CL:AIRE technical bulletin

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CL:AIRE technical bulletins describe specific techniques, practices and methodologies currently being employed on sites in the UK within the scope of CL:AIRE technology demonstration and research projects. This bulletin explores tests that are used to measure aquifer hydraulic properties for contaminant hydrogeologists.

Parameterisation of Aquifer Hydraulic Properties: A Contaminant Hydrogeology Perspective

1. BACKGROUND

The development of hydrogeology as a distinct discipline in geosciences was initially driven by the exploitation of aquifers for public and industrial water supply. Cost effective development of groundwater resources necessarily involves characterisation of the sustainable yield of an aquifer, which requires the estimation of transmissivity, storativity, permeability and/or hydraulic conductivity. This information is important for conceptual site model (CSM) development (both geologic and hydraulic), design and positioning of abstraction wells, and well pump selection. As water resource hydrogeologists tend to work at the "aquifer" scale, hydraulic properties are often determined at the scale of many 10s to 100s of metres. Parameterisation of aquifer properties at this scale is usually achieved via pumping tests, where water is pumped from a well or borehole while measurements are taken of volumetric discharge, drawdown in the well, and drawdown response in adjacent piezometers. These observations are then interpreted using analytical and semi-analytical solutions (see Kruseman and de Ridder, 2000 for a comprehensive review) that describe the physical hydrogeology of the aquifer. In 1935, Theis derived an analytical solution to the unsteady state flow of water to a well in a confined aquifer, following on from Thiem's work on steady state flow in 1906. Various refinements subsequently followed (e.g. Cooper and Jacob, 1946; Hantush, 1962; Papadopulos and Cooper, 1967), along with the development of solutions for leaky (Hantush and Jacob, 1955; Neuman and Witherspoon, 1969), unconfined (Neuman, 1974), and fractured (Gringarten and Witherspoon, 1972) aquifers. These methods involve matching pumping test data to type curves to estimate hydraulic conductivity and/or transmissivity. Today, many of these solutions and curve-matching routines are used in commercially-available pumping test interpretation software, making the determination of bulk aquifer hydraulic properties straightforward and rapid.

Some basic definitions

Transmissivity (T; L^2/t) ease of water flow through a unit width of rock or sediment

Storativity (S; dimensionless) volume of water released per unit area of aquifer per unit head change

Hydraulic Conductivity (K; L/t) measure of the ease of fluid flow through rock or sediments

Permeability (k; L^2) intrinsic ease of fluid flow, independent of fluid properties

Porosity (η; dimensionless) the proportion of a unit volume of aquifer represented by void space

Contaminant hydrogeology is, however, a much newer discipline, where emphasis is on the quantitative analysis of free-phase or dissolved pollutant transport and fate. Early strategies for the management of contaminant plumes involved primarily pump-and-treat systems, the design of which was (and still is) based largely on standard pumping tests. Many groundwater contaminant scenarios involve either light (petrol, oil, lubricants, etc) or dense (degreasing agents, coal tars) non-aqueous phase liquid (NAPL) sources. Often the spatial distribution of contaminants within a plume extending from these NAPL sources is complex (e.g. Figure 1), particularly near

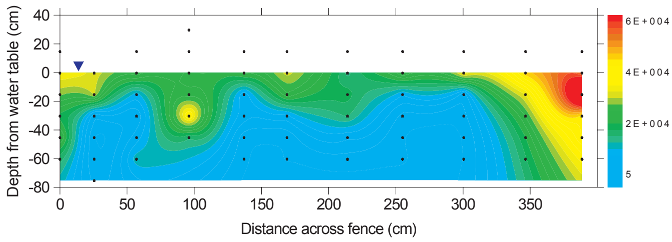

Figure 1. Contour plot of total BTEX concentration (μg/L) across a portion of a plume emanating from a nearby NAPL source underlying a petrol station forecourt. Dots indicate location of multilevel sample ports. Note high concentration gradients. Flow is into the page at ~9 cm/day.

source. This is primarily because the hydraulic properties of aquifers are invariably heterogeneous. The hydraulic conductivity of unconsolidated sediments in particular may vary over 3-4 orders of magnitude at the metre scale (typically a reflection of depositional environment and processes), while the hydraulic behaviour of bedrock aquifers is influenced to a greater (chalk) or lesser (sandstone) degree by fractures of varying trace length, connectivity, aperture and frequency. Both multiphase flow and dissolved contaminant transport is strongly influenced by this heterogeneity, resulting in complex source and plume architecture. It therefore follows that the performance of some remediation systems (including pump-and-treat – see Mackay et al., (2000)) is sensitive to complex groundwater velocity fields, making accurate spatial/temporal characterisation of hydraulic conductivity and/or groundwater velocity vital for effective design and performance. This is particularly true for passive *in situ* remediation systems (e.g. permeable reactive barriers (PRB) or biobarriers), where groundwater velocity is needed together with reaction half life to calculate residence time requirements and therefore barrier thickness. Note in Figure 1 that the benzene, toluene, ethylbenzene and xylene (BTEX) plume emanating from a typical petrol source can have contaminant concentrations spanning 5 orders of magnitude within 20-30 cm. Such discrete high mass flux paths put extreme pressure on the performance of remediation systems - failure to detect and quantify this spatial variability may mean either an over- or under-designed system. As an example, consider a simple scenario involving a 5 m wide plume migrating in a sandy aquifer bounded top and bottom by clay. The aquifer is 1.8 m thick, and has a hydraulic conductivity of 1 m/day. However, within it is a 0.2 m thick coarse sand layer with a K of 50 m/day. The local horizontal hydraulic gradient is 0.001, porosity of both layers is 0.3 and the depth-averaged plume concentration is 10 mg/L. If site characterisation failed to detect the thin high K layer, the plume mass flux would appear to be roughly 15 mg/d. However, the mass flux in the thin layer is 75 mg/d. A PRB designed to treat the apparent mass flux would clearly result in significant breakthrough of contaminants where the thin high K layer intersects the barrier. Of course the converse is true: if only the high K layer was characterised, the resulting PRB would be over-designed (with attendant higher capital and operation/maintenance costs). This simple illustration demonstrates that characterisation of the flow regime at an appropriate resolution allows for more robust remediation system design and acceptable treatment performance at minimal cost. Such data also inform the development of CSMs, monitoring programmes, and numerical or analytical modelling efforts. Unfortunately, detailed characterisation of the physical hydrogeology of aquifers is often overlooked or undervalued, with resources being instead directed to the hydrochemical and microbiological aspects of remediation systems.

