To Be or Not to Be a DUA? A Critical Review of Procedures Used to Identify Domestic Use Aquifers

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Abstract

In order to promote the protection of groundwater resources, Alberta Environment (AENV) recently introduced the concept of "Domestic Use Aquifers" (DUAs). The definition and characteristics of a DUA were first formalized in the 2007 Alberta Tier 1 and Tier 2 Soil and Groundwater Guidelines; these guidelines were updated in August 2008. Except for shallow saline groundwater, the definition of a DUA is independent of groundwater quality as the intent is to define and protect all aquifers for current and future needs. Soil contamination is a major concern for groundwater quality, especially when domestic use is involved. As a result, the ingestion pathway cannot be excluded under the Tier 1 Guidelines when a DUA may be potentially impacted. It is only possible to screen out the ingestion pathway using the Tier 2 Guidelines under certain conditions. As the degree of remediation needed for a contaminated site is guided by the vulnerability of the environment surrounding and underlying the site, properly identifying the presence or absence of a DUA underneath an impacted site is a key issue for environmental site assessment and remediation.

AENV defines a DUA by its hydrogeologic properties: thickness, bulk hydraulic conductivity and sustainable yield. AENV has provided two graphs defining a DUA based on thickness and hydraulic conductivity for confined and unconfined aquifers, respectively. An aquifer currently being used for domestic purposes or determined by AENV to be a DUA can also be classified as a DUA. Some general guidance is provided by AENV in the way to determine the hydraulic properties.

This paper will examine the rationale underlying the hydrogeologic definition of a DUA used by AENV and comment on the various methods for determining hydraulic conductivity (*K*) and their efficacy. The Farvolden or Q_{20} method, used to calculate the sustainable yield for a DUA, reaches its limit when the site hydrogeology is heterogeneous and complex. To properly examine the DUA pathway, both vertical and horizontal hydraulic conductivities are required. Common field techniques, such as pumping tests and slug tests, assess predominantly horizontal hydraulic conductivities while laboratory tests on Shelby tube samples using permeameters only provide vertical hydraulic conductivities determined on a small scale. Studies on *K* show that, in general, pumping tests would give the higher *K* values than slug tests and field tests usually give higher *K* values than laboratory tests even when vertical anisotropy is taken into account. The paper will also describe recent in situ techniques such as direct-push permeameter and hydraulic profiling to estimate *K in situ*. Finally, the definition of DUA should also take into account scale effects. In Alberta, most aquifers are highly heterogeneous in both their geometric and hydrogeologic properties and often are not continuous. Considering regional hydrogeology when defining a DUA may also lead to significantly different conclusions compared to a decision that is based on the AENV graphs using only the local aquifer thickness and hydraulic conductivity at a site of concern.

1.0 INTRODUCTION

For the purpose of selecting and applying a groundwater guideline for human health protection via the ingestion pathway, current Alberta Environment (AENV) guidelines (AENV 2008a) define a domestic use aquifer (DUA) as "a geologic unit (either of a single lithology or inter-bedded units) that is above the Base of Groundwater Protection having one or more of the following properties:

- A bulk hydraulic conductivity of 1 x 10^{-6} m/s or greater and sufficient thickness to support a yield of 0.76 L/min or greater; or
- Is currently being used for domestic purposes; or
- Any aquifer determined by Alberta Environment to be DUA."

More specific guidance regarding the definition of a DUA is provided in Appendix E of the Tier 2 guidelines document (2008b), which presents two "boundary curves" defining the hydraulic conductivities and corresponding minimum geologic unit thicknesses that would meet the DUA condition for confined and unconfined aquifers, respectively. In addition, to exclude the DUA (i.e. groundwater ingestion) pathway, there must be at least 5 m of massive undisturbed and unfractured fine-grained material with a bulk hydraulic conductivity that does not exceed 1 x 10^{-7} m/s for petroleum hydrocarbon contaminants. The document also indicates that the yield of 0.76 L/min is the 20-year sustainable yield, Q_{20}, calculated using the "Farvolden Method" (AENV 2008b). It also stipulates that aquifers with unit thickness less than 0.5 m or aquifers with groundwater having a total dissolved solids content > 4000 mg/L may be eliminated from being considered as DUAs.

The occurrence of a DUA beneath a site of concern has significant impacts on environmental practice. When a DUA is present, the groundwater ingestion exposure pathway will necessarily be included in determining remediation guidelines that, in most cases, will be lower. For example, the applicable Tier 1 remediation guideline value for benzene concentration in groundwater for a coarse-grained site under residential/parkland land use is 0.005 mg/L when the DUA pathway is included, and 0.140 mg/L (two orders of magnitude greater) when the DUA pathway is excluded (Table 2, AENV 2008a).

This paper examines the basis for the definition of DUA used by AENV and reviews the common methods for determining the hydraulic conductivity of an aquifer. Procedures are also proposed to properly quantify hydraulic conductivity, one of the parameters used to define a DUA.

2.0 THE FARVOLDEN (Q20) METHOD TO CALCULATE LONG-TERM THEORETICAL YIELD

AENV (2008b) presents the following equation to calculate the "long-term theoretical yield of an aquifer using the Farvolden Method":

$$[1] \qquad Q_{20} = 0.68 \times K \times b \times H_a \times 0.7$$

where Q_{20} is 20-year sustained yield (m^3/s), K is the bulk hydraulic conductivity, b is the thickness of geologic unit (m/s) and H_a is the available head (m). For confined aquifers, H_a is the distance between the non-pumping water level in the well prior to the pumping test and the top of the aquifer. For unconfined aquifers, H_a is chosen to be ⅔ of the difference between the base of the aquifer and the non-pumping water level of the well (or ⅔ of the saturated thickness).

An in-depth history of the "Farvolden Method" can be found in van der Kamp and Maathuis (2005). The key points are summarized as follows:

- The equation was developed by Farvolden in 1959 (in an unpublished Alberta Research Council Report) to determine the safe yield of a single pumping well when the well is drawing water from storage as evidenced by a continuously declining water level.

- Farvolden assumed that the long-term drawdown would be predicted by the Theis (1935) theory for a fully confined aquifer and, thus, would follow a straight line on a Cooper-Jacob (1946) semi-logarithmic plot.
- The pumping well would be depleted in 20 years (about 10 x 10^6 minutes); when plotted on a logarithmic scale the pumping duration from 0.1 minute to 10 x 10^6 minutes would span 8 $\log_{10}$-cycles.

Farvolden defined the "safe rate" of a pumping well as

$$[2] \qquad Q_{20} = \frac{4\pi T\left(H_a/8\right)}{2.30} S_f = 0.68 \times K \times b \times H_a \times S_f$$

where S_f is a safety factor (chosen to be 0.7 by Farvolden), T is the transmissivity ($=Kb$) and the other variables are as defined in Equation [1]. It can be seen that Equation [2] is the same as the AENV Equation [1]. As noted in van der Kamp and Maathuis (2005), Farvolden did not use the Q_{20} symbol – it was used here for easier comparison between the two equations. The "Farvolden Method" is also often referred to as the "Q20 Method"; this paper will adopt the latter terminology in subsequent discussions. The original intent of developing the Q_{20} parameter was to provide a means to compare general aquifer capability in regional hydrogeologic mapping in the Province of Alberta (Parks and Bentley 1996).

2.1 Limitations of the Q20 Method

As previously discussed, the Q20 Method was based on the Theis (1935) equation. Hence, the Q20 Method inherits the following idealization assumptions used by Theis:

- The aquifer is homogeneous, isotropic, fully confined and infinite in radial extent.
- Top and bottom boundaries of aquifer are horizontal flat and impermeable.
- The pumping well is fully penetrating and is approximated as a line source with zero radius, hence, it does not account for wellbore storage.

