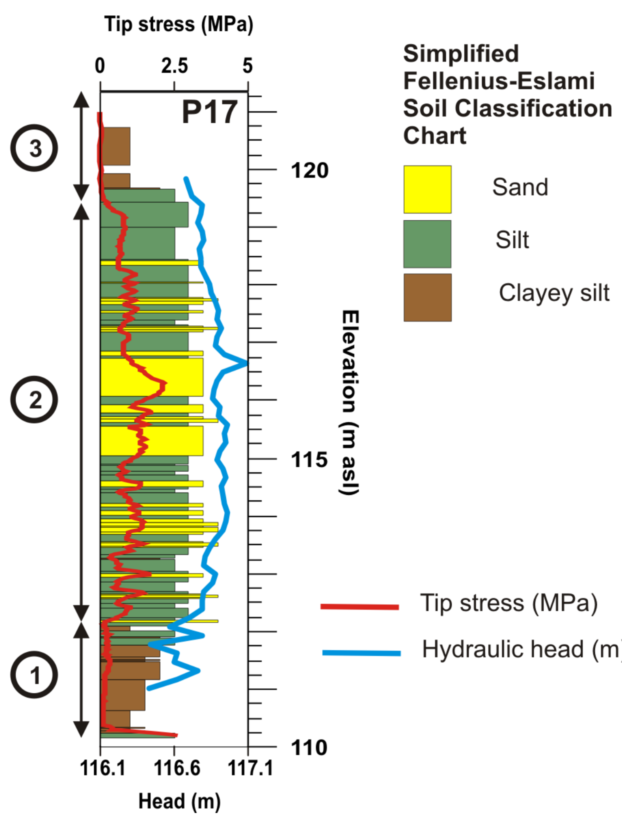


Figure 3. Hydrostratigraphy of sediments at the St-Lambert site illustrated by the P17 cone penetrometer test (CPT). Soil textures are defined according to the Fellenius and Eslami (2000) CPT soil classification chart. Host bedrock underlies this sequence of sediments.

Profiles of *K* and hydraulic heads determined as part of this study indicate semi-confined conditions locally. These conditions result from alternating sand and silt related to the formation of the spit (Figure 3). The water table is 1 to 2 m below ground surface and, from bottom to top, three distinctive chronostratigraphic events can be defined. The first event is the deposition of marine clayey silt when the level of the Champlain Sea was approximately 180-200 m asl. The actual elevation of the study area is about 120 m asl. The second phase corresponds to the formation of the spit itself when sea level was roughly at the present-day elevation of the site. In this sequence, sediments coarsen upward (silt to sand) to a maximum and then reverse and exhibit fining upward (sand to silt). This general tendency was observed in all (more than 25) cone penetrometer soundings performed across the study area. Finally, a spatially discontinuous clayey silt unit appears at the top and is related to the eventual retreat of the Champlain Sea.

## 4 RESULTS AND DISCUSSION

### 4.1 Comparison of Flowmeter and Slug-Test Data

To demonstrate the usefulness of the EM flowmeter for characterizing *K* variability in unconsolidated aquifers, high-resolution profiles of *K* obtained from EM flowmeter tests were compared with corresponding profiles determined from multilevel slug tests. Five wells were selected for this purpose and a total of 123 intervals with a vertical resolution of 15 cm were tested by both methods. Wells were selected such that tested intervals represent a wide and uniform distribution of *K*. With respect to the flowmeter, the tested interval corresponds to the distance between two successive vertical displacements of the probe whereas for the multilevel slug test, the interval is the inner distance between the two packer ends inflated against the screen.

Table 1 presents descriptive statistics of the logarithm of *K* measured by multilevel slug tests and by EM flowmeter tests. Data from all intervals tested over the study area and estimated by both methods, as well as the overlapping intervals used for comparison, are presented. For the *K* distribution incorporating all data, we note that the range of measurement for slug tests is wider than that for the flowmeter. The maximum values in the range are about the same for both methods, whereas the minimum value is higher for flowmeter tests. This lower limit for the flowmeter is dictated by the resolution of the tool and corresponds to a minimum detectable value for *K* of about $1.6\text{x}10^{-6}$ m/s. The multilevel slug tests are not constrained by this type of technical design limitation. However, their duration with the configuration used in this study can last over 20 min when *K* values are as low as $1.6\text{x}10^{-6}$ m/s.

