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The future of hydraulic tests

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Introduction

Perhaps because of the existence of a vast amount of literature, many hydrogeologists believe that well hydraulics is no longer at the frontier of our discipline. Well testing is well established both in theory and practice; its techniques have been applied for decades. However, despite more than 100 years of theoretical development, the plight of the field hydrogeologist is still not enviable (Williams 1985). Often, the data are ambiguous and the model identification is not unique (Al-Bemani et al. 2003). This matter of fact is seldom emphasized within the literature, which is dominated by the development of new theories, of new testing techniques, of new software and so on. This is understandable, brilliant papers are rarely reports of incomprehensible experiments. The aim of this essay is to try to subjectively answer the following questions: What has been accomplished? What has been the recent progress? How could this field evolve in the future?

A historical perspective

It is striking how fast after the publication of Darcy's law (1856), Dupuit (1863) provided the first analytical solutions to steady groundwater flow to wells in confined or unconfined aquifers. However, it took 40 years before these equations were used for well test interpretation (Thiem 1906), and another 30 years of experimentations—including some amazingly detailed investigations, such as a test realized in Nebraska in 1931 with 81 observation wells, and 12 men collecting data for 3 days (Wenzel 1936)—before Charles V. Theis decided to look for a transient solution. In about a year (between 1934 and 1935), Theis formalized the problem, met several mathematicians, developed the analogy with the thermal problem and finally, with the help of a former university classmate (C. Lubin), he was able to propose the analytical solution (Theis 1935) which now provides the basis for most of the interpretation techniques.

The Theis solution was the starting point for a true revolution. A whole community of scientists (hydrogeologists, petroleum engineers and civil engineers) developed the theory by adding more complexity to the aquifer, and to the boundary conditions within the aquifer and at the well. After the Second World War many new problems have been solved, improving the understanding of the drawdown behavior both in the aquifer and in the pumping well itself. The most influential steps during this period were the analysis of the influence of many perturbating factors such as: boundaries (Theis 1941), non-linear head losses within the pumping well during step drawdown tests (Jacob 1947), introduction of the skin concept to analyze the performance of a pumping well (van Everdingen 1953), the effect of the unsaturated zone in an unconfined aquifer (Boulton 1954), leakage from an adjacent aquifer (Hantush and Jacob 1955), partially penetrating well (Hantush 1961), large diameter well (Papadopulos and Cooper 1967), dense network of fractures in a porous matrix with the introduction of the double porosity concept (Warren and Root 1963), single fracture intersecting the well (Gringarten et al. 1974). It is interesting to note that amongst the most productive contributors of this period was Mahdi S. Hantush who divided his career between the New Mexico Institute of Technology (USA) and the University of Baghdad (Iraq).

In parallel with the development of analytical solutions for a broad variety of aquifers and boundary conditions in wells, researchers proposed a set of techniques involving straight-line analysis, and type curve matching to interpret field test data. The straight-line analyses were based on asymptotic solutions valid only for late or early time data. The most famous is the Jacob's solution that is the late time asymptote of the Theis solution (Cooper and Jacob 1946). These classical interpretation techniques are described in detail in numerous books (Hantush 1964; Streltsova 1988; Dawson and Istok 1991; Kruseman and de Ridder 1992; Raghavan 1993; Batu 1998) and are summarized in any groundwater textbook. The research along this *classical* path is still active and new analytical solutions are regularly proposed (Butler et al. 2001; Zhan and Zlotnik 2002; Wu 2002; Yeh et al. 2003).

During the last 25 years, a set of so-called *modern interpretation techniques* emerged in the oil industry (Horne 1995; Bourdet 2002). These techniques are mainly characterized by computerized methods and by a standard methodology that involves two systematic steps: (1) model identification, and (2) parameter identification. The model identification step corresponds to the choice of a conceptual model. This step is facilitated (in some cases) by the plot of the logarithmic derivative together with the drawdown as a function of time in logarithmic scale (diagnostic plot). The logarithmic derivative is more sensitive to subtle variations in drawdown behavior than the plot of the drawdown alone and shows some characteristic behaviors depending on the hydraulic constraints (Bourdet et al. 1983). Use of the logarithmic derivative was proposed early on in the hydrogeology community by Chow (1952) but was limited to the realm of interpreting field data with the Theis solution. Chow noticed that the logarithmic derivative is constant at late time in the case of the Theis model and that its expression is proportional to the inverse of the transmissivity. Plotting the logarithmic derivative of a data set as a function of time allows direct