Many authors (e.g., Farvolden 1961; Bibby 1979; Parks and Bentley 1996; Weyer 2003; van der Kamp and Maathuis 2005) have recognized that there are very few, if any, aquifers that would satisfy these assumptions. They propose that, in order to properly estimate the 20-year yield, the drawdown in the pumping well should be evaluated using a pumping test and matching it with the theoretical drawdown curve that is most appropriate for the aquifer that is being tested. Van der Kamp and Maathuis (2005) also suggest that "for many cases the Farvolden Q20 tends to overestimate the long-term yield".

2.2 AENV Definition of a DUA Using the Q20 Method

Guidance on how to determine if an aquifer meets the definition of a DUA is provided in AENV (2008b). AENV suggests calculating the sustained yield of the aquifer using the Q20 method using the bulk hydraulic conductivity, K, and the geologic unit thickness, b. It is further stated that K *"must be determined using pumping test or slug test information from a sufficient number of piezometers/wells completed within the unit of interest"*. To simplify the DUA calculations, two curves (termed boundary curves) showing K versus minimum geologic unit thickness are provided for confined and unconfined aquifers, respectively. When these boundary curves are plotted on the same graph as shown on Figure 1, it can be seen that the definition of a DUA is very similar for both confined and unconfined aquifers.

When calculating Q_{20} for an unconfined aquifer using Equation [1], AENV uses ⅔ the saturated thickness as the available head, H_a. Substituting $H_a = ⅔b$ into Equation [1] and rearranging terms, one can obtain b for a given K and Q_{20} = 0.75 L/min (i.e. 1.27×10^{-5} m^3/s) as:

$$b = sqrt\left(3.98 \times 10^{-5} / K\right) \qquad [3]$$

where b is saturated thickness (m) and K is the hydraulic conductivity (m/s). Using Equation [3], the AENV boundary curve for unconfined aquifer is reproduced as shown in Figure 2. Based on this comparison, it would appear that, for an unconfined aquifer, AENV is using the saturated thickness as the geologic unit thickness.

For a confined aquifer, the procedure to obtain the DUA boundary curve is not as clearly described by AENV. AENV suggests "the available head (H_a) is equal to the distance between the non-pumping water level in the well prior to the pumping test and the top of the aquifer" (AENV 2008b). When one examines Equation [1], there are three unknowns: b, H_a and K, it would appear that an additional assumption would be necessary to obtain a K versus b relationship for a given Q_{20} of 0.76 L/min. If one assumes $H_a = 1.25b$, an acceptable match with the AENV derived values is achieved as shown in Figure 3.

It appears that AENV (2008b) uses the minimum sustainable yield of 0.76 L/min to identify a new DUA. This process requires two hydrogeologic parameters: the hydraulic conductivity of the unit of concern and the thickness of the geologic unit, which may make up of a single lithology or interbedded units. The bulk hydraulic conductivity "must be determined using pumping test or slug test information from a sufficient number of piezometers/wells completed within the unit of interest". For unconfined aquifers, the geologic unit thickness is the saturated thickness of the aquifer. For confined aquifer, the geologic unit thickness is less well defined and further guidance is required to define the available head, H_a.

3.0 METHODS FOR DETERMINING HYDRAULIC CONDUCTIVITY

In most cases, the hydraulic conductivity, K, of an aquifer can be defined in three orthogonal directions: x, y and z, with x and y the horizontal directions and z the vertical direction. While K_x and K_y are grouped as horizontal hydraulic conductivity, K_h or K_r. The vertical hydraulic conductivity (denoted as K_z or K_v) is most likely to be different especially in glaciated environments such as Alberta. Anisotropy ratios (K_r / K_z) can vary with the geologic formation or between laboratory scale and regional scale. Freeze and Cherry (1979) reported values of up to 10 from core samples of clays and shales and mathematically showed that regional anisotropy can be in the order of 100 or greater due to layered heterogeneity. Spitz and Moreno (1996), summarizing data from the literature, presented values of 1.5 to 40 for varved clays, 2 for shales and 10 for sand, silt and clay.

Hydraulic conductivity can be measured using either field or laboratory methods. Among the field techniques, pumping tests and slug tests are the most commonly used and they are the methods specified by AENV to estimate K when defining DUAs. Common to all geo-science projects, a conceptual site model (CSM) capturing the geological characteristics such as stratigraphy and extent of aquifers is a pre-requisite prior to any field or laboratory testing. Based on a CSM, pumping tests and slug tests are carried out in wells screened at the interval of interest in a geologic formation. In order to minimize the disturbance of the soil during well installation, an appropriate choice of drilling method and application of careful drilling technique are necessary (Sara 2003). Newer technologies such as the direct-push permeameter, the hydraulic profiling tool or the piezocone can provide continuous K profiles (although only qualitatively at present). Laboratory methods such as constant head permeameters using soil samples collected using Shelby tubes samples are most likely to estimate K_v. The procedures of these various methods and their pros and cons are discussed in the following sections.

3.1 Slug Test

The principle of a slug test is relatively simple and can be summarized as: measure the initial or static water level in a well, then introduce a near-instantaneous change in head in the well and measure the subsequent water levels in the well to obtain time-displacement (i.e. the change in head) data (Butler 1998). The change in head can be induced either by adding to or by removing from the static water column inside a well a slug of known volume. The water level in the well is then measured at timed intervals until at least 90% of the initial displacement has been recovered. This test is also known as a falling head test when water is added to the well or a rising head test when water is removed from the well. The recorded time-displacement data are then matched against theoretical models, such as Hvorslev (1955) and Bouwer and Rice (1976), to obtain an estimate of *K*. This analysis or matching step is usually carried out using spreadsheets, e.g. Halford and Kuniansky (2002), or commercial software, e.g. AQTESOLV® (HydroSOLVE 2007); AquiferTest (Schlumberger Water Services 2007). Butler (1998) provides a very comprehensive account of the slug test; consequently, this paper will only point out some of the key points regarding good slug test practice.

Time-displacement data from slug tests are affected by many factors including:

- The nature of the aquifer – confined, unconfined or leaky confined; aquifer thickness and anisotropy ratio.
- Well characteristics – well development and well geometry such as casing diameter, wellbore diameter, screened interval relative to the formation of interest, screened interval relative to the static water table, depth to the bottom of well (full penetration or partial penetration).
- The manner in which the slug is introduced – ideally the slug should be introduced or extracted in a near-instantaneous manner.
- Appropriateness of the analysis method – the method chosen needs to be consistent with actual site conditions.

Of these factors, Butler (1998) considers well development “the single most important aspects of slug tests”. During well installation, drilling debris is formed in the formation on the borehole wall. The debris is usually of lower conductivity thus creating a well-skin surrounding the filter pack. Well development aims at removing as much as possible this well skin and can be achieved by various method including overpumping, mechanical or air surging, and air lifting (Driscoll 1986). Butler (1998) shows that *K* can vary by as much as 2 orders of magnitude with well development, while Everts and Kanwar (1993) report an average increase in *K* of about 44% after 10 purgings for piezometers installed in a “loamy glacial till” aquitard.

An appropriate measuring device should be used to measure and record water level readings. For medium to high *K* formations, automatic dataloggers set at an appropriate logging interval would be the preferred measuring device; while an electrical tape (interface probe) would be acceptable. When using automatic dataloggers in a test lasting more than an hour, barometric compensation using either an additional logger to record barometric pressures or a vented cable will be required. Also, when first installed in a well, a datalogger may take up to 10 minutes for it to reach the same temperature as that of the groundwater.

During a slug test, the key parameters to be recorded are:

- Water level readings – these include the initial water level, the volume of slug added or removed, the water level immediately after adding or removed (used to calculate the initial displacement, H_o) and water levels during recovery.
- Effective casing radius – based on casing and borehole radius, sand pack porosity and permeability.

