ground water

Determining Hydraulic Conductivity Using Pumping Data from Low-Flow Sampling

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Abstract

Hydraulic conductivity values computed using the steady-state discharge and drawdown attained while low-flow sampling were evaluated to determine if they were equivalent to those determined from slug testing. Based on testing 12 wells, it was found that the results were statistically equivalent. Conductivity values computed using low-flow sampling parameters were also evaluated as to their reproducibility in actual practice by analyzing consultant data for three wells sampled over three quarterly monitoring periods by four field technicians. The results were found to be reproducible within about a factor of 2 or better. Since the method is based on only one pair of parameters, diligence is required in attaining steady state and in accurately measuring the flow rate and drawdown. Conductivity values computed using this approach can enhance the use of low-flow data gathered in water quality sampling, avoid the need for slug testing in a subsequent phase of investigation, and help reduce the cost of characterizing sites when multilevel samplers are used. Given the practical range of discharge in low-flow sampling, the method was found to be applicable at conductivity values somewhat greater than 10^{-6} cm/s. Given the typical accuracy of water level meters and pressure transducers and a maximum discharge of 1 L/min, as mandated by regulatory guidance, the method has a calculated upper conductivity limit in the range of 10^{-3} to 10^{-2} cm/s.

Introduction

Following the publication of Puls and Barcelona (1996), the U.S. EPA and many state environmental regulatory agencies adopted guidance for the collection of ground water quality samples using low-flow sampling. This in turn has spurred on environmental equipment suppliers to develop pumping and flow cell systems to monitor low-flow sampling parameters. Typically, low-flow sampling entails pumping at a low discharge rate (less than 1 L/min), adjusted to minimize drawdown, until a steady-state drawdown is achieved and indicator parameters are stabilized. Drawdown and discharge may be monitored and recorded periodically using a water level tape and through timing the quantity of water that fills a graduated cylinder to some level (U.S. EPA, Region 1 1996). Alternatively, they may be continuously monitored in automated low-flow sampling systems (e.g., QED Environmental Systems 2008).

Following sampling, and typically during a subsequent phase of deployment, slug testing is performed to determine hydraulic conductivity. Slug testing has become the most widely means of characterizing hydraulic conductivity at contamination sites owing to, among other factors, its simplicity and the avoidance of disposing of large quantities of contaminated water (Butler 1997).

In this study, we assessed the use of the steady-state discharge and drawdown attained during low-flow sampling to determine hydraulic conductivity as an alternative to slug testing. Our assessment entailed two parts. First, we statistically compared hydraulic conductivity values computed using steady-state discharge and drawdown from a sampling round conducted using low-flow

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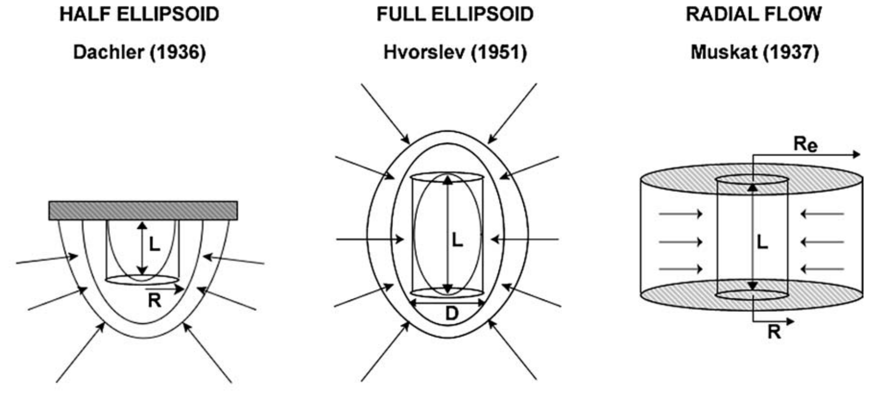
sampling with previously determined slug test results. Second, to assess reproducibility under real world conditions, we analyzed data from field notes obtained from a consulting firm that had been recorded by four different field technicians who collected samples at three wells over three quarterly rounds of sampling. If results were found to be comparable to that of slug tests and reproducible, one could avoid an additional phase of deployment to determine hydraulic conductivity. Furthermore, it would enhance the value of low-flow sampling data. It would provide hydraulic conductivity values indicative of conditions during the time of water quality sampling. It would provide a convenient method for monitoring changes in hydraulic conductivity values owing to, among other causes, alterations in ground water geochemistry induced by remediation methods (e.g., Johnson et al. 2008). Such a method would also be a means of reducing effort and cost associated with conducting enhanced site investigations that entail the use of multilevel well clusters.