For the distribution data used for comparison in Table 1, the mean values of *K* for both methods are slightly different. As presented in section 2.3, the same average *K* was used by both methods in the data analysis. However, null measurements (below detection limit) with the flowmeter were not used for the comparison (since there is no measurement to compare with). Consequently, the *K* mean associated with flowmeter tests is inherently higher than for slug tests. The logarithms of *K* for both the complete and comparison data sets are not normally distributed (kurtosis-skewness distance probability <0.001). However, it is not necessary for the measurements themselves to follow a normal distribution. Indeed, there is a high probability that they will not do so because tested intervals were specifically chosen to yield a wide and uniform distribution of *K* measurements rather than provide a random sample.

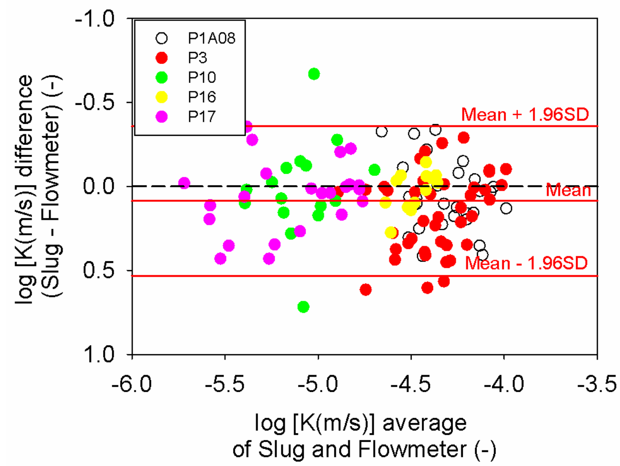


Figure 4. *K* data measured in five wells (color code shown in inset): difference between multilevel slug tests and borehole flowmeter measurements versus average of values measured by the two methods with 95% limits of agreement. The vertical resolution of the measurements is 15 cm. For normally distributed differences (slug – flowmeter), the 95% limits should lie between mean +/- 1.96 SD (SD refers to Standard Deviation).

Figure 4 shows the differences between logarithms of *K* derived from the multilevel slug tests and the EM flowmeter against their mean. This type of plot is an effective way of displaying data when (Bland and Altman, 1999): (1) the range of variation in the measurements is large in comparison with the differences between the methods, and (2) there is an increase in variability of the differences as the magnitude of the values increases. Because we do not know the true, verifiable values of the *K* we are measuring, we use the mean of the values determined by the two methods as our best estimate. Here we are concerned with the theoretical relationship of equality and deviations from it. For 123 intervals tested in five different wells, the mean difference of the logarithm of *K* is 0.086 with 95% limits of agreement of 0.52 and -0.35. As shown in Table 1, there may be a consistent tendency for the flowmeter data to exceed the slug test measurements. However, this bias is due to the estimation of an average *K* that includes the sections of null measurements. The flowmeter measures relative changes in *K* and the resulting data need to be scaled with respect to an average absolute value from an independent method (i.e., slug test, pumping test).

The distribution of the differences between the logarithms of *K* obtained from flowmeter and slug test methods is normally distributed, as shown by a K-S distance probability greater than 0.2. (Table 1). The systematic error can also be determined by the rank correlation between the absolute differences and the average in Figure 4. The Spearman's rank correlation coefficient is 0.04, meaning that the error is statistically random. Also, due to the high correlation between both methods and the reasonably large sample size, the confidence intervals for the limits of agreement are narrow. For example, by converting the difference between the logarithms of *K* on the vertical axis of Figure 4 as a % of their average, the 95% limits of agreement become 7.7 and -11.5% (with a mean of -1.9%). Figure 5 shows that both individual 15-cm intervals and average *K* values for the wells are very well correlated. Unbiased correlations were obtained by adjusting the radius of influence in the Thiem equation used to derive the transmissivity of the entire tested interval based on the drawdown induced by pumping.