This technical bulletin explores various tests that can provide estimates of aquifer hydraulic properties at a scale appropriate for the different needs of contaminant hydrogeologists. As discussed above, traditional (i.e. large scale) pumping tests do not provide data at a scale appropriate to effectively understand and manage many contaminant situations. However, for comparative purposes and completeness, these tests are briefly considered. Subsequently, other established methods are examined that can be used or adapted to provide comparatively high-resolution information on hydraulic properties at reasonable cost, with an assessment of some aspects of data quality.

2. PUMPING TESTS

Pumping tests are a long-established method used to estimate the bulk hydraulic properties of an aquifer, be it pore- or fracture-flow dominated. There has been, and continues to be, development of pumping test configurations and related mathematical interpretations that provide hydraulic parameters for an array of different scenarios. Innovations tend to make refinements on the conventional approaches to account for special circumstances. The most simple are single well techniques, where a well (or rock borehole) is pumped at a known rate: hydraulic head is monitored from the start of pumping through to aquifer recovery after pumping is stopped. During tests, the pumping rate may be changed to generate a step change response in the aquifer to provide additional data (e.g. step-drawdown tests). These techniques tend to have a fairly localised "reach" into the aquifer, and result in an estimate of average K across the tested zone (using an assumed aquifer thickness). It is important to note that this averaging may mask considerable vertical variation in the K-field. Consequently, using a straddle-packer set-up with a short test zone (TZ) interval provides greater resolution of the variability in hydraulic conductivity with depth (Thornton and Wealthall, 2008).

Wells, boreholes and filter packs

Herein wells are defined as a length of pipe with a screen or screens spanning the interval(s) of interest, installed in loosely consolidated or unconsolidated media. Boreholes are those drilled in competent media that remain open. It should be noted that well screens (and occasionally boreholes hosting multilevel or nested wells) are often installed with a filter pack. The presence of a filter pack will strongly influence any form of hydraulic testing, and are not always accounted for in the mathematical interpretation.

Multiple well methods are also common, where one well is pumped and the hydraulic response in nearby observation wells is monitored. The estimated aquifer K from such tests represents the bulk properties of the media between the pumped and monitored intervals, which can in some cases be 10s or 100s of metres and incorporate considerable variation. Various mathematical interpretation methods have been developed to account for transient conditions, partial screen penetration, asymmetric boundary conditions, vertical leakage from confining layers, multi-layered systems, and aquifers of limited areal extent. Figure 2 shows the results of a pumping test conducted with a straddle-packer arrangement, showing the response of water levels within and above the TZ, monitored using pressure transducers. The TZ water level increases slightly as the packers are inflated, but then drops rapidly during the pumping phase, leading to a steady-state condition, after which pumping is stopped to allow the water level to recover. In this example, a slug test was also undertaken (see below). The 'above the test zone' (ATZ) water level does not vary during the test and indicates that the TZ was effectively sealed by the inflated packers (i.e. no short-circuiting between the packer assembly and borehole wall). Estimates of K obtained from the pumping test and slug test results are shown on Figure 2. Different methods (with associated assumptions) were used to interpret each dataset, contributing to the difference between the K estimates.

Because conventional pumping tests performed with long TZ intervals provide estimates of average and bulk aquifer hydraulic properties, the spatial resolution needed to interpret solute transport at contaminated sites cannot often be achieved with this method (Thornton and Wealthall, 2008). Most remediation options will require a comprehensive understanding of the groundwater flow regime and hence, distribution of hydraulic properties. As an example, this information is necessary to estimate contaminant mass flux for the design of some remediation systems, in particular, the required residence time within a reactive (i.e. zero valent iron barrier)

