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An Analysis of Low-Flow Ground Water Sampling Methodology

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Abstract

Low-flow ground water sampling methodology can minimize well disturbance and aggravated colloid transport into samples obtained from monitoring wells. However, in low hydraulic conductivity formations, low-flow sampling methodology can cause excessive drawdown that can result in screen desaturation and high ground water velocities in the vicinity of the well, causing unwanted colloid and soil transport into ground water samples taken from the well. Ground water velocities may increase several fold above that of the natural setting. To examine the drawdown behavior of a monitoring well, mathematical relationships can be developed that allow prediction of the steady-state drawdown for constant low-flow pumping rates based on well geometry and aquifer properties. The equations also estimate the time necessary to reach drawdown equilibrium. These same equations can be used to estimate the relative contribution of water entering a sampling device from either the well standpipe or the aquifer. Such equations can be useful in planning a low-flow sampling program and may suggest when to collect a water sample. In low hydraulic conductivity formations, the equations suggest that drawdown may not stabilize for well depths, violating the minimal drawdown requirement of the low-flow technique. In such cases, it may be more appropriate to collect a slug or passive sample from the well screen, under the assumption that the water in the well screen is in equilibrium with the surrounding aquifer.

Introduction

Many current sampling techniques significantly lower the water level in a monitoring well during extraction of water from the well. It is not uncommon to evacuate three or more well volumes of water from a well prior to sampling, which can involve dewatering wells positioned in soils or rock of relatively low hydraulic conductivities. Lowering of the water table increases the ground water velocity and can cause turbulence in the vicinity of the well as it attempts to recharge. The increase in ground water velocity near the well is obvious from the relative increase in hydraulic gradient near the well. Typical natural gradients are a few percent or less. Gradients can approach unity near the well screen under large drawdown conditions during well pumping. Ground water turbulence can be an issue for certain combinations of short well screens, coarse-grained soil, fracture size, and/or large drawdowns. Increases in velocity and turbulence relative to the natural ground water flow conditions may cause the mobilization of soil particles and/or colloids that would not otherwise be moving under the natural ground water seepage velocities. On the other hand, some studies have shown that colloidal transport can occur in coarse-grained soils, such as coarse sands and gravels, under natural ground water seepage gradients (Ryan and Gschwend 1990).

Sampling-induced particle transport is of concern relative to mobilization of inorganic or organic compounds that may be sorbed to mobile

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soil particles or colloid surfaces (Enfield and Bengtsson 1988; McCarthy and Zachara 1989; Puls et al. 1990; Puls 1990). Significant lowering of the water level in a well can also result in other problems, such as entraining iron flocs or fine sediment, attached to the interior well wall, into the water remaining in the well cavity. This can add a loading of suspended solids to the sample water. Significant dewatering can also lead to screen desaturation, which may lead to screen clogging over time within that portion of the screen that becomes desaturated.

Various monitoring well sampling techniques have been developed to avoid aggravated disturbance of the well bore and surrounding aquifer during sampling (Barcelona et al. 1994; Puls and Barcelona 1996). The concept of low-flow (minimal drawdown) sample collection incorporates a constant pumping rate that is small enough not to significantly decrease (drawdown) the water level in the monitoring well. This technique was developed in an effort to minimize disturbance to the ground water well system when sampling from monitoring wells. By limiting water level drawdown, it minimizes the potential for artificially inducing suspended solids into the sample and thereby minimizes artificial sample turbidity. Since disturbance to the well is minimized, the collected ground water sample usually is not filtered, thus allowing for the potential to measure any naturally occurring colloid contribution to the ground water chemistry. In sediments where colloidal transport occurs naturally, the effect of migrating colloids on chemical transport through the ground water can thus be measured with this technique.