Operationally, the flowmeter is a practical tool for quantifying the spatial variability of K at a reasonable expense. It takes much less time (by a factor of approximately 5 to 8) with the flowmeter method to perform the same measurements as with the multilevel slug method for the range of K observed at the St-Lambert site. However, the detection limit of the flowmeter probe cannot be exceeded (here K < $1.6\text{x}10^{-6}$ m/s) and K values need to be scaled with another method. In studies where some magnitudes of K lie below the detection limit of the EM flowmeter, multilevel slug tests and flowmeter tests can be employed in a complementary manner.

Table 1. Descriptive statistics of *K* from multilevel slug tests and borehole flowmeter measurements. Statistics are derived from all tested intervals in the study area as well as from common intervals tested by both methods. Also shown are statistics related to the differences in the log of *K* between slug tests and borehole flowmeter measurements. SD refers to Standard Deviation and K-S Dist to Kurtosis-Skewness distance.

| | **Size** | **Mean** | **SD** | **Range** | **Max** | **Min** | **Skewness** | **Kurtosis** | **K-S Dist (K-S Prob.)** |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | **All data used for aquifer characterization** | | | | |
| *Slug Test* | 227 | -4.75 | 0.54 | 2.09 | -3.92 | -6.02 | -0.62 | -0.63 | 0.11(<0.001) |
| *Flowmeter* | 141 | -4.67 | 0.42 | 1.84 | -3.94 | -5.79 | -0.70 | -0.18 | 0.10(<0.001) |
| | | | | | **Subset used for comparison** | | | | |
| *Slug Test* | 123 | -4.57 | 0.43 | 1.80 | -3.92 | -5.72 | -0.72 | -0.41 | 0.13(<0.001) |
| *Flowmeter* | 123 | -4.66 | 0.43 | 1.84 | -3.94 | -5.79 | -0.72 | -0.09 | 0.09(0.007) |
| | | | | | **Difference (Slug – Flowmeter)** | | | | |
| *Difference* | 123 | 0.086 | 0.227 | 1.38 | 1.71 | -0.67 | 0.05 | 0.56 | 0.065(0.20) |

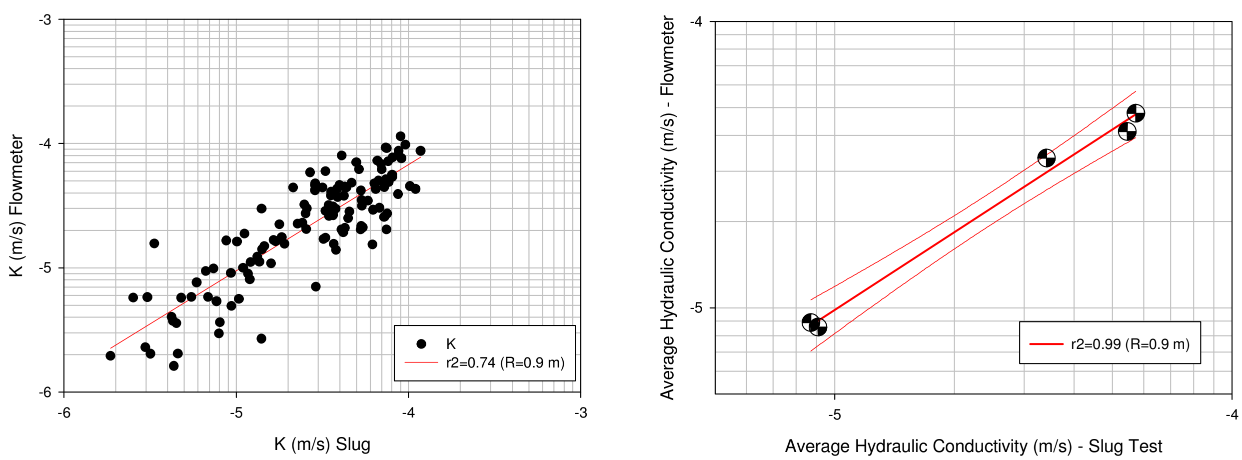


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Figure 5. Correlation of *K* from the flowmeter and multilevel slug tests. (Left) *K* for all 15-cm intervals with flowmeter values obtained by adjusting the radius of influence in the Thiem equation to maximise $r^2$. (Right) Average *K* per well.