Butler (1998) recommends at least three slug tests should be performed in each well using different initial displacements and different flow directions (falling-head and rising-head). These tests enable the assessment of the effectiveness of well development (well-skin effect) and the evaluation of the suitability of the analysis methods for the time-displacement data obtained.

3.1.1 Estimating *K* from slug test data

From the time-displacement data obtained from slug tests, the *K* of a formation can be estimated by matching the data with analytical solutions. Each theoretical solution is formulated with its own set of assumptions regarding material properties (e.g., homogeneity, isotropy), domain geometry (e.g., axisymmetry, confined or unconfined aquifer), well geometry (full or partial penetration, screen interval relative to water table), and boundary conditions (e.g., infinite extent of aquifer, skin effects). To obtain a reliable *K* estimate, the chosen analysis method should reflect the actual site conditions. Table 1 summarizes, for common slug test analysis methods, the various parameters that are included in their derivation. In this paper, discussions will be limited to confined and unconfined aquifers of medium to low *K* (clay, silt to fine sand formations). Hence, in Table 1, methods that can account for oscillatory responses (indicating inertial effects) are not included since they are normally observed only in formations with high *K*s (coarse sands and gravels).

Table 1. Summary of Common Slug Test Analysis Methods (data from Duffield 2007)

Analysis Method	Aquifer Type	Wellbore Skin	Partial-Penetrating Well	Anisotropy Ratio	Formation Storage
Bouwer & Rice (1976), Bouwer (1989)	C / UC	N	Y	(PP)	N
Hvorslev (1955)	C / UC	N	Y	(PP)	N
Cooper et al. (1967)	C	N	N	N	Y
Dagan (1978)	UC	N	Y	Y	N
KGS (with skin effect) (Hyder et al. 1994)	C / UC	Y	Y	Y	Y

Note: C denotes confined; UC denotes unconfined
(PP) denotes for partial-penetration well only
Y denotes Yes; N denotes No
KGS denotes Kansas Geological Survey

The most commonly used solutions for slug test analyses are the Hvorslev (1955) and the Bouwer and Rice (1976) (B&R) methods due to their versatility (for confined and unconfined aquifers) the simplicity in their application (by fitting a straight line to the time versus logarithm of displacement data). Hvorslev was originally developed for confined aquifers while B&R was developed for unconfined aquifers. Bouwer (1989) observed that the water-table boundary in an unconfined aquifer has little effect on slug test response unless the top of the well screen is positioned close to the water-table; in this manner, Hvorslev and B&R can be extended to unconfined and confined aquifers, respectively. Brown and Narasimhan (1995), using numerical experiments, found that B&R “estimates of *K* were consistently superior to those obtained with Hvorslev” although B&R tended to underestimate *K* because of “the presence of a damaged zone around the well or when the top of the screen is close to the water table”. As shown in Table 1, KGS is the only method that encompasses all of the listed flow parameters including wellbore skin. The common analysis methods shown will provide a lower bound estimate for K_r (Butler 1998) and K_v is obtained indirectly through the anisotropic ratio used in obtaining a straight-line fit.

In order to ascertain whether skin effects and other factors might have affected bail test data, Butler (1998) recommends the following procedure for slug test analysis:

1. Compare measured initial displacement, H_0, with expected initial displacement, H_0^* - a lower H_0 indicates possible entrapped air in filter pack or an effective casing radius larger than the nominal casing radius (for wells screened across the water table).
2. Plot normalized displacement (H/H_0) versus logarithm of elapsed time (log t); a straight line plot is expected. When repeated tests with different H_0s are carried out, non-coincident H/H_0 versus log t curves indicate possible skin effect or deviation from conventional theory. Possible deviations from a straight line include: double-straight line effect for wells screened across the water table (Bouwer 1989) and a concave upward curve resulting from significant formation storage (Butler 1998).
3. For wells installed in confined aquifers or wells screened below the water table in unconfined aquifers, use Cooper et al. (1967). Storativity is evaluated by calculating the non-dimensionalized storage parameter, $\alpha = (r_w/r_c)^2 S_s b$, where r_w is the radius of the wellbore, r_c is the radius of the casing, S_s is specific storage and b is the thickness of the aquifer or depth of well penetration. When a reasonable S value is obtained, analysis can proceed using an appropriate conventional method: B&R, Cooper et al. or Hvorslev methods. Butler (1998) suggests that α should be greater than $1\text{x}10^{-6}$; a low α value indicates either significant vertical flow (for partial-penetrating wells in confined aquifers) or non-ideal conditions (e.g. skin effects) and the KGS method would be a more appropriate model.
4. For wells screened across the water table in unconfined aquifers, drainage from the filter pack and the change in effective well screen length corresponding to a change in H_0 need to be considered in the analysis. As an initial step, it is necessary to examine if the test response is dependent on H_0 using repeated tests. If the response is independent of H_0, then B&R is the method of choice; otherwise the Dagan method may be more appropriate.

In summary, the chosen analysis method for data obtained from a slug test should reflect the actual site conditions and the K estimates thus obtained are usually K_r. In addition, Butler (1998) recommends "that the hydraulic conductivity estimate obtained from a program of slug tests always be viewed as a lower bound on the conductivity of the formation in the vicinity" of the screened interval of the well.

3.2 Pumping Tests

In environmental practice, pumping tests are primarily conducted in order to identify the hydraulic properties of an aquifer such as transmissivity ($T = Kb$) and storativity ($S= S_s b$) and to determine possible hydraulic boundaries (including the nature of the confining unit, if present). In general, a pumping test is carried out by inducing a change in water level (head) by extracting water at the pumping well and measuring drawdowns at the pumping well and nearby observation wells over a time period.

Many aspects of the pumping test, such as an appropriate CSM, well development, screen interval and using appropriate measuring devices, are similar to those of the slug test as previously discussed. Addition factors that need to be considered for an effective pumping include the location of the observation wells and pumping durations.

If a pumping test is carried out with more than one observation wells, then reliable estimates of the storativity and the head losses in the well can be obtained (Neville, 2007). In addition, two or more lines of observational wells will help to estimate directional dependence of *K* and establish possible flow boundaries such as those imposed by surface water (constant head) or barriers (no flow). Kruseman and de Ridder (1990) recommend having at least one additional observation piezometer available.

Observation wells should be as small in diameter as feasible to minimize response time (Nielsen, 2005). The placement of observation wells depends on aquifer type, aquifer transmissivity, pumping duration, the discharge rate, screen length and whether the aquifer is stratified or fractured. It should be noted that the drawdown at an observation well is affected by the diffusivity (*T/S*) around the observation well and the flow from an extraction well is affected by the hydraulic conductivity of the formation radially beyond an observation well. In order to avoid the zone of vertically converging flow, the minimum distance between an observation piezometer and a partial penetrating pumping well can be estimated using:

$$[4] \qquad r_{obs} > 2b\left(K_r / K_v\right)^{0.5}$$

where r_{obs} is the distance between the pumping well and the observation piezometer and b the aquifer thickness (Midwest Geosciences 2007). Nielsen (2005) suggests this minimum distance should be $2b$. For a fully penetrating well, vertical flow is generally not a concern and spacing between pumping and observations wells can be spaced closer.

Pumping rate affects the signal-to-noise ratio for the measurements and, when constant extraction rate is attained, does not affect the test scale. The duration of pumping depends on the type of aquifer and the degree of accuracy desired in establishing its hydraulic characteristics. Theoretically, in an extensive aquifer, as long as the flow to the well is unsteady, the cone of depression will continue to expand as pumping continues. Better (more reliable) data are obtained if pumping continues until steady or pseudo-steady flow has been attained. Table 1 provides a summary of the average times to reach steady state for different types of aquifers.

Table 2. Average time to reach steady state for aquifers in unconsolidated formations (data from Kruseman and de Ridder 1994)

Aquifer Type	Average Time to Reach Steady State
Leaky	15 – 20 hours
Confined	24 hours
Unconfined	3 days

During a pumping test, the key parameters to be recorded are:

- Water level readings – data recorded using dataloggers should be barometric compensated.
- Time history of pumping rate.