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identification of the transmissivity if this derivative becomes constant. The analysis of the logarithmic derivative became standard in the oil industry after the work of Bourdet et al. (1983). The parameter identification step then consists of automatic regression analysis (McElwee 1980) coupled with confidence interval calculations (Bardsley et al. 1985; Rosa and Horne 1991). Importantly, the introduction of the numerical Laplace inversion allowed the development of this computerized approach. Historically, the Laplace transform has been used in well testing initially in the oil industry by van Everdingen and Hurst (1949). But it is with the rapid development of computers and the concomitant research on numerical Laplace inversion (Stefhest 1970; Talbot 1979), that applications could appear in well testing (Moench and Ogata 1984). This eliminated the need for numerical evaluation of complicated closed-form solutions, some of which are obtained by analytical inversion only with great difficulty, and extended significantly the number of models available. While the use of Laplace transform is now a standard amongst well hydraulics researchers (Walton 1996; Lee 1999) and is used transparently together with automatic fitting techniques by many field hydrogeologists through commercial software, the use of the derivative for model identification and the calculation of confidence intervals is only slowly emerging within the groundwater literature (Spane and Wurstner 1993; Hamm and Bideaux 1996; Walker and Roberts 2003; Renard in press). Nonetheless, over the last few years the usual hydrogeological well test interpretation software, such as Hydrotec (http://www.geologik.com/), AquiferTest (http://www.flowpath.com), Aqtesolv (http://www.aqtesolv.com) or Aquifer Win32 (http://www.aquifer-analysis.com), have started to offer derivative plots.

Recent trends

From a theoretical standpoint, the groundwater community—which has invested a considerable amount of research in stochastic techniques—has provided very important findings on the impact of aquifer heterogeneity on well hydraulics. The main issue was: what is the significance of estimated parameters of a heterogeneous aquifer when based on the 'best' fit between a homogeneous model and measured data? Another related question was: is it possible to infer some statistical parameters describing the heterogeneity from a pumping test? The answers have been on one hand disappointing. Inferring the degree of heterogeneity (variance, covariance function) from well testing is extremely difficult unless a large amount of interference tests be conducted (Noetinger and Gautier 1998; Sánchez-Vila et al. 1999). On the other hand, these studies have shown that the parameters that are identified by well test interpretation can have a clear theoretical meaning: in many cases they are the equivalent transmissivities of the medium that would be obtained by upscaling under uniform flow (Meier et al. 1998; Indelman 2003).

An important trend recognized by both petroleum engineers and hydrogeologist is the increasing role of numerical modeling and inversion techniques to interpret well test data. On one hand, numerical models allow the effect of different geological structures on the drawdown behavior to be investigated when analytical solutions would not be tractable (Zambrano et al. 2000). On the other hand, numerical models and inversion methods offer a great flexibility, they allow, for example the ability to interpret data sets in complex geological environments, or to simultaneously analyze pumping test and tracer test data (Lebbe 1999; Hsieh 2000; Lavenue and de Marsily 2001; Vesselinov et al. 2001).

What future?

First of all, it is obvious that incremental development of new analytical solutions will continue. This is very important in improving our knowledge of the behavior of aquifers and wells under different circumstances. For example, fundamental issues such as the effect of inertia (quadratic head losses) have still not been properly solved and require theoretical investigations. This is of utmost importance in the author's opinion since one of the key objectives of well testing is to estimate the amount of water that can be exploited from a well (Misstear and Beeson 2000). However in practice, we are still using the empirical concept introduced by Jacob (1947) to interpret step-drawdown tests, while the physical understanding of inertia and fluid mechanics has advanced (Skjetne and Auriault 1999). Even if some approximate solutions have been presented recently (Wu 2002) to account for these effects, there is still a lack of a satisfactory model to simulate the transient behavior of the drawdown in a well as a function of a variable pumping rate.