When using the low-flow technique, a necessary and sufficient condition is the development of a relatively small, steady-state drawdown prior to the collection of a ground water sample. The water sample is extracted from the screen section of the well and not from the well standpipe above or below the screen. Once steady-state drawdown is achieved, water entering the sample collector is entering the well screen from the aquifer with little or no additional water coming from the column of water that exists in the standpipe above or below the well screen.

Since drawdown is related to the ground water velocity at the well screen, minimizing drawdown controls shearing of colloids from the aquifer material, mobilization of the soil particles inside or outside the well sand pack, the degree of turbulence at the well screen, and stripping of aggregated masses (e.g., iron flocs or fine-grained sediments) attached to the inside of the well standpipe and screen. By keeping the drawdown as low as possible, the relative increase in ground water velocity, compared to prepumping conditions, is minimized. The average amount of velocity increase can be calculated by comparing the hydraulic gradients before pumping and during pumping near the well screen, remembering that the actual ground water velocities at the well are not uniform due to heterogeneities in the geologic formation outside the well. The degree of drawdown is an indicator of whether the low-flow technique will be practical in sampling a particular well. With excessive drawdown of the water level in a well, sediment may accumulate in the well standpipe, settling to the bottom of the screen or clinging to the interior wall of the well, even in satisfactorily constructed and developed wells. The low-flow methodology significantly reduces the mobilization of such sediment through the well screen.

Typically, water sample turbidities of less than 5 NTU have been sought to assure that the aquifer and well are relatively undisturbed by the sampling procedures. However, in some anaerobic and contaminated ground water conditions, turbidities may be naturally higher than 5 NTU (Backhus et al. 1993; Ryan and Gschwend 1990). Poorly constructed monitoring wells, where silt or clay sediment resides in the sand pack of the well screen as a result of well construction, can add turbidity to the sample. If the turbidity of 5 NTU cannot be achieved, at least a constant sample turbidity can be sought, but care must be exercised in the use of the water quality analytical results in such samples. Usually, dedicated sample tubing or submersible pumps are used in wells so that disturbance to the water column from insertion of these items during each sampling event can be avoided. This also eliminates the effects of rapid pump or repeated bailer deployment into the well, which can suspend solids in the well or screen sand pack. Often other considerations than sample turbidity and minimized drawdown may also dictate when to collect the sample, such as stabilization of dissolved oxygen, specific conductance, pH, or temperature of the pumped water.

The above is a brief overview of the low-flow sampling methodology in use today. The focus of this paper is on the mathematical relationship between pumping rate and the water level behavior in the well under idealized conditions. This paper examines how to estimate the steady-state water level drawdown in a well and the approximate time to achieve this drawdown using low-flow sampling methodology. The mathematical development results in a relationship between well geometry, aquifer hydraulic conductivity, and sampling flow rate. This information can be used to evaluate how much pumping time is required before a sample can be collected or what portion of the sample water is originating from the aquifer at any point before the drawdown stabilizes. Although this treatment is for idealized well geometries and uniform aquifer conditions, it has been found useful in planning low-flow sampling programs and providing guidance to field technicians as to when to collect a sample from certain wells.

Development of Steady-State Drawdown

When water is withdrawn from within a monitoring well, there are two sources to this water: (1) ground water from the aquifer outside of the monitoring well screen; and (2) water from storage within the monitoring well casing. The instantaneous flow rate to the sampler can be defined as the sum of these two flow quantities, thus

$$q_t = q_a + q_c \tag{1}$$

where q_a is the instantaneous ground water seepage rate from the aquifer, and q_c is the instantaneous rate of contribution from well casing storage. The instantaneous rate of water that is removed from the well casing is the limit of the incremental drawdown (Δh) times the area of the well casing divided by an increment of time (Δt) as Δt approaches zero. This results in the expression

$$q_c = \pi r_c^2 \frac{dh}{dt} \qquad (2)$$

where r_c is the internal radius of the well casing. As pumping from the well at a constant rate approaches a steady-state drawdown, q_c approaches zero because at steady-state all the water entering the pump is from the aquifer.