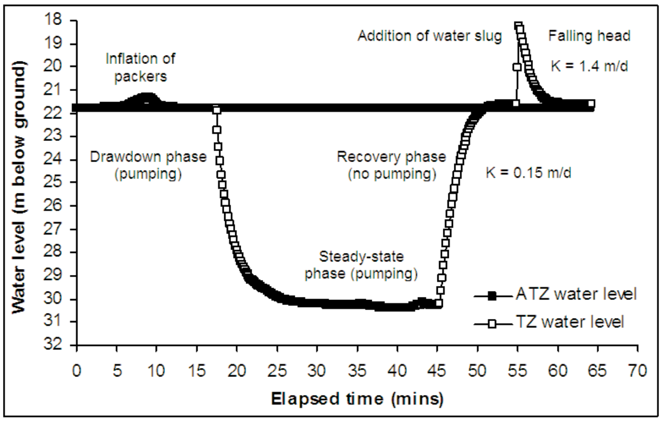

Figure 2. Example results for combined pumping and slug tests undertaken with a straddle-packer arrangement, showing response of water levels within the 2 m test zone (TZ) and above the test zone (ATZ) recorded with pressure transducers during different phases of the test (see text for discussion).

or biobarrier treatment system, or the breakthrough time of contaminants through a sorption barrier. The design and performance of even simple pump-and-treat systems will benefit from a more detailed understanding of subsurface hydraulic properties, in terms of optimising pumping well location, screen length and depth, and treatment system capacity. While it is possible to conduct pumping tests in wells with long TZ intervals and monitor responses in short screen piezometers or multilevel samplers (MLS), the test assumptions may make the results unreliable. Fortunately, there are other methods available to gather data at a scale of resolution that aids remedial system design and therefore treatment performance. These methods are described below in order of decreasing scale of observation, considering the utility of data obtained and the quality or reliability of those data.

3. SINGLE WELL HYDRAULIC TESTS

3.1 Slug Tests

Slug test theory (including small-scale pump drawdown/recovery tests) is well established. These tests involve a relatively sudden perturbation of the water level (up or down) in the well and monitoring the recovery back to rest state. A rising head test involves lowering the water level in the well using either a pump or by removing a slug (length of weighted solid rod slightly smaller in diameter than the well) rapidly from the well, and monitoring the recovery of water level back to the rest state. A falling head test involves plunging a slug or volume of water into a well and monitoring the fall in water level back to the rest state. A typical response is shown in the TZ water level profile in Figure 2. Often, all that is needed to generate high quality data are the borehole dimensions or monitoring well completion details, a stopwatch and a water level meter. Alternatively, water level response can be monitored using pressure transducers, which provide high temporal resolution for cases of rapid aquifer response (Figure 2). The mathematical analysis of the recovery phase was first developed by Hvorslev in 1951, and was limited to confined aquifer scenarios. Bouwer and Rice (1976) developed an expanded solution for both unconfined and confined aquifers. This latter solution is also appropriate for partially penetrating wells in confined aquifers. Water level recovery data are normalised to rest head (water level) and plotted on a log scale versus linear time (Figure 3a). The goodness of fit of a least square regression is a measure of the reliability of the derived K estimate (accounting for measurement error and non-ideal near-well hydraulics). Depending on the circumstance, K is found by solving either the Hvorslev equation:

$$K = \frac{r^2 \ln\left(\frac{L}{r_w}\right)}{2LT_o} \qquad \text{Equation 1}$$

where r is well screen radius, r_w is well radius (including gravel pack or disturbed zone), L is screen length, and T_o is time at which normalised head has a value of 0.37 (see Figure 3a), or the Bouwer-Rice equation:

$$K = \frac{r_c^2 \ln\left(\frac{R}{r_w}\right) \ln\left(\frac{h_o}{h}\right)}{2Lt} \qquad \text{Equation 2}$$

where r_c is casing (well screen) radius, r_w is the radial distance from the well centre to undisturbed aquifer, L is well screen length, h_o is rest water level and h is observed water level at time t. R is the radius of pressure pulse of perturbation (the reach of the test into the aquifer), found by determining intermediate parameters A and B (for unconfined aquifers) or C (confined) and relating them to R in the form of $\ln(R/r_w)$ – see Bouwer and Rice (1976) for details. The value of t should be selected where h_0/h is between 0.2 and 0.3 (Butler, 1998), i.e. where water level has recovered to 70-80% of the rest state. For reliable estimates using the Hvorslev method, recovery should ideally be 75-85%, and the ratio of well screen length to screen radius (L/r_w) should be greater than 8. Bouwer (1989) noted that when wells screened across the water table were slug tested, a double straight line is often observed. The first segment represents drainage from the gravel pack, while the second is the aquifer response. Therefore, it is the second straight line that should be used to estimate K using the Bouwer and Rice (1976) solution. Also, a correction must be made to the casing radius to account for gravel pack drainage: in Equation 2, r_c should be replaced by an equivalent casing radius equal to $[(1\text{-}n)\ r_c^2 + n r_w^2]^{½}$, where n is effective porosity of the gravel/filter pack, r_c is casing radius and r_w is well radius. In other cases, there may be a concave upward appearance in the plotted data, which becomes more pronounced as the dimensionless storage parameter (r_w^2S/r_c^2) increases (S is the aquifer storage coefficient).