4.2 Hydrofacies Generalization Method

In the preceding section, it was shown that the flowmeter effectively measures *K* at a vertical resolution as small as 15 cm. However, this resolution is not always practical, especially when the objective is to develop a regional numerical model. The spatial correlation among high-resolution *K* data may be difficult to assimilate when well density over the study area is low. Under such conditions, it would be best to identify and distinguish large zones having homogeneous *K* (hydrofacies) before interpolation or zonation is performed between wells to define the hydrostratigraphy. In that perspective, the following method is proposed to distinguish individual hydrofacies using borehole flowmeter measurements (Figure 4):

- Calculate the *K* for each tested interval following the method of Molz et al. (1989). Care must be taken to use the appropriate average *K*, and the same method should be used for all wells. This ensures a uniform scaling of *K* values and avoids misinterpretation when comparing wells;
- Convert individual *K* values into a curve of cumulative % of transmissivity (*T* or *K* if interval lengths are uniform). This is done by normalizing *K* values by the sum of all values over the screen length independently for each well;
- Define hydrofacies from distinct breaks in the slope of cumulative *T* curve. This is done graphically and each line between breaks corresponds to a hydrofacies unit;
- Calculate the resulting *K* for each hydrofacies from the average of individual values within the vertical interval.

An example is illustrated in Figure 4a (first profile), where a straight line is first drawn between each break in the cumulative curve. For this profile, five hydrofacies are defined and numbered. The slope of the straight line associated with each hydrofacies is related to the *K* and an average *K* value is calculated from individual values. The resulting hydrofacies and their *K* are presented in the second profile of Figure 4a.

In Figure 4c and Figure 4d**,** this generalization method is applied to well P10 using a vertical resolution of 15 and 60 cm, respectively. Hydraulic head profiles are also depicted alongside the *K* data. In these profiles, contrasts in *K* are gradual, as is the hydraulic gradient between the upper and the middle-bottom part of the well. For this well, the aquifer is reduced to a single hydrofacies when using low-resolution measurements (Figure 4d). Consequently, the subtle contrasts in *K* are lost as is the possibility of simulating confined conditions with a numerical model.