The rate of recharge to the well from the aquifer is a function of the well geometry, aquifer hydraulic conductivity, and the water level drawdown in the well relative to static ground water conditions. A means of estimating the rate of aquifer recharge could be one of the relationships developed by Hvorslev (1951). For instance

$$q_a = \frac{2\pi LKh}{\ln\beta} \qquad (3)$$

Where h is the total water level drawdown relative to the static ground water level, K is the horizontal hydraulic conductivity of the aquifer, L is the length of the zone contributing ground water to the well (typically the sandpack zone of the monitoring well), β is the ratio of the effective well radius, r_e, to r_w. The effective radius in this case is

$$\frac{mL}{2} + \left(r_w^2 + \left(\frac{mL}{2}\right)^2\right)^{1/2}$$

and can be viewed as a shape factor relating the well geometry to an idealized recharge boundary. The square root and the ratio of horizontal to vertical hydraulic conductivity is m, and r_w is the radius of the borehole in which the well is installed or the external radius of the sandpack surrounding the well screen. This equation assumes a partially penetrating well in a confined aquifer. The Hvorslev formulas provide a straightforward relationship between these variables, compared with more rigorous solutions to the diffusion equation (e.g., Cooper et al. 1967). Use of a Hvorslev relationship appears to be suitable, providing excessive drawdown or a highly compressive aquifer are avoided. These two conditions can result in significant release of water from storage, which violates the assumptions of the Hvorslev equations. Furthermore, the Hvorslev equation assumes uniform aquifer properties. This relationship was selected because of its extensive current use; other expressions that relate to the well geometry and aquifer properties with the flow rate into the well would also be satisfactory.

Although not necessary to minimize drawdown, the flow rate of the sampling pump for the low-flow sampling procedure has been normally kept constant to date. For a given constant sampler flow rate (i.e., constant q_t), Equations 2 and 3 can be combined into Equation 1 to yield

$$q_t = \pi r_c^2 \frac{dh}{dt} + \frac{2\pi KLh}{\ln\beta} \qquad (4)$$

Equation 4 can be rewritten, after combining terms

$$dt = \pi r_c^2 \left(q_t - \frac{2\pi KLh}{\ln\beta}\right)^{-1} dh \qquad (5)$$

Integrating to obtain h as a function of t, assuming that there is no drawdown at t = O, results in

$$t = -\frac{r_c^2 \ln\beta}{2KL} \ln\left(1 - \frac{2\pi KL}{q_t \ln\beta} h\right) \qquad (6)$$

Development of Approximate Time to Reach Steady-State

As t becomes large, Equation 6 reduces to

$$h_s = \frac{q_t \ln\beta}{2\pi KL} \qquad (7)$$

which is the steady-state flow equation for a well (Theim 1906) with an idealized recharge boundary at a distance of r_e from the well centerline. Thus h_s is the steady-state drawdown in the well at a constant pumping rate of q_t. Equation 7 can be used to calculate the amount of steady-state drawdown during sampling. Equation 6 has an exponential character in time and, therefore, theoretically never reaches steady state. However, we can approach as close to steady state as we wish by pumping long enough. The drawdown at any time t calculated by Equation 6 can be divided by the steady-state drawdown from Equation 7 to obtain

$$\frac{h}{h_s} = 1 - \exp\left(-\frac{2KLt}{r_c^2 \ln\beta}\right)$$

Solving for time results in

$$t = \frac{-r_c^2 \ln\beta}{2\,KL} \ln\left(1 - \frac{h}{h_s}\right) \qquad (8)$$

Therefore, once the ratio of drawdown to the steady-state drawdown is selected for defining the proximity to steady state, then given the soil hydraulic conductivity and the well characteristics, the time to reach this ratio can be calculated by Equation 8. For instance, if it is desired to be within 5% of the steady state drawdown, then $\frac{h}{h_s}$ is 0.95.The 0.95 can be inserted into Equation 8, along with the appropriate well and aquifer parameters, resulting in the pumping time required to achieve the selected drawdown ratio. This equation is useful in examining how