Pumping well drawdown data from typical tests indicate that, compared to head losses in the formation, the additional drawdowns due to turbulence and skin effects are established relatively soon after pumping starts. Since the additional drawdowns are constant, the time rate of change of drawdown is a function only of the formation. Therefore, the Cooper-Jacob (discussed later) estimate of transmissivity is not influenced by skin effects and turbulent well losses (Neville 2007).

3.2.1 Estimating *K* from pumping test data

Similar to slug tests, *K* estimates can be obtained from pumping test data (well drawdown versus time) by comparing the data with plots derived from close-form analytical solutions; in this case, the analytical data can be straight-lines or curves (called type curves). A summary of the common analysis methods is presented in Table 3. Of these methods, the Theis (1935) solution is the most commonly used solution for confined and unconfined aquifers. However, Duffield (2007) and Neville (2007) recommend using Cooper and Jacob as an initial screening tool to investigate the effect of storativity on the solution for all aquifers. It should be noted that all of the methods summarized will provide an estimate for K_r and S, while estimates for anisotropy ratio (K_v/K_r) and aquifer thickness (b) can only be obtained when using a partial-penetrating well or in conjunction with observation well data.

Table 3. Common Analysis Methods for Pumping Test Data

Confined	Unconfined
Thiem (1906) - FP: Steady state solution Requires at least 2 observation points	
Theis (1935) / Hantush (1961) – FP/PP: • Plot log(dd) vs. log(time); • Match type curve • Can be used for variable pumping rate or step-drawdown • Use with Agarwal plot for recovery data	Theis (1935) / Hantush (1961) – FP/PP, • Plot log(dd) vs. log(time); • Match type curve – late time response to give *T* and S_y
Cooper-Jacob (1946) - FP: • Plot dd vs. log(time); • Straight line fit for late time. • Valid when u $\left(=\frac{r_w^2 S}{4Tt}\right) \leq 0.01$	Cooper-Jacob (1946) – FP, with Jacob's correction for dewatering of aquifer: • Plot dd vs. log(time); • Straight line fit – early-time (for *T, S*) and late time response (for *T,* S_y)
Papadopoulos and Cooper (1961) – FP with wellbore storage, finite diameter well; • Plot dd vs. log (time); • Match straight line with tweaking	Neumann (1974) – FP/PP: • Constant pumping rate • Plot log (dd) vs. log (time); • Select $\boldsymbol{\beta = (r/b)^2 (K_z/K_r)}$, match Type A curve to early time data to estimate T and S; match Type B curve to late time data for T and Sy.
Dougherty and Babu (1984) – FP/PP with wellbore storage , wellbore skin and formation storage • Plot dd vs. log (time); • Match straight line with tweaking.	Moench (1997) – FP/PP: • Added wellbore storage, wellbore skin and delayed observation well response to Neuman's solution.

Note: FP denotes fully penetrating well
PP denotes partially penetrating well
dd denotes drawdown

To facilitate fitting displacement-time data to a type curve, many authors have advocated using derivative plots and other diagnostic tools (e.g. Bourdet et al. 1989; Park and Bentley 1996). Table 4 summarizes the features of derivative plots and common diagnostic plots to screen pumping test data. Based on this screening, analysis methods that include the appropriate aquifer characteristics, such as skin effect and wellbore storage, can be chosen.

Table 4. Features of Common Diagnostic and Derivative Plots for Assessing Aquifer Characteristics [Data from Duffield, 2007]

Plot Type	Plot Axes	Feature	Flow / Aquifer Characteristics
Radial flow	s vs. log(t)	Late-time straight line	Radial flow in an infinite-acting confined aquifer
		Double straight line	Increase in slope in late time shows possible no-flow boundary. Decrease in slope in late time indicates possible river, recharge, leakage or K-contrast
		Reversed S-curve	Delayed gravity in unconfined aquifer
	log (s) vs. log (t)	Early-time unit slope	Wellbore storage
Linear flow	log (s) vs. log (√t)	Early-time unit slope	Linear flow to a single fracture with infinite K or uniform flux along the fracture
		Late-time unit slope	Linear flow in a strip aquifer (between 2 barrier boundaries, in plan view)
Derivative plots	$log(\frac{\partial s}{\partial \ln t})$ vs. $log(t)$ usually superimposed on a displacement vs. time plot	Zero slope	Cooper-Jacob straight line fit for confined aquifer
		Hump followed by zero slope	1½ log cycles from hump is the start of the Cooper-Jacob straight line
		Hump (or peak)	Wellbore storage
		Unit-half(1:2) slope	Linear flow in a channel (plan view) aquifer
		Oscillating with similar amplitude and no constant slope	Unconfined aquifer
		Oscillating with decreasing amplitude	Radial flow in a double-porosity confined aquifer

Note: s denotes displacement, t denotes time

3.3 Other Methods of Estimating *K*

AENV (2008b) states that saturated hydraulic conductivity, *K*, is “usually measured by performing bail tests or slug tests on a monitoring well, but is also sometimes measured in the laboratory on undisturbed soil samples. Hydraulic conductivity is measured for the soil strata through which groundwater is flowing, especially more permeable strata which may dominate groundwater flow. If measured from a monitoring well, the well must be screened across the stratum of interest”. As previously discussed, bail tests and pumping tests will usually provide direct estimates for the horizontal hydraulic conductivity (K_r) and indirect estimates of vertical hydraulic conductivity (K_v) through anisotropy ratios. In evaluating vertical separation between contamination and a DUA, K_v can be measured in the laboratory using vertical samples collected using Shelby tubes. In this section, laboratory methods and other more modern methods for determining *K* are discussed.

3.3.1 Laboratory Methods

Laboratory tests to determine K are most commonly performed on small, “undisturbed” soil samples collected during field investigation. Traditionally Shelby tube sampling is the most common “undisturbed” sampling technique used in environmental practice. The laboratory apparatus commonly used are either the constant-head permeameter or the falling-head permeameter (Bowles 1992). Since the soil sample is collected in the vertical direction, these methods provide an estimate of K_v. In Alberta, the constant-head test is more commonly used. K_r can also be measured using a radial flow test which uses a cell with a central sand drain and a porous outer boundary (Olson et al. 1981); however this is not commonly used. In this case, the sample may have to be remoulded.

Laboratory grain-size analyses can also be used to provide indirect estimates of K. A number of formulae (such as Hazen and Kozeny-Carmen) have been proposed to relate some measure of grain-size distribution of granular porous media to hydraulic conductivity. These theoretical relationships are usually developed using the Navier-Stokes equations and models of the porous medium. A comprehensive summary of K estimation methods using grain-size distributions can be found in Fredlund (2004). The grain-size methods can usually provide K estimates to within one to two orders of magnitude (Cronican and Gribb 2007).

3.3.2 Recent advances in direct-push (DP) technologies

The basic principles of all DP systems are similar: a small diameter rod string, with sensors at its lower end, is pushed into the subsurface using a hydraulic ram, sometimes assisted by a high-frequency hammer, acting against the weight of a large truck (Sellwood et al. 2005). DP technology is usually used in relatively shallow, less than 20 m depth, unconsolidated formations (finer than coarse gravels). Traditionally, Shelby tube samples are collected using a form of DP technology. The more recent variants can collect samples using dual tube samplers (Geoprobe Systems 2007), install small-diameter temporary or permanent monitoring wells and collect *in situ* geophysical, geochemical and geotechnical measurements of subsurface conditions (Sara 2003, USEPA 2005). Each *in situ* method gives different result with its accuracy depending on whether K is obtained directly or need site-specific correlation to obtain an estimate. In this latter case, caution is advised in the interpretation of the results. Because of their speed and smaller volume of drill waste generated (Kram et al. 2001), DP technologies can be used at more locations at a site to assess the spatial variation of K. However, it should be noted that the pushing of soil material creates a zone of compaction in the immediate vicinity of the DP tool and may influence K estimates (Butler et al. 2001).

