

Pumping Tests for Aquifer Evaluation—Time for a Change?

by James J. Butler Jr

For more than a century, ground water hydrologists have used pumping tests as a means to evaluate how an aquifer will respond to ground water exploitation. These tests are commonly performed by pumping a well at a near-constant rate while measuring changes in water level at the pumped well and, if available, nearby observation wells. The changes in water level, termed drawdown, are analyzed using various models of the well-aquifer configuration to obtain estimates of the parameters characterizing the transmissive and storage characteristics of the aquifer. The original methods for the analysis of pumping tests were developed to estimate transmissivity (T) from steady-state drawdown (Dupuit 1857; Thiem 1906), but these methods are equally valid for the analysis of drawdown during the flow regime termed transient steady state (Kruseman and de Ridder 1990) or unsteady state, steady shape (Heath and Trainer 1968; Butler 1990; Bohling et al. 2002). In one of the most fundamental advances in ground water hydrology, Theis (1935) extended the realm of pumping test analyses to the fully transient case. The Theis model and its truncated series approximation (Cooper and Jacob 1946) form the basis of modern methods for pumping test analysis used in both ground water hydrology and petroleum engineering (Streltsova 1988; Kruseman and de Ridder 1990; Batu 1998; Bourdet 2002). Recently, Yeh and Lee (2007), among others, have questioned the utility of information obtained from pumping tests, pointing out that natural systems are far different from the ideal homogeneous aquifer conceptualizations commonly invoked to analyze test data. Given the concerns that have been expressed, I thought this was an appropriate time to step back and consider exactly what we can expect to get from this traditional “work horse” of applied hydrogeology.

Pumping tests for aquifer evaluations have been performed and, to a much lesser extent, analyzed in essentially the same way for well over a half a century. As

an applied hydrogeologist with more than two decades of experience, I explain this not as blind adherence to the traditional ways but rather as a pragmatic reaction to what we observe in the field. In my experience, one often obtains a remarkable agreement between the drawdown measured at an observation well and the theoretical responses generated using models of homogeneous aquifers. Eventually, at large times of pumping, this agreement may deteriorate as additional mechanisms (e.g., impacts of boundaries, long-term water level trends, and other pumping wells), which, in practice, may be difficult to incorporate into the analysis, begin to affect the measured drawdown. The often observed agreement between field data and theoretical models of homogeneous aquifers, coupled with reasonable explanations for their divergence at large times, has prompted applied hydrogeologists to continue to perform and analyze these tests in a similar manner for decades. Has this been a wise practice or has a “serendipitous” agreement between test data and theoretical responses led us to wrongfully ignore the true heterogeneity of natural systems and inadvertently produce aquifer evaluations that are highly suspect in nature?

Theoretical investigations carried out over the last two decades can shed some light on the “serendipity” of this agreement. My colleagues and I at the Kansas Geological Survey used a series of semianalytical solutions to assess the impact of simplified heterogeneous structures on pumping test drawdown (e.g., Butler 1990; Butler and Liu 1993). We found that drawdown in observation wells located at some distance from the pumping well should, in general, be in close agreement with the homogeneous aquifer models of the well hydraulics literature. For example, Butler (1990) demonstrates that the impact of a disk of low- T material embedded in an aquifer can be ignored, even if that disk has an order of magnitude lower T than the aquifer and is adjacent to the observation well, when the observation well is located at a distance more than 10 times the disk radius from the pumping well. At smaller distances, and even at the pumping well itself, the disk’s impact can be readily removed from T estimates by using the Cooper-Jacob semilog-in-time method to analyze the test data, as proven by Butler and Liu (1993) for simple configurations and demonstrated, for the general heterogeneous case, by Sánchez-Vila and colleagues (Meier et al. 1998;

Kansas Geological Survey, University of Kansas, 1930 Constant Ave., Campus West, Lawrence, KS 66047; (785) 864-2116; fax (785) 864-5317; jbutler@kgs.ku.edu

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Sánchez-Vila et al. 1999). The diffusion-like processes governing the physics of pumping-induced flow to a well create a relative insensitivity or “robustness” to heterogeneous conditions, whether natural or anthropogenic (e.g., insufficient well development) in origin, that certainly works in our favor. The commonly observed agreement between drawdown measured at observation wells and theoretical responses for models of homogeneous aquifers should therefore be the expected situation in many field settings (e.g., Tóth 1966).