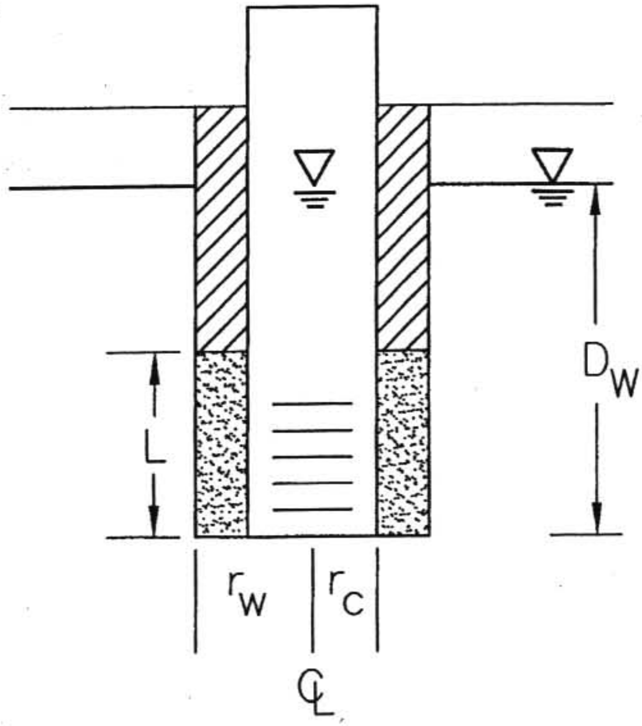

Figure 1. Well construction detail.

long it may take to reasonably approach steady-state drawdown to determine if the time is excessive (e.g., many hours).

Time to Replace Water Within Well Standpipe with Aquifer Ground Water

Another useful calculation is to estimate the amount of time required to replace the initial water volume in the well screen with fresh aquifer ground water. This is appropriate for pumping from within the well screen, and preferably at a mid-screen depth (Puls 1999, personal communication). It further assumes the aquifer water does not displace the standing water above the well screen, except for that which is removed in order for drawdown to occur. Once drawdown has ceased, it assumes the water column above the screen remains stagnant and does not mix or minimally mixes with the ground water entering the screen. The initial volume of water in the well screen (ignoring water in the surrounding sand pack) is related to the screen length and the radius of the well casing. By Figure 1, the volume of water in the well screen, is $\pi r_c^2 L$. The volume of water associated with the drawdown is $\pi r_c^2 h$, which when the water level reaches steady state is $\pi r_c^2 h_s$. Therefore, the total volume of water to replace is $\pi r_c^2 (L + h_s)$. Here we have assumed that L is a good approximation of the screen length (Figure 1). The time to replace this total volume with aquifer water can be determined by integrating the aquifer flow rate (q_a) over time and determining when the volume of aquifer water equals the initial well screen water volume and drawdown water volume. Thus