Hydraulic Profiling

Hydraulic profiling can be used to provide vertical profiles of lithological and hydrological information in a single borehole (Healey and Sellwood 2004). The common hydraulic profiling tools include the Waterloo Profiler (Cho et al. 2004) and Hydraulic Profiling Tool (HPT) (Geoprobe Systems 2007). The HPT combines a downhole pressure transducer with an electrical conductivity (EC) probe at the tip of the push rod. As the push rod is being advanced at a speed of about 1 ft/min (0.3 m/min) (Barritt, R. private communication), water is injected into the soil at a constant rate (up to 300 mL/min). The transducer measures the pressure response of the soil to the injection of water while EC is measured simultaneously. A relative low-pressure response would suggest a relatively large grain-size and be indicative of a zone with higher K values. A relatively high-pressure response however would indicate a relatively small grain-size and lower K values. Static pressure measurements can also be made by stopping at discrete depths, thus allowing the static water pressure to be determined. EC profile is useful for determining the lithological variations (fine-grained versus coarse-grained) within the substrata. The HPT usually plots EC, maximum injection pressure and maximum flow rate against depth as shown in Figure 4. These plots provide a qualitative representation of the variation in K with depth. In a recent paper, Dietrich et al. (2008) developed a relationship linking *K* to the injection pressure and flow rate; however, this relationship requires parameter calibration using actual *K* values.

Methods are currently being developed so that HPT can be used for direct slug testing to determine actual hydraulic conductivity values (e.g. Butler et al. 2000, Sellwood et al. 2005, Knobe 2006). These methods are usually carried out at discrete depths by stopping the probe and performing slug tests. In this manner, they allow multi-level slug testing in a single probe hole without drilling and installing a permanent well.

Direct-push permeameter

The direct-push permeameter (DPP) is another approach for obtaining high-resolution information about vertical variations in hydraulic conductivity in shallow unconsolidated formations. The DPP is a small diameter tool with a short-screened section and a pair of pressure transducers that are inset into the tool above or blow the screen. The tool is attached to a string of steel pipe and advanced into the subsurface by pushing, while water is injected through a tube in the trunk line to keep the screen clear. On reaching a depth at which a *K* estimate is desired, pushing and injection are stopped and excessive pressure heads are allowed to dissipate. A short hydraulic test is then performed by injecting water through the screen at a constant rate (less than 4 L/min) while pressure changes are monitored at the transducers locations. Butler et al. 2007 describe an analysis method for the DPP uses the pumping-induced head gradient between the 2 transducers.

DPP can provide accurate high-resolution *K* estimates that are in good agreement with estimates obtained through other means, under conditions commonly faced in the field (Liu et al. 2007). The DPP can be used to accurately characterize *K* variations along a vertical profile. However, a defensible characterization of the lateral continuity of layers cannot be obtained from one or a series of DPP profiles. Limitation of the method is also the relatively low depth achieved and the vulnerability of the *K* estimates to the effects of media alteration. In certain conditions, vertical channels can be created along the pipe leading to implausibly high *K* estimates. (Butler et al. 2007). At present, the DPP is still at a prototype stage and is not available for industrial use.

Direct push cone-penetration testing

The direct push cone penetration testing (CPT) measure the resistance on the tip of a cylindrical rod with a conical point pushed through the soil at a constant rate (cone resistance) by a mechanical or hydraulic system (Sara 2003). Depending on the sensors attached, CPT can sense soil stratigraphy, relative density, shear strength, equilibrium groundwater pressure, pore-water pressure and resistivity. (Conetec 2003). Similar to hydraulic profiling, a profile of hydraulic conductivity can be inferred from pore-water pressure measurements using an electrical piezocone. However, excessive pore-water pressures are only generated when the cone is pushed through saturated soils.

Geophysical methods

Geophysical methods can also be used to provide qualitative indications of stratigraphic and soil water content variations. Advantages of geophysical methods include their ability to determine properties of soil that cannot easily be sampled, avoid sample disturbance that may influence laboratory testing and test a volume of soil or rock that is larger than that which can be tested in the laboratory (Sara 2003).

This paper will limit discussions to downhole geophysical methods in which a probe with the appropriate sensors is slowly lowered into a borehole. For environmental investigations and in order to prevent cross-contamination, the borehole is usually cased using a 2” (0.05 m) diameter PVC pipe. The downhole geophysical logging methods that can be used in PVC-cased holes and the parameters they measure are summarized in Table 5 using data from USEPA 2001 and Benson 2006. They include natural gamma, neutron, electrical induction (conductivity) and electrical resistivity logging. Of these methods, natural gamma and electrical induction are especially helpful in determining lithology. Natural gamma logs record the amount of natural gamma radiation emitted by the formation surrounding the borehole. Clays or shales typically emit relatively high amounts of gamma radiation. Electrical induction uses an electromagnetic method to measure the electrical conductivity (EC) of a formation. EC is a function of soil and rock type, porosity, permeability and the pore-fluids. Variations in EC with depth may indicate changes in clay content, hydraulic conductivity or fractures (Benson 2006). Typical natural gamma and EC logs are shown in Figure 4.

Table 5. Summary of Common Downhole Geophysical Methods Used in PVC-Cased Boreholes.

Downhole Log	Properties Measured	Potential Application	Radius of Measurement
natural gamma	natural gamma radiation	lithology related to clay/silt contents	6 to 12 in.
neutron	hydrogen content	saturated porosity, moisture contents	6 to 12 in.
induction	electrical conductivity	conductivity, changes in clay contents, permeability or fractures	30 in.

3.4 Spatial variations in *K*

Numerous studies have demonstrated that spatial variability in *K* is the norm rather than the exception and its importance in controlling solute transport (e.g. Sudicky 1986, Sudicky and Huyakorn 1991, Butler 2005). For example, in a detailed investigation of a 2.25 m thick sand aquifer covering approximately 1,200 m^2, the hydraulic conductivity varied between $1x10^{-5}$ m/s and $2x10^{-4}$ m/s (Sudicky 1986).

However reliable in giving direct estimate of *K*, pumping tests and slug tests do not provide information about spatial variation in hydraulic conductivity between wells. Pumping tests will yield an average hydraulic conductivity estimate over a relatively large volume of an aquifer; while slug test *K* estimates is heavily weighted towards the properties of the formation in the immediate vicinity of the screened interval (Butler 2005). As discussed in the previous section, direct push methods and downhole geophysical methods can only provide qualitative *K* estimates up to about 0.15 m from the wellbore. Although more modern methods such as borehole-flowmeter tests, multi-level slug tests and dipole-flow tests can provide quantitative estimations of variations in K along the screened interval of a well, they are still limited to providing information about the formation in the immediate vicinity of the well in which they are used (Butler 2005).

Given the relative small number of wells at most sites (and the cost of drilling and installing new ones), more attention needs to be given to the development of techniques that can provide information about *K* variations between wells. Currently the most direct approach for obtaining information about *K* variations between wells is to monitor the movement of tracers through the unit of interest (Butler et al. 2007). Logistical cost and regulatory constraints significantly restrict the use of tracers for site characterization activity. Recently, Yeh and Lee (2007) advocated the use of hydraulic tomography, which is a cross-hole hydraulic test followed by inversion of all the (pumping and drawdown) data to map the spatial distribution of aquifer hydraulic properties, to obtain much detailed subsurface characterization beyond the reach of traditional technologies.