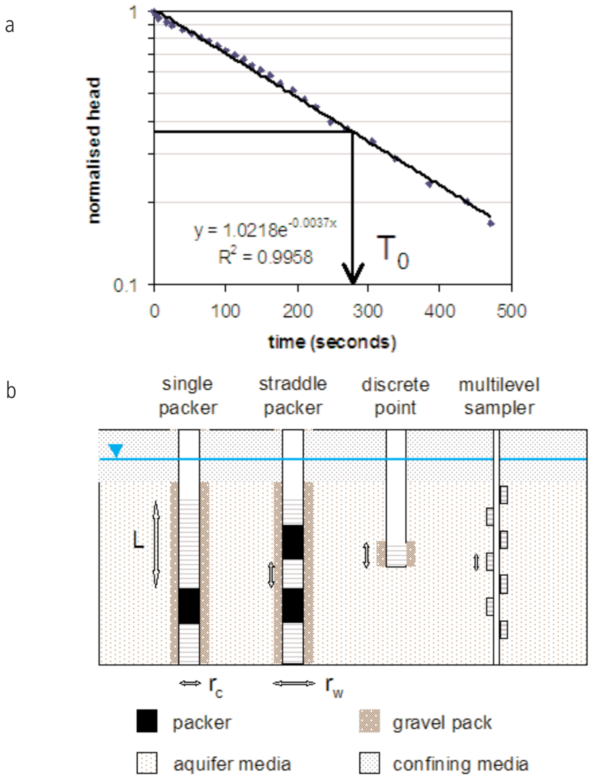

Figure 3. a) example of data from a falling head slug test in unconsolidated porous media. Arrow shows T_0 – the point at which normalised head is 0.37, required in the Hvorslev equation. b) 4 possible slug test configurations. r_c = casing radius, r_w = well radius, L = screen length (test interval).

There are several common configurations for slug tests: single packer, straddle packer and discrete points arranged as nested short-screen wells, direct push drive points or multilevel sampler (MLS) devices (Figure 3b). The value to the contaminant hydrogeologist is that multiple straddle packer tests conducted within a long well screen provide a vertical profile of horizontal (radial) K. Figure 4 shows such a profile from an unconsolidated multilayered sandy aquifer, compared with K estimates obtained by repacked permeametry and grain size analysis (methods described below) of subsamples from a continuous core taken when the monitoring well was installed. When the core was logged, a layer of fine-grained, dense sand was noted between 6-9 m. Also, a fining up sequence (fine gravel to medium sand) is present between 14-12 m. Both features are evident in the straddle packer slug test profile and grain size data, but are somewhat attenuated in the permeametry profile. Fines were lost during the permeameter tests (observed in the effluent water), resulting in the over-estimation of K in less permeable horizons. The permeametry also under-estimated K in the lower horizons (12-14 m depth), probably because the method is not strictly appropriate for high permeability media – see below. Thus, the straddle packer and grain size-derived K values are more reliable. Also, repeat straddle packer tests at the same horizon were remarkably consistent (±2%), and the goodness of fit on the normalised head/time plots were all >99.9%.

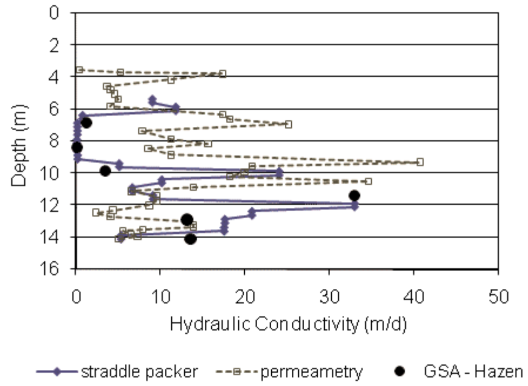

Figure 4. Comparison of K values derived from repacked permeametry and grain size analysis (GSA) of subsampled core, and straddle packer tests performed in a long screened well subsequently installed in the cored hole. Aquifer was an unconsolidated massive layered sand system.

If a line of monitoring wells or MLS devices are placed transverse to groundwater flow, a 2-D K field can be developed from vertical profiles of these measurements, which can be spatially interpolated and compared with solute concentration data. These K fields can be combined with a measured local hydraulic gradient to produce a groundwater velocity field for the estimation of contaminant mass flux. Mass flux is rapidly becoming a preferred basis for the performance assessment of both natural attenuation and engineered remediation systems, considering the technical limitations of alternative assessment approaches (Wilson et al., 2004).

3.2 Dipole Flow Tests

It should be noted that the slug tests described above do not take account of anisotropy in hydraulic conductivity. A vertical hydraulic recirculation method developed in the 1980s in Germany (Unterdruck Verdampfer Brunnen - UVB) to strip volatiles from water was adopted by others as a vertical groundwater recirculation method for the treatment of contaminants. A triple packer arrangement is installed in a well or borehole to create two isolated chambers (Figure 5). Water is extracted from one chamber (-'ve pole) and re-injected in the other chamber (+'ve pole). The result is a torus-shaped dipole flowfield that is spherical in homogeneous, isotropic media but extended in the horizontal direction in anisotropic media. Starting with the Hantush (1961) solution for drawdown around a partially penetrating well, Kabala (1993) developed non-linear mathematical expressions describing the drawdown induced by an extraction chamber and the drawup in the injection chamber. These expressions allow estimation, using an iterative solver, of both radial and vertical K. Dividing radial K by vertical K gives the anisotropy.