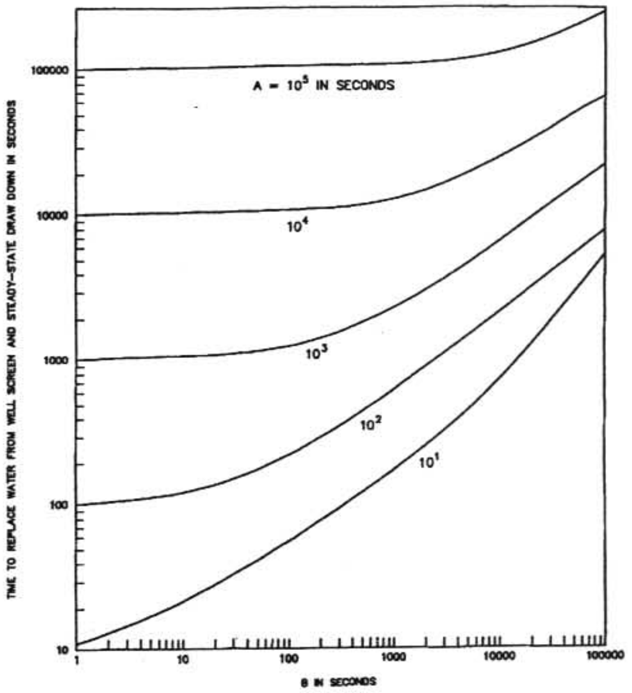

Figure 2. Time to replace well screen water and steady-state draw down.

$$\pi r_c^2\,[L + h_s] = \int_o^{t_r} q_a dt = \int_0^{t_r} \frac{2\pi LKhdt}{\ln\beta}$$

Substituting for h from Equation 6

$$\pi r_c^2\,[L + h_s] = \int_o^{t_r} q_t\left(1 - \exp\left(\frac{-2KLt}{r_c^2\ln\beta}\right)\right) dt$$

Carrying out the integration results in

$$\frac{\pi r_c^2\,[L + h_s]}{q_t} = t_r - \frac{r_c^2\ln\beta}{2KL}\left(1 - \exp\left(\frac{-2KLt_r}{r_c^2\ln\beta}\right)\right) \quad (9)$$

where t_r is the time required to replace the water volume in the well screen with aquifer ground water.

The form of Equation 9 is not readily solved explicitly. Graphically, the equation is easily expressed in terms of two parameters:

$$A = \frac{\pi r_c^2}{q_t}[L + h_s] \qquad \text{and } B = \frac{r_c^2\ln\beta}{2KL}$$

Furthermore, substituting for h_s from Equation 7, A becomes

$$A = \pi r_c^2 = \left[\frac{L}{q_t} + \frac{\ln\beta}{2\pi KL}\right]$$

The roots of Equation 9 for various A and B are shown in Figure 2. Note that the units of A, B, and t_r are in seconds in Figure 2. Therefore, in order to calculate t_r, the well geometry and aquifer properties are used to calculate A and B. Figure 2 is then entered to obtain the amount of time to pump prior to obtaining all water

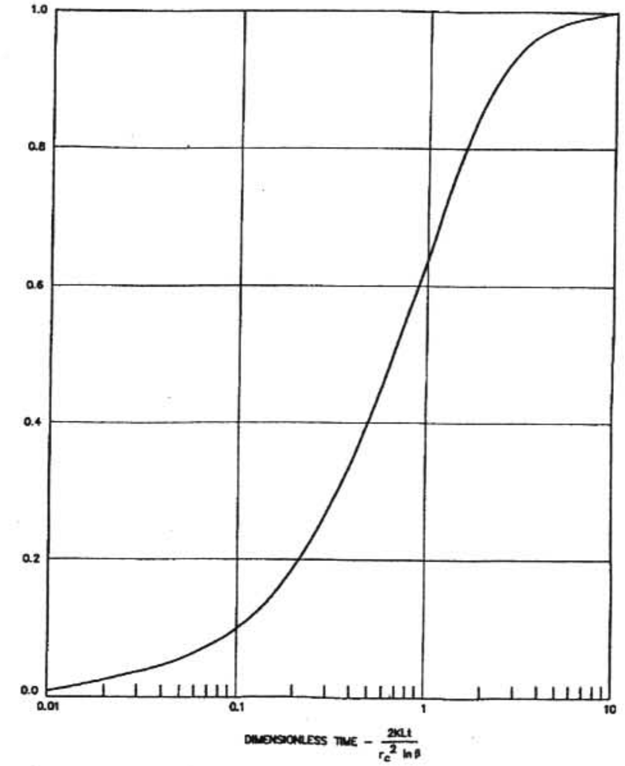

Figure 3. Relative portion of aquifer recharge to well screen.

from the aquifer, t_r.