3.5 Comparing *K* Estimates from Slug Tests and Pumping Tests – Size Effects

Differences between *K* estimates from slug test and pumping testing have been the subject of numerous journal articles, most of the time imputing scale effect. In fact the duration of most pumping tests is on the order of hours to days and thus the formation that is affected by the average pumping tests, is considerably larger than that affected by a slug test lasting only for minutes or hours. For example, in a sandstone aquifer, the long-term pumping test has a radius of influence of approximately 10,000 m giving a value of *K* at a regional scale. The lab test have values at about one thousandth that of the regional value, while small-scale field measurements slug-test has values at about one tenth of the regional value (Bredehoeft et al. 1983). However it is known that for a given well the use of one or another of these two methods will give different results, pumping test generally giving the higher *K* values (Butler et al. 1998). Schulze-Makuch et al. (1999), based on data collected from 39 geological formations ranging between 1 and 100,000 m^3 in volume tested, reported that In heterogeneous porous media, half an order of magnitude *K* increase with each order magnitude increase in the volume of material tested in heterogeneous unconsolidated media and an order of magnitude increase in *K* in fracture flow media.

Rovey (1998) suggests the increase in hydraulic conductivity with scale is a natural consequence of heterogeneity; possibly, high conductivity heterogeneities are more effective in raising hydraulic conductivity over the regional scale than at local scale. Using a numerical model, he concludes that “as the scale increases, a greater portion of the flow occurs within the high-conductivity heterogeneities. Therefore, as the test area enlarges under radial flow, the weighting is shift more and more toward the high-conductivity heterogeneities”.

On the one hand, Chapuis et al. (2005) assessed hydraulic conductivity at three different scales within an unconfined sand aquifer in Lachenaie, Quebec. On the small scale, 0.25×10^{-3} m^3 to 1×10^{-3} m^3, *K* was estimated from grain-size curves and the three methods of Hazen, NAVFAC and Chapuis. On the intermediate scale, 0.05 m^3 to 0.10 m^3, was estimated by falling head/slug tests, and on the large scale, >6.0 m^3, by pumping tests. Their study revealed no significant scale effect for this sand aquifer but pointed out that at a very small scale (<1 cm) or a very large scale (regional), scale effects may become significant.

Hendry (1982) demonstrated that fractures in till in Alberta significantly modified the overall *K* of aquifers. Tills can be separated into two zones: a weathered zone in the upper part and the un-weathered zone in the lower part. Field and laboratory methods discovered two different fracture patterns: a main pattern and a second pattern filled and coated with different kind of oxides with two separate populations of hydraulic conductivities. A higher *K* attributed to the large-scale fractures and lower *K* attributed to small-scale fractures. Excluding the effect of fractures, both weathered and non-weathered tills had a very similar texture and matrix, with a very low *K*.

Butler and Healey (1998) propose that, prior to using a natural scale dependence to explain the difference between pumping test and slug test results, drawdown data should be closely examined and consideration given to incomplete well development and uncertainty concerning aquifer thickness and vertical anisotropy. Failure to account for incomplete well development (or a low-*K* skin) and, to a lesser extent, vertical anisotropy can result in a *K* estimate from a slug test that is much lower than the average *K* of the formation. By contract, when using semi-log analyses or using observation well data, *K* estimates from pumping tests are not significantly affected by a low-*K* skin or vertical anisotropy.

3.6 Stratified Formations

For interbedded geological units, AENV (2008b) states “for the purpose of the definition of a DUA, both single lithological units and interbedded geological units must be considered. Many of the bedrock units in Alberta are composed of deltaic deposits, which as a result of the depositional environment are lenticular and discontinuous. Therefore, these units should be considered a single hydrostratigraphic unit". In the following discussion, the effect of stratification on K is examined.

Terzaghi and Peck (1948) provided the following discussion on the "permeability of stratified masses of soil". For flow parallel to bedding planes, the equivalent hydraulic conductivity, $\overline{K}$, for flow parallel to the bedding planes, is given by

[5] $$\overline{K} = \frac{\sum_{i-1}^{n} K_i h_i}{\sum_{i=1}^{n} h_i}$$

where K_i and h_i are the hydraulic conductivity and thickness, respectively, of the i-th layer of soil. This equation was derived assuming the flow in each layer was occurring under the same hydraulic gradient. Lefkovits et al. (1961) and Sokol (1963) obtained the same equation for flow to a vertical well penetrating a number of horizontal layers. Since both K and thickness of each layer will affect $\overline{K}$, Equation [5] shows the importance of screening a well only in the zone of interest.

For flow at right angles to the bedding planes, based on the principle of continuity of flow, Terzaghi and Peck (1948) calculated the equivalent hydraulic conductivity, $\overline{K}$, for flow perpendicular to the bedding planes as

[6] $$\overline{K} = \frac{\sum_{i-1}^{n} h_i}{\sum_{i=1}^{n} \frac{h_i}{K_i}}$$

Equation [6] can be used to calculate the average K for the stratified soils that make up the zone of separation between contaminated groundwater and a DUA.

4.0 DISCUSSION

AENV (2008b) defines a DUA as an aquifer having a bulk hydraulic conductivity of at least 1×10^{-6} m/s and sufficient thickness to support a (20-year) sustainable yield of at least 0.76 L/min. Bulk hydraulic conductivities must be determined using pumping tests or slug tests from a sufficient number of wells completed within the unit of interest. Unit thickness can be determined using site borehole information and data from Alberta Environment Water Well Record Database. In addition, the DUA pathway can be excluded by geologic barriers, between the contaminated zone and the DUA, when at least 5 metres of massive, undisturbed, unfractured fine-grained material meeting appropriate guidelines with a bulk hydraulic conductivity that is at least 1×10^{-7} m/s, or an equivalent thickness of natural geologic material supported by technical information regarding its lithological properties. The 5-metre thickness is applicable only to petroleum hydrocarbon contaminants. It would appear that, when making these recommendations, AENV is referring to the horizontal hydraulic conductivity, K_h, when considering sustainable yield and referring to vertical hydraulic conductivity, K_v, when considering barriers. In addition, AENV has included some form of attenuation of the contaminant when migrating through a geologic barrier.

Accepting that a 20-year sustainable yield of 0.76 L/min as the appropriate definition for a DUA, it is unclear as to how the boundary curve (limiting geologic unit thickness versus K curve) for confined aquifer was derived. There are also uncertainties regarding K estimates obtained from pumping tests, slug tests and laboratory tests. Previous discussions in this paper have pointed out that, in general, K estimates increase with the size of material tested: K from laboratory sample < *K* from slug tests < *K* from pumping tests. In addition, K_v (obtained from laboratory testing) is usually significantly smaller than K_h (obtained from *in situ* well testing). The question arises as to which is the appropriate method to determine *K* for DUA identification. Since it is unlikely that 100% well development can be achieved, Butler (1998) recommends that the hydraulic conductivity estimate obtained from a program of slug tests always be viewed as a lower bound on the conductivity of the formation in the vicinity of the well.

To obtain K estimates from pumping tests and slug tests, the test data (time-drawdown curves) are usually matched against theoretical solutions employing various idealization for aquifer conditions. Reliable estimates can only obtained when the actual aquifer condition are incorporated in the assumptions used the analysis method. The important aquifer conditions included aquifer type (confined or unconfined), anisotropy ratio, wellbore storage, skin effects and well penetration.

If testing methods are limited to pumping tests and slug tests, it would be impossible to obtain information on the spatial variability of *K*. Yeh and Liu (2007) recommend using hydraulic tomography to assess spatial variability; in addition, Walton (2008) suggests using more robust numerical methods to estimate *K*.

5.0 RECOMMENDED PROCEDURE FOR DETERMINING A DUA

The section presents a procedure to standardize the identification of DUA within our company. The following procedure takes into account of commonly accepted practice, currently available technology and software.