The “robustness” to heterogeneous conditions is comforting but, to return to the original concern motivating this commentary, how useful is the information resulting from these tests? Pumping tests for aquifer evaluations are typically performed to obtain estimates of large volumetric averages of T and the storage coefficient (S), as well as to assess possible impacts of hydrologic boundaries. The large volumetric average of T , particularly when estimated using the Cooper-Jacob semilog-in-time method, should be a reasonable value for local water supply investigations and, depending on the duration of the test and the scale of the model, for larger-scale numerical models (e.g., Meier et al. 1998). The S estimate, however, may be more problematic, as spatial variations in T can have a large impact on S (e.g., Butler 1988; Schad and Teutsch 1994; Sánchez-Vila et al. 1999). This situation arises because (1) we only directly estimate the hydraulic diffusivity (T/S) and T from drawdown in the absence of boundary effects and (2) those parameters represent conditions in different portions of the aquifer. The diffusivity estimate is primarily a function of material between the pumping and observation wells, whereas the T estimate represents an average over a much larger area (e.g., Butler 1990; Schad and Teutsch 1994). One obtains an S estimate by assuming that the large volumetric average of T also is representative of the material between the pumping and observation wells and then substituting that T value into the diffusivity. Thus, variations in T between these different portions of the aquifer can introduce error into the S estimate. Results from numerous multiwell pumping tests have shown that it is not uncommon to obtain a near-constant T but large variations in S from analyses of drawdown at different observation wells (e.g., Schad and Teutsch 1994). Given this origin of at least a portion of the observed variability in S , one would expect more representative S estimates as the distance between the pumping and observation wells increases.

In terms of hydrologic boundaries, there is no question that a pumping test can provide valuable information about boundary impacts over the period of pumping and subsequent recovery. Petroleum engineers, in particular, have devoted considerable effort to the development of methods for identifying boundary impacts from drawdown and recovery data (e.g., Streltsova 1988; McKinley and Streltsova 1993; Bourdet 2002). One must be careful, however, not to equate the observed boundary impacts with those that might occur over much longer durations of pumping. An assessment of the response of an aquifer to pumping over the long term should not solely depend on information from a pumping test of limited duration; one must use other information on the regional hydrogeology, and so forth, to make that determination.

Pumping tests are commonly performed at sites of ground water contamination but not necessarily for

the same purpose as in water supply investigations. At contaminant sites, we are often interested in assessing the threat that the site poses to neighboring water users and how best to design a strategy to clean up the site. In this case, a pumping test can provide useful information about well yields, how water levels in neighboring wells will respond to remediation pumping, and how the site fits within the larger-scale hydrogeologic context. However, for contaminant movement predictions and remediation system designs, the large volumetric average of T is often of limited utility. What we really need for those tasks is information about the spatial variations in hydraulic conductivity (K) that can be such a critical control on contaminant movement (e.g., Hyndman et al. 2000; Zheng and Gorelick 2003; Liu et al. 2004; Tiedeman and Hsieh 2004). These K variations cannot be characterized using conventional pumping tests (e.g., figure 19 of Butler [2005]), so we must look to other approaches. One possibility is the hydraulic tomography (HT) method advocated by Yeh and Lee (2007). The HT approach for aquifer characterization has been the subject of active theoretical, laboratory, and field research for more than 15 years (e.g., Tosaka et al. 1993; Gottlieb and Dietrich 1995; Butler et al. 1999; Yeh and Liu 2000; Bohling et al. 2002, 2007; Brauchler et al. 2003; Zhu and Yeh 2005, 2006; Illman et al. 2008; Fienen et al. 2008). This work has shown that HT can provide information of value for contaminant site investigations, although characterization of the fine-scale K variations that often are major controls on contaminant movement may prove difficult in practical applications (Bohling et al. 2007). A particularly promising alternative for getting at that fine-scale detail in relatively shallow, unconsolidated settings is the combination of new direct-push profiling methods (Butler et al. 2007; Dietrich et al. 2008) with geophysical surveys (see papers in Rubin and Hubbard [2005] for a review of geophysical methods), perhaps supplemented with a few HT or small-scale tracer tests. The coupling or “fusion” of information from different methods is a promising path for contaminant site characterization, but the role of conventional pumping tests in that effort may be limited (Vasco et al. 1997).

In conclusion, as a discipline, we should derive considerable satisfaction from the success that we have achieved with the conventional pumping test in water supply investigations. We must not, however, lose sight of the limitations of the approach, as it is clearly not a hydrogeologic panacea. The large volumetric averages of hydraulic parameters must be used with caution in assessing the threat that a contaminant site poses and how one might design effective remediation strategies for that site. However, for those interested in evaluating how an aquifer will respond to ground water exploitation, the conventional pumping test will continue to provide information of great practical value. Thus, despite its origins in the early days of our discipline and its limitations for site characterization applications, this traditional “work horse” of applied hydrogeology still has some distance to run.

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