Methodology

Useful formulas for analyzing steady-state flow to wells are shown in Figure 1. The formula from Dachler (1936) is based on flow to a line source that partially extends downward or upward from an impermeable boundary. Equipotential surfaces form semiellipsoids. The formula provides an approximate solution for a cylindrical intake where L is much greater than R. The full ellipsoid formula was presented by Hvorslev (1951) by applying mirror imaging to the Dachler equation. Flow lines and equipotential surfaces are symmetrical with respect to the horizontal plane through the center of the intake. In this case, equipotential surfaces form full ellipsoids. The solution is approximate for a cylindrical intake where L is much greater than D. It applies to the case where the well screen is fully submerged and surrounded by uniform material. It should be recognized that these formulas form the bases for the Hvorslev slug test equations derived by equating Q to $\pi r_c^2 \frac{dh}{dt}$ (where r_c is the radius of the riser, and dh/dt is the rate of change in water level in the riser) and integrating the head as a function of time. The equation from Muskat (1937) is applicable to radial flow to a fully penetrating well. It is also applicable to a partially penetrating well, where one assumes formation anisotropy constrains flow to radial flow. The equation from Muskat (1937, figure 12, case 9) was used by Hvorslev (1951) to derive a slug test relation for radial flow. The slug test form of the radial flow model is generally referred to as the Bouwer and Rice equation, following their work to derive a means to estimate R_e and to correct for backfill zone drainage and recovery (Bouwer and Rice 1976; Bouwer 1989). Their method to derive R_e is applicable in solving the Muskat equation.

Henebry and Robbins (2000) developed a linear regression approach to determining hydraulic conductivity using the equations in Figure 1. Their method involved conducting pumping at three or more flow rates to determine corresponding steady drawdowns. The pairs of drawdown and discharge data were then regressed and hydraulic conductivity values determined from the slopes of the discharge-drawdown curves. Using this approach, Bartlett et al. (2004) compared hydraulic conductivity



$$Q = \frac{2\pi LKH}{2.303\log\left[\frac{L}{R} + \sqrt{1+\left(\frac{L}{R}\right)^2}\right]} \qquad Q = \frac{2\pi LKH}{2.303\log\left[\frac{L}{D} + \sqrt{1+\left(\frac{L}{D}\right)^2}\right]} \qquad Q = \frac{2\pi LKH}{2.303\log[R_e/R]}$$

Where:
Q = steady state flow rate
L = intake length
K = hydraulic Conductivity
H = steady state drawdown
R = intake radius
D = intake diameter
R_e = radius of influence

Figure 1. Constant flow rate models.

values derived from slug tests and steady-state pumping tests. They showed that hydraulic conductivity results obtained by steady-state pumping (13 tests that entailed at least 3 flow rates each) were statistically equivalent to slug test results (92 tests) in the same wells based on an analysis of variance .

In this study, a single pair of steady-state drawdown and discharge data attained during low-flow sampling is substituted directly into the equations in Figure 1, along with the well parameters, to compute hydraulic conductivity. Given the use of a single pair of values, the method is heavily dependent on achieving steady-state conditions and the accuracy of discharge and drawdown determinations.

Study Sites

Water Resources Field Station, Storrs, Connecticut

The Water Resources Field Station (WRFS) is located on the University of Connecticut campus, in Storrs, Connecticut, and used for training and research. The overburden at the site is characterized by a fine sandy confined aquifer overlain by clay and underlain by crystalline bedrock. Table 1 lists the pertinent properties of wells used in this study.

They are a combination of direct push and hollow stem auger wells, with sand packs or prepacks. With the exception of WRFS-1 and WRFS-6, the slug tests were performed prior to this study. Well WRFS-1 was tested using a Geoprobe™ Systems Pneumatic Slug Test Kit because of its high hydraulic conductivity. WRFS-6 was tested in a similar manner as the other wells. The slug tests were either slug-out or slug-in tests. They were timed with a stopwatch and water levels periodically monitored with a water level tape. The results are summarized in Table 2. The data were analyzed using either the Hvorslev or the Bouwer and Rice slug test equations, depending on whether the aquifer was partially or fully screened, respectively. In the latter case, R_e was obtained for fully penetrating screen intervals using the empirical relation developed by Bouwer and Rice, which relates well and aquifer properties to R_e by an expression that incorporates an empirical coefficient "*C*." Values for "*C*" were computed from the polynomial fit function developed by Van Rooy (1988) as reported in Butler (1997, 109).