- Formulate a conceptual site model (CSM) of the site of interest based on as much site information as available regarding soil stratigraphy as well the nature and the extent of contaminations. These data are used to determine whether the existence of a DUA needs to be considered and, if so, whether a geological barrier exists. A CSM is a living document that requires updating as more information becomes available.
- On a site with insufficient stratigraphic information, use direct push HPT or geophysical logging to obtain qualitative stratigraphic profile and determine screen intervals for *in situ* hydraulic testing (pumping tests or slug tests). HPT can be used in formations finer than fine gravels; for coarser formations, downhole geophysical logging may be required subsequent to drilling and installing a well.
- Drill and install wells for *in situ* hydraulic testing. Well screen lengths and depths are determined using HPT or geophysical results. During drilling, Shelby tube samples may be collected for laboratory determination of K_v and grain-size distribution analyses. For a typical service station site, at least three test locations are recommended. Subsequent to well installation, wells should be adequately developed (e.g. using turbidity as a yard-stick).
- Carry out in situ hydraulic testing. If slug testing is to be performed, the use of a solid slug is recommended – using a solid slug, a falling-head test (when the solid slug is introduced) is naturally followed by a rising-head test (when the slug is removed). If a pumping test is to be carried out, it should last an adequate time period.
- Obtain K estimate using an appropriate method of analysis.

Figure 6 illustrates the results of tests carried out at a site to identify a possible DUA. The tests carried out included HPT, laboratory constant head permeameter tests on Shelby tube samples, and a rising-head slug test. Also shown in this figure are the approximate depth of petroleum hydrocarbon (PHC) impact, the screened length of the well used for slug testing and the soil classification using visual inspection of samples obtained during drilling. The HPT pressure profile shows up the non-homogeneity in K_h – a higher injection pressure would indicate a lower K value. The K_v values in m/s obtained from laboratory testing are 7.9 x 10^{-10} (at 2.4 m below ground surface [bgs]), 3.6 x 10^{-7} (at 7.6 m bgs), 4.9 x 10^{-8} (at 10.6 m bgs) and 4.2 x 10^{-9} (at 14.3 m bgs). Based on the HPT results, a vertical well was installed screened between 9.0 m and 15.2 m. The geometric mean of two ball test analyses results was 1.4 x 10^{-6} The DUA pathway was ruled out because there was more than 5 m of geological barrier (with $K_v < 10^{-7}$ m/s) separating PHC impact and any possible DUA below the maximum depth of investigation of 16.2 m.

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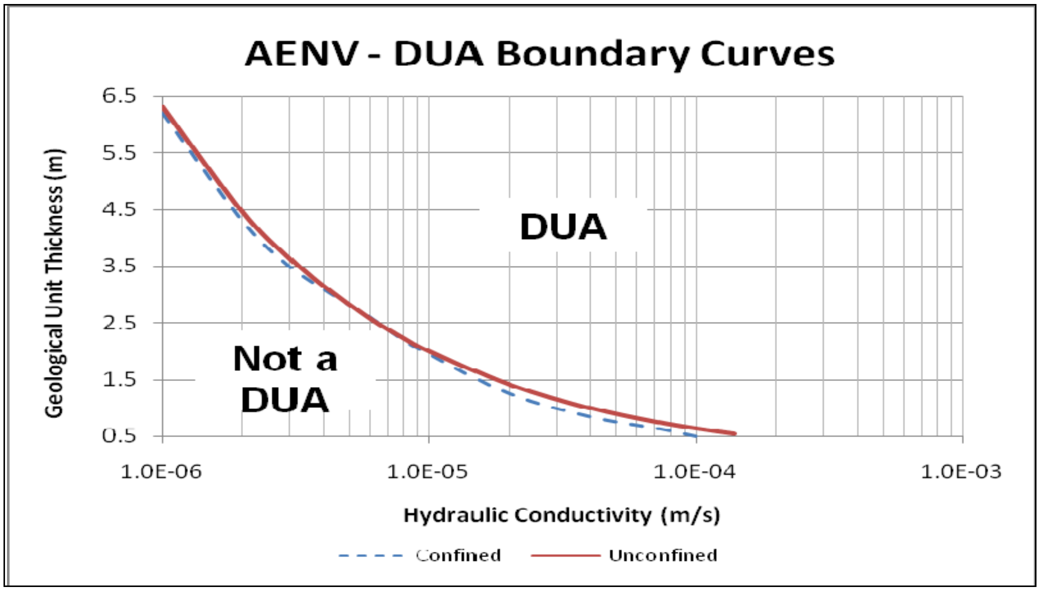


Figure 1. AENV DUA Boundary Curves Defining Limiting Conductivity and Thickness Values for Confined and Unconfined Aquifers (Data from AENV 2007b)

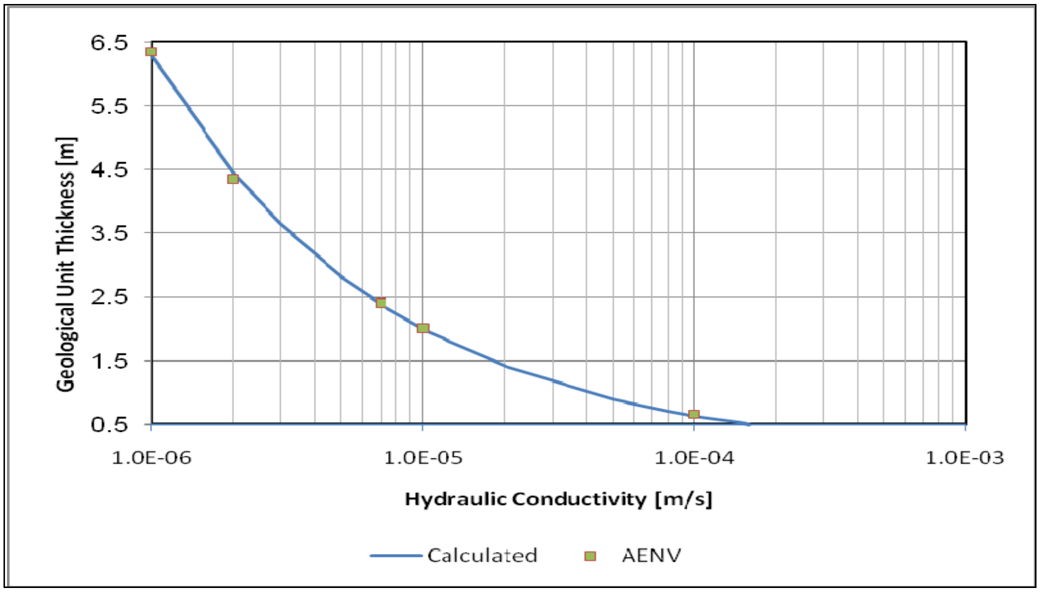


Figure 2. DUA Boundary Curve for Unconfined Aquifers – Comparing Calculated Values with AENV Boundary Chart