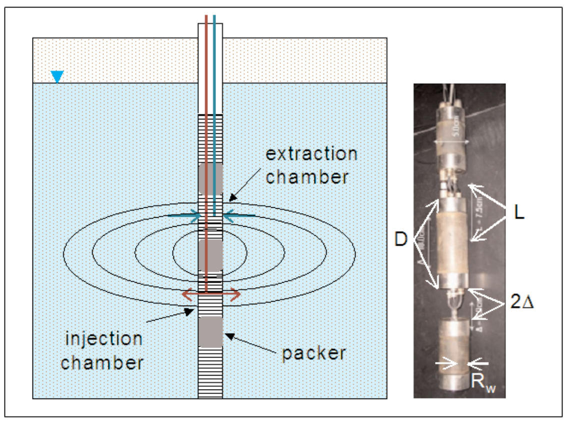

Figure 5. Schematic of dipole assembly in well and resulting idealised flowfield. Design and operational parameters are D (central packer length), L (half dipole length), 2Δ (chamber length), Q (pump rate). Dipole is constructed to fit a given R_w, well radius.

Estimates of K derived from dipole flow tests were compared to straddle packer tests conducted in a well installed in the medium sandy aquifer at Canadian Forces Base Borden, Canada, for which the average value of K is well known (Sudicky et al., 1986). The 5 cm diameter dipole shown in Figure 5 was used to generate both conventional straddle packer data (by inflating only two packers) and dipole data, from which estimates of K were calculated. Those data are shown in Figure 6 along with the published average K value for the Borden aquifer. The similarity between the two datasets highlights the potential utility of dipole flow tests, which have also been used to deliver and recover conservative tracers to resolve both flow and transport parameters (Sutton et al., 2000). Other workers have explored the application of reactive tracer tests within dipole flowfields, to resolve sorption, biodegradation and cation exchange characteristics of aquifers (on-going at the universities of Sheffield and Waterloo).

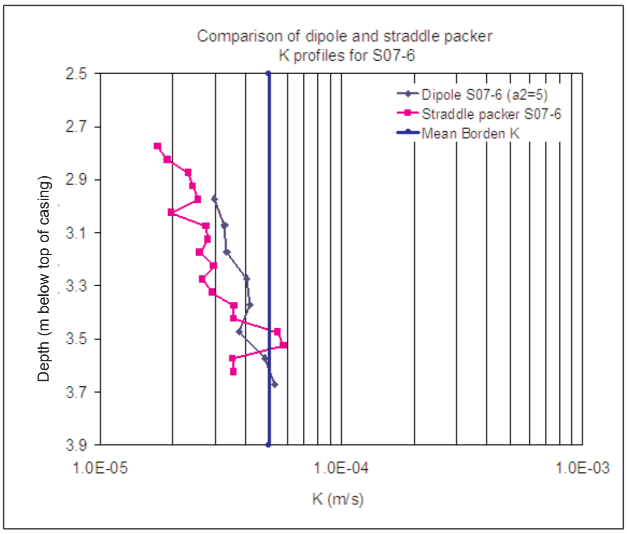

Figure 6. Favourable comparison of dipole and straddle packer derived K values from the Borden Aquifer, Canada. Downward trend of increasing K has been previously noted in that aquifer. Well S07 was installed by direct push without a sand pack.

4. ESTIMATING HYDRAULIC CONDUCTIVITY FROM CUTTINGS AND CORE

When boreholes are drilled or monitoring well screens installed, there are usually cuttings from the drilling process. Whether using hollow stem auger, rotary, or cable tool drilling methods, subsurface materials are brought to the surface where they can be grab-sampled and analysed. Some drilling methods allow for the collection of discrete or continuous rock or sediment cores. Such samples provide an opportunity to generate high-resolution data on key parameters such as hydraulic conductivity and porosity.

4.1 Repacked Sample Permeametry

The hydraulic conductivity of grab samples of drill cuttings or sections of sediment core can be estimated using a permeameter. Such devices are used extensively in geotechnical research, and are relatively straightforward to construct and operate. A grab sediment sample is placed in a cylinder (often acrylic) and tamped down to approximate the aquifer bulk density (given by measured mass per known volume of vessel). Alternatively, core samples can be directly extruded into the permeameter cell to preserve the layering structure. A graduated tube or burette attached to the top or (ideally) the bottom of the vessel is filled with water and the sample is allowed to fully saturate. In the "falling head" mode of operation (Figure 7a), a valve is closed, the tube is filled, and the water level noted. The valve is then opened and the time taken for the water level to fall some distance (i.e. flow through the sample) is recorded. Hydraulic conductivity is estimated by:

$$K = \frac{d^2 L}{D^2 t} \ln\left(\frac{h_0}{h_i}\right) \qquad \text{Equation 3}$$

where L is sample length, d is water tube diameter, D is sample diameter, t is time, h_0 is start head and h_i is measured head at time i.