Table 1
WRFS Well Specifications

Well	Casing Inner Radius, R_c (cm)	Intake Radius, R (cm)	Screen Length, L (m)	Install Method	Well Type
WRFS-1	0.95	2.53	1.22	DP	Sand pack
WRFS-2	0.95	2.53	0.610	DP	Sand pack
WRFS-3	0.95	2.53	1.676	DP	Sand pack
WRFS-4	0.95	2.53	1.219	DP	Sand pack
WRFS-5	1.14	1.91	0.305	DP	Prepack
WRFS-6	0.95	2.53	0.914	DP	Prepack
WRFS-7	2.53	10.15	2.743	HSA	Sand pack
WRFS-8	5.08	12.71	2.743	HSA	Sand pack
WRFS-9	0.95	2.53	1.067	DP	Sand pack
WRFS-10	0.95	2.53	1.372	DP	Sand pack
WRFS-11	1.27	2.70	0.305	DP	Prepack
WRFS-12	1.27	2.70	1.219	DP	Prepack
WRFS-13	1.27	2.70	0.610	DP	Prepack

Note: DP = direct push; HSA = hollow stem auger.

Table 2
WRFS Slug Test Results

Well	Test Type	*K* (cm/s)
WRFS-1	Pneumatic slug in	3.18E-03
WRFS-2	Slug in	1.99E-04
WRFS-3	Slug out	4.38E-05
WRFS-4	Slug out	1.18E-04
WRFS-5	Slug in	4.94E-04
WRFS-6	Slug out	8.26E-05
WRFS-7	Slug out	2.78E-04
WRFS-8	Slug out	2.81E-04
WRFS-9	Slug in	2.55E-04
WRFS-10	Slug out	3.25E-04
WRFS-11	Slug out	3.20E-04
WRFS-12	Slug in	2.16E-06
WRFS-13	Slug out	6.10E-05

Water quality sampling was conducted by low-flow sampling using a peristaltic pump connected to a Geotech Environmental Flowcell/Flowblock for measuring indicator parameters. Periodically, drawdown and discharge were determined using a water level tape and through timing the amount of water pumped to a graduated cylinder over a period of time. In the case of well WRFS-1, water levels were monitored using the pressure transducer from the pneumatic slug test kit. Low-flow drawdown and flow rate were substituted into the steady-state versions of the flow models used in analyzing the slug test data.

Central Connecticut Quarterly Monitoring Wells

Field notes were obtained from a consulting firm for a site in central Connecticut undergoing contaminant remediation and monitoring. Data were extracted for three wells that had been sampled over three quarterly monitoring periods by four different field technicians. The wells were all drilled by hollow stem auger drilling. Table 3 lists pertinent well properties. In this case, the wells were screened in a glaciofluvial silty sand deposit and were bottomed on an underlying low-permeable till. Values for R_e were computed using the same approach described previously for the WRFS. The water levels and discharge were also determined by the field technicians in a similar manner as previously described for the WRFS. The shallow well was pumped with a peristaltic pump, whereas the others were pumped with a submersible pump.

Table 3
Central Connecticut Monitoring Wells

Well Specification	Well 3-5	Well 6-1	Well 6-3
Polyvinyl chloride casing diameter (cm)	5.08	5.08	5.08
Boring radius (cm)	11.43	11.43	11.43
Screen length (m)	3.048	6.096	6.096
Depth to well bottom (m)	7.742	23.012	23.012

Results

Table 4 summarizes the results of the low-flow hydraulic conductivity determinations at the WRFS. Well WRFS-12 had the lowest permeability based on slug testing. The well never achieved steady-state flow during low-flow sampling, even when the pumping rate was lowered to a minimum achievable rate of about 30 mL/min. Figure 2 shows a scatter plot of the steady state and slug test results with a regression line. The data are highly correlated. Hydraulic conductivity values determined from the two methods for 11 out of the 12 wells tested were within a factor of 2. The hydraulic conductivity value for the remaining well was within a factor of 3 to 4. Table 5 is a summary comparison. In terms of characterizing aquifer conditions, both methods provided about the same mean values and have similar frequency distributions. Based on probability plots, the data approximate normal distributions. Using Minitab™ software, a paired *t*-test was performed to compare the pairs of hydraulic conductivity determinations. Within a confidence interval of 95%, there was no significant difference.