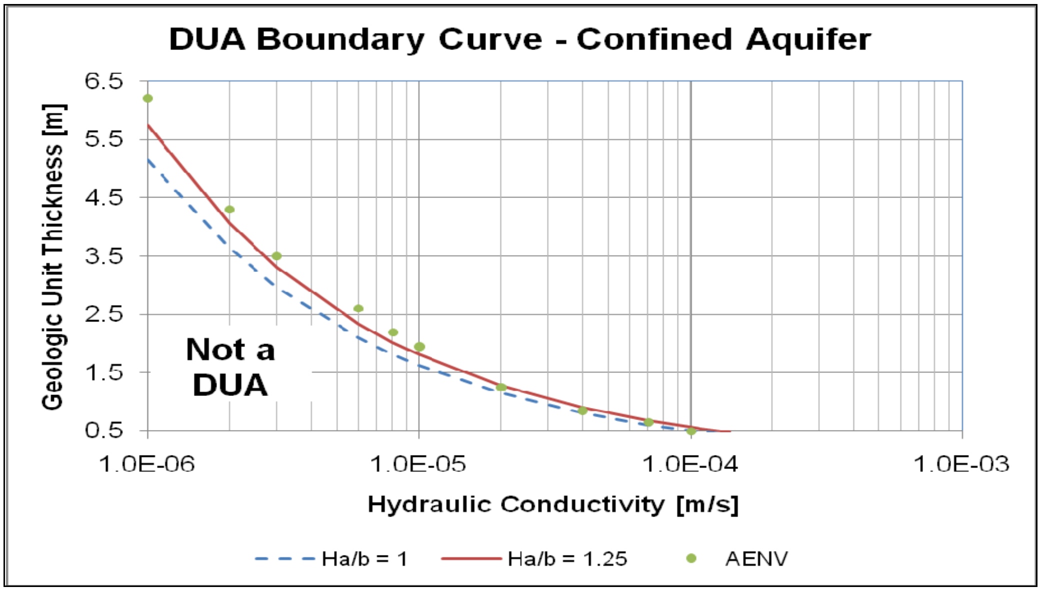


Figure 3. Matching the AENV DUA Boundary Curve for a Confined Aquifer by Varying H_a/b Ratio

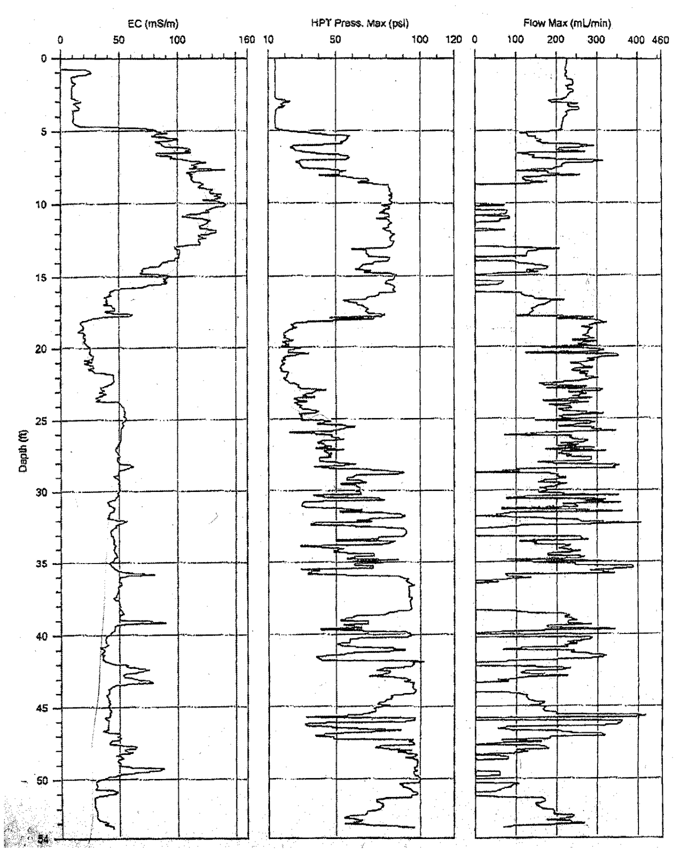


Figure 4. Typical HPT Output Showing Stratigraphic Variation – peaks in EC and injection pressure plots indicate finer-grained soils

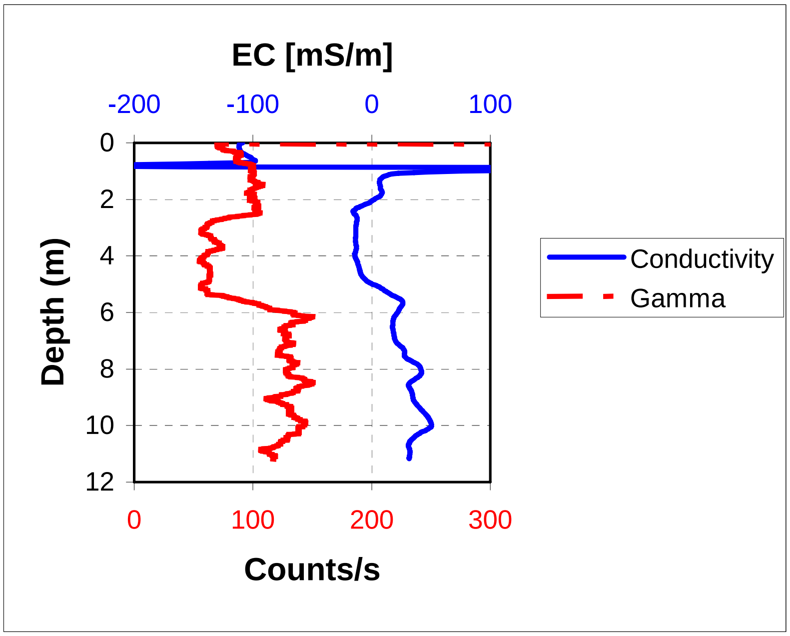
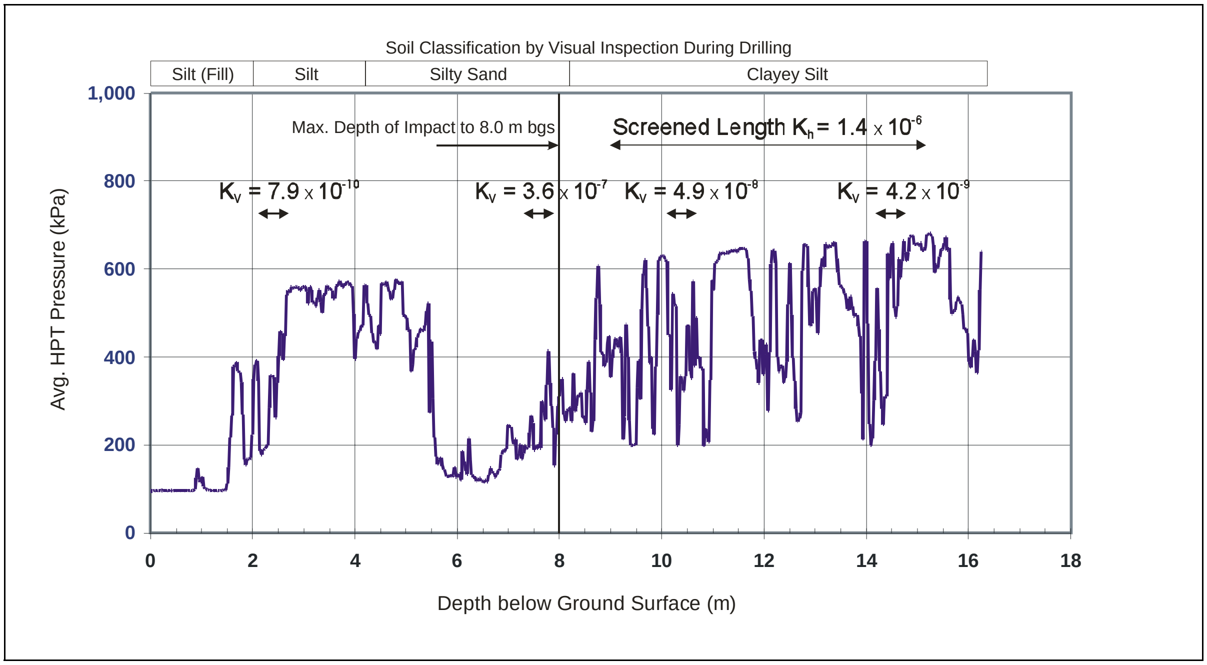


Figure 5. Typical Downhole Geophysical Logs Showing Natural Gamma and Electrical Conductivity (EC) Plots



K_h: geometry mean of horizontal hydraulic conductivity from slug test [m/s] fr

K_v: vertical hydraulic conductivity from laboratory test [m/s]

Figure 6. HPT Injection Pressure Profile and Variation of K Values with Depth