As previously noted, this development assumes pumping from the well screen and that the aquifer water displaces the water in the well screen without mixing from the water column in the well standpipe above the screen.

Proportion of Water Sources During Sampling

Another use of Equations 2 and 3 is to estimate the instantaneous proportion of water entering the monitoring well from the aquifer (q_a) to the constant sampling rate (q_t). In the case of relatively low hydraulic conductivity formations where the low-flow technique is applied, it is not practical to wait to reach a condition where all the sampling water is entering the well from the aquifer because of the significant drawdown at steady state. As noted earlier, excessive drawdown leads to significant disturbance of the well conditions, potentially leading to entrainment of solids into the water sample that would not be there under undisturbed conditions.

This development approximates the relative proportion of water coming from the aquifer as a function of time and is obtained by taking the ratio of q_a to q_t

$$\frac{q_a}{q_t} = \frac{q_a}{q_a + q_c} \tag{11}$$

Substituting Equations 2 and 3 into Equation 11, with the help of Equations 5 and 6, results in

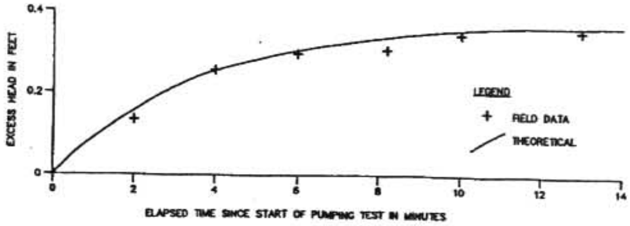

Figure 4. Field results.

$$\frac{q_a}{q_t} = 1 - \exp\left(\frac{-2KLt}{r_c^2 \ln\beta}\right) \tag{12}$$

Plotting of the ratio $\frac{q_a}{q_t}$ versus dimensionless time $\frac{2KLt}{r_c^2 \ln\beta}$ is shown in Figure 3.

This calculation makes no conclusion about the relative proportions of aquifer and standpipe waters entering the sampler, only the proportions entering the screen section of the well. Of course, one could assume that any water being sampled from the screen is the result of uniform and instantaneous mixing of the standpipe water and aquifer water within the screen section of the well. Since the aquifer is rarely, if ever, homogeneous, more aquifer water will be entering the sections of the well screen adjacent to the more permeable aquifer layers than from the less permeable layers. Uniform mixing of these water sources is unlikely and the actual source of water to a sampler intake placed at mid-screen will be unknown. However, the calculation is useful to qualitatively evaluate the potential source of the water to the sampler.

Example of Use of Equations

Most ground water scientists and engineers are familiar with using the Hvorslev constant discharge equations. Using the well configuration shown in Figure 1, the steady-state water level drawdown in a well, for various constant sampling flow rates, can be calculated using Equation 7. Typical flow rates used to date for the low-flow sampling technique range from about 0.00062 to 0.0033 L/s (i.e., 37 to 200 mL/min). Say our example well is sampled at a rate of 0.0012 L/s (i.e., 70 cm^3/min). The hydraulic conductivity of the aquifer at this well was determined by performing a slug test to be 3.6×10^{-6} m/s (3.6×10^{-4} cm/s) and is isotropic (i.e., m = 1). The well parameters for this calculation are L = 1.52 m (5 feet), $r_c = 0.0260$ m (1.025 inches) and $r_w = 0.0508$ m (2 inches). These sample well and aquifer parameters are based on an actual well installed into a silty sand deposit. A steady-state drawdown of 0.12 m (0.38 feet) was calculated by Equation 7.

The results of the calculated drawdown versus time for the well is illustrated in Figure 4. Actual drawdown data from a well with these parameters is also shown in Figure 4. Figure 4 shows that there is good agreement between the calculated curve and field data, justifying use of this method.