Table 6 summarizes the hydraulic conductivity values determined from the low-flow sampling data collected at the three monitoring wells in central Connecticut. The hydraulic conductivity values were found to be highly reproducible at each well over the three rounds of sampling, despite two of the wells being sampled by different field technicians at each sampling round. Data precision as revealed by the percent relative standard deviation values (100 × standard deviation/mean) was high. That is, the conductivity values for each well were better than or within a factor of 2. The results for well 6-3 showed more scatter. This likely resulted from errors in determining the low pumping rate and small amount of drawdown attained during the June 2007 sampling round.

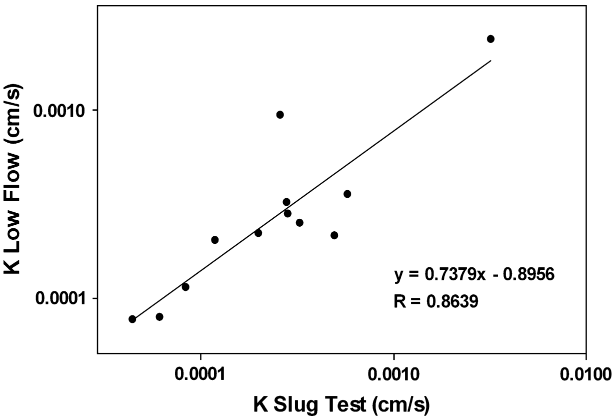


Figure 2. Comparison of low-flow and slug test hydraulic conductivity values.

Discussion

The results demonstrate that low-flow sampling data can provide hydraulic conductivity values that are comparable to those based on slug testing. Furthermore, the results were found to be highly reproducible in practical application. Since the method is based on a single pair of determinations, it requires diligence in ensuring that steady state is achieved and in measuring the discharge and drawdown.

Table 4
WRFS Low-Flow Hydraulic Conductivity Determinations

Well	Steady-State Discharge, *Q* (ml/min)	Static Depth to Water (m)	Steady-State Depth to Water (m)	Steady-State Drawdown, *H* (m)	Method	*K* (cm/s)
WRFS-1	265	Set to 0	0.067	0.067	Radial flow	2.41E-03
WRFS-2	110	2.042	2.533	0.491	Radial flow	2.21E-04
WRFS-3	55	0.640	0.988	0.347	Radial flow	7.63E-05
WRFS-4	95	0.597	0.884	0.287	Radial flow	2.02E-04
WRFS-5	55	0.396	1.125	0.728	Half ellipsoid	2.16E-04
WRFS-6	90	1.332	1.878	0.546	Radial flow	1.14E-04
WRFS-7	135	0.677	0.771	0.094	Radial flow	3.26E-04
WRFS-8	105	0.567	0.646	0.079	Radial flow	2.80E-04
WRFS-9	90	0.512	0.561	0.049	Half ellipsoid	9.56E-04
WRFS-10	95	0.533	0.835	0.302	Half ellipsoid	2.52E-04
WRFS-11	65	1.271	1.734	0.463	Half ellipsoid	3.60E-04
WRFS-12	—	—	—	—	—	—
WRFS-13	42.5	1.484	1.999	0.515	Radial flow	7.95E-05

Table 5
Summary Comparison of Low-Flow and Slug Test Hydraulic Conductivity Values

Parameter	Low Flow	Slug Test
Mean *K* (cm/s)	4.91E-04	4.58E-04
Standard deviation (cm/s)	8.63E-04	6.56E-04
SE mean (cm/s)	2.49E-04	1.89E-04
Median *K* (cm/s)	2.67E-04	2.37E-04
Minimum *K* (cm/s)	4.40E-05	7.60E-05
Maximum *K* (cm/s)	3.18E-03	2.41E-03

Note: Paired *t*-test results: $n = 12$; 95% CI for mean difference: (−0.000178, 0.000245); *t*-test of mean difference = 0 (vs. not = 0); *t* value = 0.35; *p* value = 0.734; df = 11.