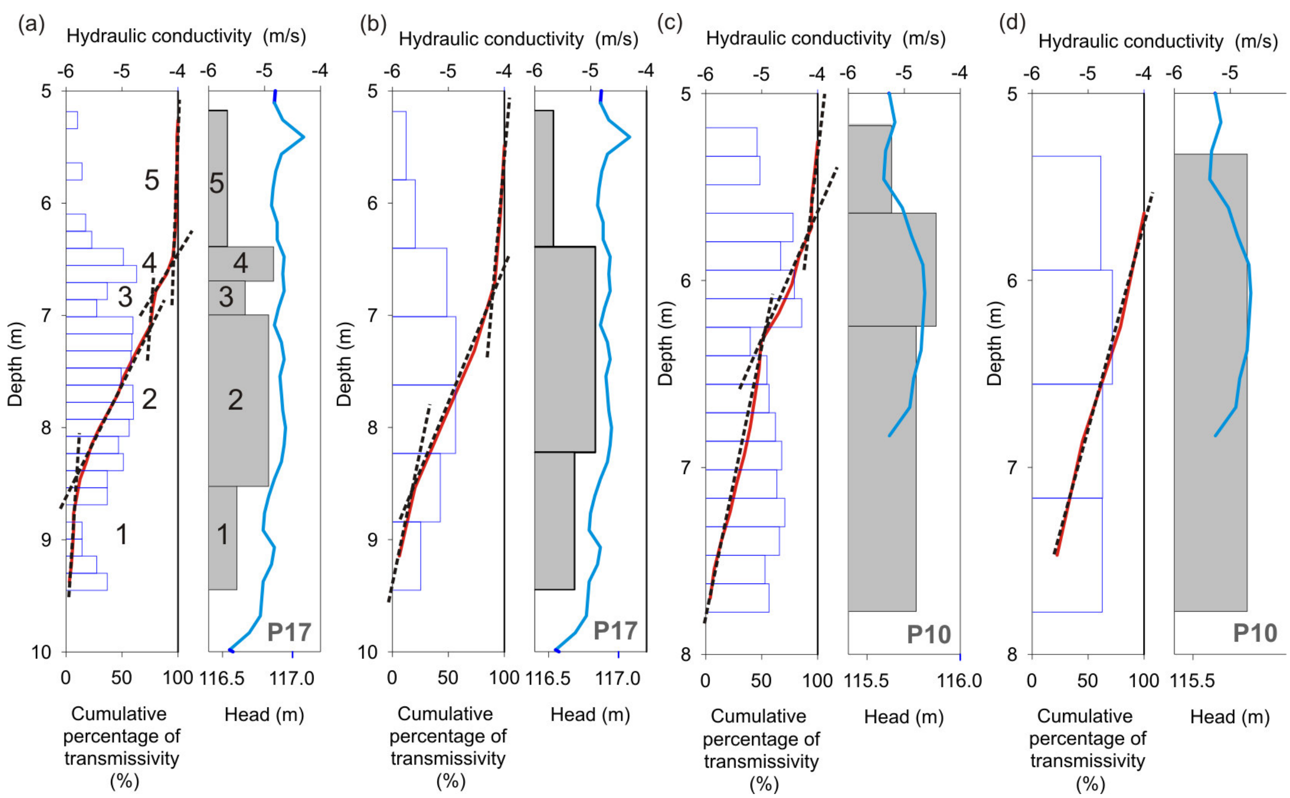


Figure 4. *K* and hydraulic head profiles: application of the generalization method to the cumulative transmissivity (T) curve. (a) Well P17 showing sharp changes in hydraulic conductivity at a vertical resolution of 15 cm; (b) Well P17 at a resolution of 60 cm; (c) Well P10 showing confined conditions at a vertical resolution of 15 cm; (d) Well P10 displaying one uniform hydrofacies at a resolution of 60 cm. Black dashed lines represent slopes of the cumulative T curves. Hydraulic head profiles were measured within the dual-packer assembly during multilevel slug tests.

Hence, it is important to acquire borehole flowmeter measurements at a high resolution in order to adequately delineate hydrofacies. This approach requires a compromise between the scale of the heterogeneity and the flow detection limit of the probe. If vertical intervals used are too large, the *K* variability will not be represented. For instance, for the range of *K* observed over the study area, a resolution of 15 cm is an efficient choice. For more homogeneous aquifers, larger intervals could be used to reduce the testing time. For less permeable aquifers, a testing program with larger intervals could be implemented to avoid too many measurements below the detection limit of the flowmeter.

## 5 CONCLUSION

This study aimed to develop the practical application of the borehole flowmeter in characterizing heterogeneous unconsolidated aquifers. The main conclusions are:

- To be useful, measurements of *K* derived from the borehole flowmeter or multilevel slug tests must initially rely on proper well installation and extensive well development. In unconsolidated aquifers, wells installed by the direct-push technique should be favoured over more conventional methods (i.e., hollow-stem auger, mud-rotary) that use backfilled material (natural or gravel-pack). The direct-push method minimizes disturbance to the aquifer fabric and is more suitable for hydrogeologic studies that employ downhole measurements;
- The borehole flowmeter is a practical tool for quantifying the spatial variability of *K* in unconsolidated sediments. Values of *K* measured with a borehole flowmeter are comparable to those obtained from multilevel slug tests. Furthermore, this method is time-efficient in comparison to slug tests performed at the same vertical resolution provided that the detection limit of the probe is not exceeded.

The proposed generalization method based upon the cumulative transmissivity curve is useful to distinguish individual hydrofacies. The resulting units can be delineated at scales that are computationally manageable for regional aquifer modelling, and that adequately represent the relative contrasts in the *K* of heterogeneous unconsolidated aquifers. However, in order to avoid the loss of important spatial details, borehole flowmeter measurements should be performed at a high sampling resolution (15 cm for this study). The choice of the vertical resolution should be based on a balance between the detection limit of the borehole flowmeter and the degree of aquifer heterogeneity.

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