When designing a permeameter it is important to use a water tube with sufficient diameter to avoid friction-related head loss. Note that the form of Equation 3 is similar to the Bouwer and Rice slug test equation described above. As for slug tests, a plot of ln-normalised head (H_0/H_i) against linear time should give a straight line. If the water level falls at a slow enough rate, it is good practice to record as many observations as possible. Since the head gradient at time zero is the highest, early time rate of fall is greatest. As the head gradient decreases, the rate of water level fall slows. Because of the rapid early time fall of water, this method is appropriate for moderately permeable media such as well-sorted medium sand or fine silty sand. However, care must be taken with poorly sorted media to avoid washing fine particles out of the sample during testing (especially replicates conducted to assess precision),

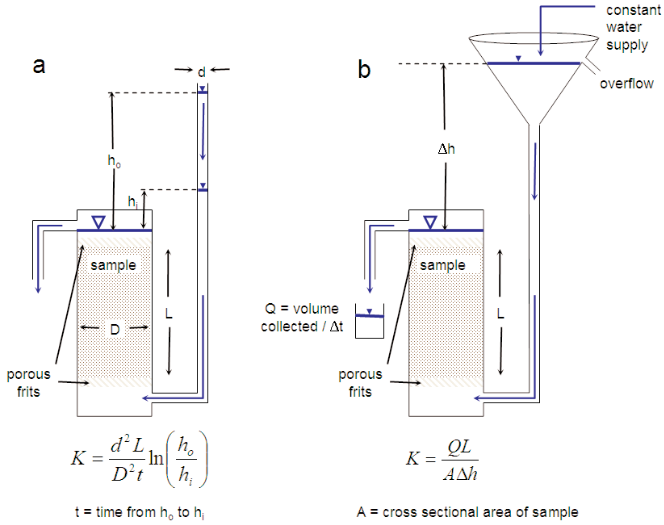

Figure 7. Schematic of falling head (a) and constant head (b) permeameter setups

which can result in over-estimation of K. This is the reason why the permeametry-derived K values shown in Figure 4 (between 6-10 m depth) are higher than those found using straddle packer slug tests. Glass wool or sintered silica disc filters may be used to limit loss of fines, but it is also important to avoid collecting fines at the filter interface.

In a comprehensive study, Sudicky (1983) sectioned several continuous cores collected from the well-studied Borden Aquifer, Canada, into 2-5 cm segments and conducted falling head permeameter tests on each segment. The resulting data provided a series of very high-resolution K profiles, which ultimately led to one of the first applications of stochastic theory in hydrogeology. This work showed that high-resolution data can be used to produce autocorrelation lengths for a given aquifer system, which are distances within which K can be estimated with high certainty. This is a very powerful method of site investigation that can, with focussed effort, provide key understanding for the design of remediation systems.

With coarse sands and well-sorted gravels, water falls too quickly to accurately read water levels, yielding poor linearity in data plots and unreliable estimates of K. A constant head arrangement is usually used for such media. A modification to the falling head setup (Figure 7b) allows a constant volumetric flux of water to be applied. The ratio of rest water level to that at steady state is entered into Equation 4, which is a direct application of the Darcy Equation:

$$K = \frac{QL}{A\Delta h} \qquad \text{Equation 4}$$

where Q is volumetric flow rate, A is the cross sectional area of the sample perpendicular to flow, L is the sample length and Δh is the ratio of rest head and steady-state head. The sample can be tested over a range of steady-state flows to generate the statistics necessary to assess the reliability of K estimates obtained with this method.

Cohesive fine-grained silts, clays and rock samples are usually tested in a triaxial cell flexible-wall permeameter. A rubber membrane is placed around the sample, which is then installed in the cell and gas or water is introduced to compress the membrane against the sample. This prevents flush water from by-passing the sample along the cell wall. Flush water is introduced via a pressurised delivery system and the pressure difference across the sample is recorded (pressure head is equivalent to elevation head) until it reaches steady-state, as is done for constant head permeametry. For particularly low-K media, the water pressure can be increased considerably to induce a sufficiently high gradient to provide useful estimates.

4.2 Intact Sample Permeametry

When sediment is repacked in a permeameter, bedding scale layering (i.e. heterogeneity) is destroyed. In addition, when core is extruded into a permeameter cell, any layering in the sample is oriented perpendicular to the induced water flow. In the former case, measured K is an average of vertical and radial values (i.e. anisotropy is not preserved). In the latter case, measured K reflects vertical rather than horizontal values of this property. Neither is truly representative of radial or horizontal K, which is ordinarily the parameter required. To address this, workers at the University of Waterloo, Canada, trialled a square core tube that was then cut into lengths and tested across the tube in both directions (using the falling head technique) to directly measure horizontal K (unpublished data). It is also possible to collect horizontal cylindrical core samples from test pit walls or other exposures, which can then be tested in the conventional equipment to provide estimates of horizontal K. However, given that the anisotropy ratio of most unconsolidated sediments is of the order of 2-5, it is rarely necessary to stray beyond the standard permeametry methods.

4.3 Grain Size Analysis

In 1892, Hazen proposed a relationship between the hydraulic conductivity of a sediment sample and a certain grain size fraction, derived from the analysis of sample particle size distribution:

$$K = C d_{10}^{2} \qquad \text{Equation 5}$$

where the d_{10} value is the particle size (in mm) below which 10% of the sample grains are smaller, and C is a dimensionless coefficient reflective of sediment size and sorting that Hazen found to vary between 1 and 1.5. This gave K in units of cm/s. Hazen cautioned that this equation was valid only for d_{10} values between 0.1 and 3 mm, and a coefficient of heterogeneity (d_{10}/d_{60}) between 1 and 5. Shepherd (1989) performed an extensive power regression analysis on 19 sets of unconsolidated sediment grain size analyses (ranging from 8 to 66 pairs). This showed that the exponent in the Hazen equation varied from 1.1 to 2.05 (averaging 1.72), and C varied from 0.05 to 1.18. Others (see Fetter, 2001) give C values to be used when grain diameter is expressed in cm, to yield K estimates in cm/s. Ranges of C for different types of sediment are compiled in Table 1. The distinction between sediment types should be based on a full particle size analysis of the sediment sample so that the appropriate value of C in Table 1 is used in the estimation of K.