It is illustrative to examine a well placed in a relatively low hydraulic conductivity formation. Let's assume a formation with an average hydraulic conductivity of 3.6×10^{-8} m/s (3.6×10^{-6} cm/s). Using the same well geometry as in the above example and calculating for a sampling flow rate of 0.00063 L/s results in a steady-state drawdown of 6.2 m (about 20 feet). This could be equivalent to or exceed the depth of water in a shallow monitoring well. This amount of drawdown also violates the primary requirement for low-flow sampling, that is, minimal drawdown. In such a case, attempting to apply the low-flow technique to obtain a steady-state drawdown is essentially no different from using the standard purge methodology where a well volume or more of water is purged from the well casing prior to sampling. The excessive drawdown at steady state increases the ground water velocity in the soil adjacent to the well, resulting in potential shearing and transport of solids into the well and thus possible artificial sample turbidity. Under such a circumstance, it is more pragmatic to simply obtain a water sample from the screen portion of the well assuming that the water in the well screen is in chemical equilibrium with the surrounding aquifer, rather than risk aggravated soil or colloidal transport into the sampler which may effect the sample's chemical analysis results. Equation 12 would indicate, in the case of sampling immediately, that no water is entering the sampler from the aquifer. However, it may be more realistic to assume that the water in the well screen is in chemical equilibrium with the ground water immediately outside of the screen if the well screen is less than a few meters long. The well screen water likely represents the ground water immediately outside the screen if taken from the central portion of the screen. Thus, the excessive drawdowns could be avoided by collecting a slug or passive sample from the well screen. That is, an instantaneous sample without purging water from the well screen and standpipe.

Equation 12 suggests that waiting longer results in a greater proportion of ground water entering the screen from the aquifer as pumping proceeds in low hydraulic conductivity formations. The time required to achieve 95% of the steady-state drawdown for the example low hydraulic conductivity well can be calculated using Equation 8. Utilizing the information given for this later example, a time of 63,000 seconds (about 17 hours) is calculated to reach 95% of the steady-state drawdown. Prior to this, water entering the sample is moving downward from the water column in the well casing as well as from the aquifer. Depending on the well geometry and aquifer hydraulic conductivity, the amount of water being pumped from the stagnant water column in the well will vary. In sandy soils, where the drawdown is a matter of a few tenths of a foot or less and assuming a typical well screen length of 5 to 10 feet, a significant amount of water from the stagnant water column does not enter the screen or, therefore, the sampling pump, as in the first example above. However, for a low permeability formation, combined with a short well screen, much of the water obtained during the initial pumping period is from the overlying water column stored in the well casing above the screen. Equation 12 becomes useful in estimating the relative proportion of ground water possibly entering the sampler at the time of sampling where steady-state drawdown is not achieved. For instance, after 15,000 seconds (about 4 hours) of pumping the drawdown in the later example above is 3.1 m (about 10 feet) and only 50% of the water entering the well cavity at the screen is originating from the aquifer.

Conclusions

Equation 8 provides a useful tool to decide when to collect ground water samples from standard monitoring wells using low-flow sampling methodology. Low-flow sampling may result in excessive water level drawdowns in monitoring wells positioned in relatively low hydraulic conductivity formations. In such a case, the excessive drawdowns may result in soil particle and/or aggravated colloidal transport into the well. This condition may suggest that in relatively low hydraulic conductivity materials, a slug or passive sample from the well screen may provide a more representative sample of the aquifer ground water than excessively dewatering the monitoring well. These calculations suggest that a criterion for drawdown is appropriate for low-flow sampling, as this reflects the ground water velocities near the well screen relative to the natural ground water seepage velocity. However, until the effects of ground water velocity on aggravated colloidal transport and soil particle migration are better understood so a specific drawdown criterion can be calculated, the low-flow sampling method will help control these problems and minimize artificial sample turbidity. Experience suggests drawdowns of less than a few feet (unless there is only a few feet of water in the well), typically minimize sample turbidity. Experience also shows less accumulation of sediments in wells routinely sampled where drawdowns are minimized and limited.

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