The method has a number of practical limitations. Being based on the same equations as those commonly used in analyzing slug tests, the results hinge on the extent to which well and aquifer conditions match the mathematical models. As with slug testing, the results can also be influenced by skin effects, since little water is involved (Henebry and Robbins 2000). From a practical standpoint, in consideration of achieving steady-state drawdown at a high enough pumping rate to minimize the duration of sampling, the method appears applicable above a hydraulic conductivity greater than 10^{-6} cm/s. Given the typical regulatory mandated maximum sampling rate of 1 L/min or less, in high-conductivity environments, one may not be able to accurately discern the amount of drawdown. A practical upper conductivity limit was calculated using the radial flow equation and a pumping rate of 1 L/min, assuming an accuracy of drawdown measurement with a water level tape of 0.6 cm. This resulted in a conductivity of about 10^{-3} cm/s. If a sensitive pressure transducer is used to measure drawdown, one may push this upper limit higher into the 10^{-3} to 10^{-2} cm/s range.

The approach demonstrated in this study has two advantages over slug testing. For wells that are screened across the water table, slug test response is influenced by sand pack drainage and resaturation (Bouwer 1989; Binkhorst and Robbins 1998). This results in nonlog linear drawdown-time response that requires a subjective pick of which part of a multisegmented curve represents the formation. It also requires correcting for the effective well intake radius. The use of the low-flow data avoids this situation, since the sand pack will have drained to the steady-state drawdown. In high permeable environments, slug tests may exhibit oscillatory drawdown-time response (Butler 1997). This requires a complex method of analysis to determine the hydraulic conductivity, which entails the use of equations derived from those discussed here. If the steady-state, low-flow drawdown can be accurately measured, one can avoid this complex analysis.

It has long been argued that conventional site investigations can be highly misleading, owing to concentration averaging in typical monitoring wells (Robbins 1989;

Table 6
Central Connecticut Monitoring Well Low-Flow Hydraulic Conductivity Determinations

Well	Date	Steady-State Discharge, *Q* (ml/min)	Static Depth to Water (m)	Steady-State Depth to Water (m)	Steady-State Drawdown, *H* (m)	Saturated Screen Length at Steady State, *L* (m)	Technician ID	Model	*K* (cm/s)	Mean *K* (cm/s)	Standard Deviation (cm/s)	%RSD
W 3-5	December 2006	130	3.48	4.45	0.97	3.05	A	Half ellipsoid	4.64E-05			
	March 2007	150	3.36	4.67	1.30	3.05	A	Half ellipsoid	3.98E-05	3.96E-05	6.87E-06	17
	June 2007	135	3.44	4.86	1.43	3.05	A	Half ellipsoid	3.27E-05			
W 6-1	December 2006	380	14.48	14.61	0.13	6.10	B	Half ellipsoid	5.89E-04			
	March 2007	380	14.40	14.55	0.16	6.10	A	Half ellipsoid	4.97E-04	5.57E-04	5.18E-05	9
	June 2007	140	14.70	14.75	0.05	6.10	D	Half ellipsoid	5.83E-04			
W 6-3	December 2006	500	16.86	17.91	1.05	4.95	B	Radial flow	7.34E-05			
	March 2007	200	16.75	17.30	0.55	5.56	C	Radial flow	5.14E-05	8.29E-05	3.72E-05	45
	June 2007	120	17.16	17.30	0.14	5.56	D	Radial flow	1.24E-04			

Note: %RSD = percent relative standard deviation.

Martin-Hayden and Robbins 1997; Metcalf and Robbins 2007). The same may be said with respect to characterizing hydraulic conductivity. Improved site characterization may be achieved through conducting a three-dimensional (enhanced) site investigation that entails multilevel sampling. However, one is faced with increased costs and effort to perform sampling and slug testing, relative to a more conventional investigation that entails the use of fewer typical monitoring wells. The use of the low-flow data to derive hydraulic conductivity can help lower the costs of a detailed site characterization effort.

Conclusions

The use of the discharge and drawdown attained during low-flow sampling to compute hydraulic conductivity has been found to provide equivalent values to that derived from slug testing. The method has also been shown to be highly reproducible in practical application.

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