Table 1. Hazen C values for different types of sediment (K in cm/s when d_{10} is cm)

Sediment type	C
Very fine sand, poorly sorted	40-80
Fine sand, high % fines	40-80
Medium sand, well sorted	80-120
Coarse sand, poorly sorted	80-120
Coarse sand, well sorted	120-150

Since Hazen, many researchers have proposed a range of alternative semi-empirical equations, some based on the analysis of a specific type of sediment (there being no such thing as a "typical" sediment), while others involved regression analysis of many (some in excess of 1000) grain size analyses (see Cronican and Gribb, 2004 for a review). Of the many, one of the most robust relationships is the Kozeny-Carman equation:

$$K = \frac{\rho g}{\mu}\left(\frac{n^{3}}{1-n^{2}}\right) * d_{10}^{2} * C_{k} * n \qquad \text{Equation 6}$$

which was originally proposed by Kozeny in 1927 and then refined by Carman in 1937. In Equation 6, ρ is soil density (g/cm^3), g is the gravitational constant (m^2/s), μ is fluid viscosity (Pa s), n is porosity and d_{10} is as defined above and expressed in mm. To yield K in cm/s, C is 0.83. Variants include those proposed by Terzaghi and Peck (1964) for coarse sands and gravel (cm/s):

$$K = \frac{g}{v}\cdot C_{t}\cdot\left(\frac{n-0.13}{\sqrt[3]{1-n}}\right)^{2} d_{10}^{2} \qquad \text{Equation 7}$$

Beyer (1964), for gravels and sands (m/s):

$$K = \frac{g}{v}\times 6\times10^{-4}\log\frac{500}{C} d_{10}^{2} \qquad \text{Equation 8}$$

and Slichter (1899), for medium sands (m/d):

$$K = \frac{g}{v}\times 1\times10^{-2} n^{3.287} d_{10}^{2} \qquad \text{Equation 9}$$

where ν is kinematic viscosity (m^2/s) and other parameters as defined above (in consistent units). Because they are semi-empirical, the user should be cautioned that these equations appear in the literature in different forms depending on the units of K. Repeated evaluation by a number of researchers over the past 70 years has shown that, overall, the Kozeny-Carman equation gives the most reliable estimate of K.

5. EXAMPLE APPLICATION OF HYDRAULIC TESTING IN CONTAMINANT HYDROGEOLOGY

In some instances of groundwater contamination, greater detail on the spatial variability of the aquifer K-field is required to better predict contaminant transport and develop cost-effective site management strategies (Thornton and Wealthall, 2008). The example below illustrates the value of conducting hydraulic tests at a resolution which is appropriate for the contamination scenario, in this case a former filling station site on the Upper Chalk aquifer contaminated with unleaded fuel containing the ether oxygenate compounds methyl tertiary butyl ether (MTBE) and tert-amyl methyl ether (TAME). A fracture log for the cored borehole shows significant variation in the fracture frequency, with highly fractured zones between 27-32 m depth (given here as metres below forecourt level, mbfl) and 36-40 m depth (Figure 8a). Straddle-packer pumping tests, conducted in the same borehole with a test zone length of 2 m, reveal a zone of relatively high aquifer hydraulic conductivity around 26 m and 31-36 m depth (Figure 8b). Note that high fracture frequency does not necessarily correspond with high aquifer hydraulic conductivity. In this case the vertical distribution in K is influenced more by fracture aperture than frequency, such that a few relatively wide and conductive fractures are responsible for a significant volume of the groundwater flux through the monitored section. These zones are preferential pathways for contaminant transport in the aquifer, which were subsequently considered in the design of a MLS installed in the borehole (Figure 8c). The resulting groundwater quality data reveal the distribution of MTBE and TAME in the plume at this site. This validates the decision to conduct the high resolution aquifer hydraulic conductivity tests undertaken. Without such understanding, it is not possible to anticipate contaminant distribution, peak concentrations and high flux zones (Figure 8d). Further information on the site characterisation strategy used in this case study is given in Thornton and Wealthall (2008).

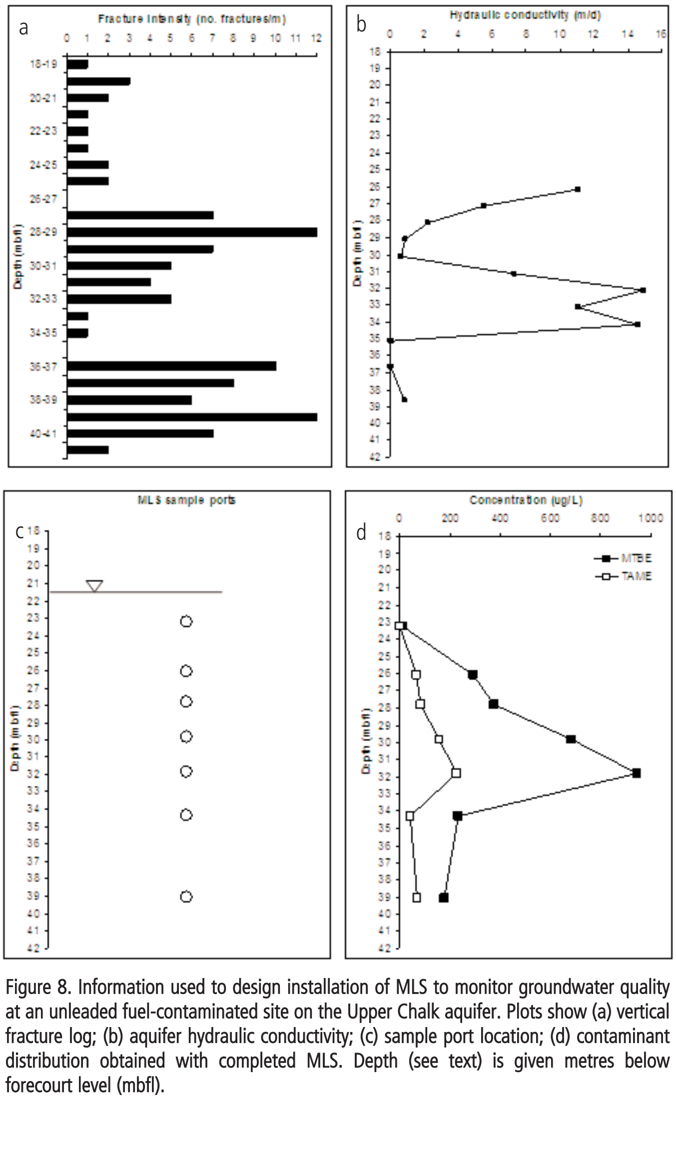

Figure 8. Information used to design installation of MLS to monitor groundwater quality at an unleaded fuel-contaminated site on the Upper Chalk aquifer. Plots show (a) vertical fracture log; (b) aquifer hydraulic conductivity; (c) sample port location; (d) contaminant distribution obtained with completed MLS. Depth (see text) is given metres below forecourt level (mbfl).

6. ACCURACY AND REPRESENTATIVENESS

Error is the difference between the measured and true value of a property, while uncertainty is the magnitude of variation around the true value, determined from repeat measurements. Unfortunately, in hydrogeology the "true" value of an aquifer property is often difficult to estimate, since many parameters (e.g. K) vary with scale. Therefore, the best quality parameterisation is that which derives K from data where sources of error and uncertainty have been minimised. Each hydraulic testing method discussed above has sources of error: experimental (measuring head, recording time), sampling (averaging, processing bias), and calculation (goodness of fit, validity of assumptions, appropriateness of equation used) are just a few examples. Experimental error can be easily reduced through care, experience, good planning, and using appropriate equipment. The use of semi- or fully automated data collection devices (i.e. pressure transducers for slug tests) significantly reduces experimental error, but requires careful calibration and maintenance to ensure data reliability. Sampling error can be addressed by selecting a test methodology consistent with the desired measurement scale or spatial resolution. Uncertainty can be quantified by performing replicate tests (which also gives an indication of method precision), but uncertainty cannot be reduced since it is inherent in the physical aquifer system. For example, relatively simple and inexpensive conventional pumping tests (even of discrete horizons) average K across the TZ, and thus embody greater uncertainty than grain size analysis of a core subsample. Where derived parameters are used in calculations to estimate others (e.g. mass flux or residence time), the error is propagated and uncertainty amplified. Thus it is desirable to reduce sources of error in the data acquisition.

Whether an estimated parameter is representative or not is more a function of whether the assumptions inherent in the chosen method were not violated and the limitations not exceeded. For example, the Theis method of pumping test interpretation assumes 1) perfect radial flow to the well, 2) aquifer isotropy and homogeneity, 3) the well screen is 100% efficient and 4) the aquifer is confined and of infinite extent. In most situations, at least assumption 2 is violated, and the derived K therefore not representative. The limits of the Hazen method of estimating K from grain size analysis is that d_{10} fraction should be between 0.1 and 3 mm. Also, there have been numerous methods developed to interpret pumping tests to account for partially or fully penetrating wells, unconfined, confined and leaky aquifers, and local boundary conditions (Krusmann and de Ridder, 2000). The specific aquifer scenario therefore needs careful consideration to select the appropriate pumping test method and mathematical interpretation to provide representative results.

There are many examples in the literature where favourable or unfavourable comparisons have been made of aquifer parameter values derived using different methods. The fact that there is no clear bias suggests that the differences are more a reflection of trying to compare different sets of assumptions and limitations rather than a measure of the accuracy and representativeness of any single method. It should also be kept in mind that each test method described above represents a certain scale of observation and so when values from two different methods are compared, the aquifer sample they represent is effectively different. For example, pumping tests average aquifer K values between the pumped well and the observation point, slug tests measure K near the well bore, and both permeametry and grain size analysis are performed on samples that do not preserve *in situ* grain and pore space configuration. The slug and dipole tests could be viewed as representing the *in situ* hydraulic properties of the aquifer best, as well as measurement at a scale most appropriate for the contaminant hydrogeologist. The debate is likely to carry on for some time, but for the foreseeable future the logical approach is to focus on fit-for-purpose data resolution with the potential bias and errors in mind.

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Further information

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