Furthermore, it is highly probable that the diagnostic plot will become a standard tool in hydrogeology in the next 10 years. Most of the available software already provides this option. Therefore, the author strongly believes that there is now a need to promote these techniques in most education programs. Computerized techniques—aiming at facilitating interpretation—will continue to expand, however, even if several attempts are made to develop expert systems, a sound analysis will always require a knowledgeable and experimented analyst. More generally, and as noted by Misstear (2001), too often standard interpretation techniques are misused. This emphasizes once again the need for a good education in well hydraulics for providing a solid understanding of the flow behavior, rather than cookbook recipes.

The non-uniqueness of the interpretation is an intrinsic property of inverse problems that are usually ill-posed (Hadamard 1932). To work around this difficulty, and to make the mathematical problem over-determined, the principle that has been applied with success up to now is to use models, which are as simple as possible, but still capture the main characteristics of the problem. Consequently, for more than a century, hydrogeologists have been using the homogeneous aquifer assumption and this is why they were able to solve, in many cases, the inverse problem and determine a unique transmissivity. This is also why simple analytical models have still an important role to play in the 21st century. This author also believes that understanding of the links between these well-identified parameters and the underlying intrinsic heterogeneity will be improved, as has been the case for the Theis model thanks to the recent progress in stochastic theory. Most probably, the next decade will provide new results in this direction for more complex aquifer situations and for stronger heterogeneity.

On a related topic, there is a strong need to improve our techniques for estimating the uncertainty associated with the parameters derived from well test interpretation. The Bayesian approach seems the most appropriate and accounts for the physical nature of the parameters. It requires then a better knowledge of the a priori distribution of all the parameters and in this respect a substantial effort should be put on a systematic collection and statistical analysis of published data. This tedious effort would provide a major contribution to our community.

On the other hand, more and more attempts to interpret well test data and integrate them with geological observations and geophysical data through numerical modeling and inverse procedures will be done. Following this track will allow the characterization of aquifers to be improved by producing spatial distributions of parameters coherent with many observations for site-specific situations. In the case of fractured rocks, the vision of Paul Hsieh is that well testing itself is insufficient. It is only one technique among others used to characterize an aquifer and then, according to him: "*Effective integration of the different techniques is a key challenge for the future.*" (Hsieh 2000).

Effective research also requires that the various communities involved in well hydraulics to communicate. It is not apparently better nowadays than in the 1980s when Ramey was already pointing out this important lack and wishing a better future: "*The future promises closer communication between these two technologies, [*petroleum engineers and hydrologists*] with obvious benefits for the public.*" (Ramey 1982). An effort in this direction would probably help avoid such annoying situations as a simple method to interpret recovery data published in 1980 in the oil industry, and described in several petroleum engineering books (Raghavan 1993; Horne 1995), was plagiarised in 2003 in the hydrogeological literature (Ground Water 2004).

Finally, a point that has not often been mentioned: why have well hydraulics seen so little controlled experimentation in the lab? There are noticeable exceptions such as the tremendous efforts conducted by Williams (1981) to construct a piece of aquifer and to study the impact of different well screens and gravel packs on the efficiency of a water well. There are also the more recent experiments conducted by Silliman and Caswell (1998) that demonstrated very clearly the impact of aquifer heterogeneity on well tests. But is that all? How can all the theories, analytical and numerical models really be tested without hard data obtained under controlled conditions?

Considering the issue of deciding whether well testing may have past its research peak and have shifted into the realm of engineering application is a wrong question. When Theis had difficulties interpreting field data, most of the hydrogeological community was using well-established techniques. Probably, many hydrogeologists at that time would have considered hydraulic testing as belonging already to the realm of engineering applications. Nonetheless a revolution occurred. Today the most widespread opinion is that improving transmissivity estimates slightly by conducting additional research in well testing is useless in practice. This may be true in many cases. However, not being able to correctly understand the hydraulic behavior of a given well in a given aquifer is not a good starting point to start dealing with even more complex phenomena in practice, such as reactive solute transport or multiphase flow for CO_2 sequestration in deep aquifers.

In conclusion, this paper has outlined what the author believes to be the most probable future trends of well hydraulics during the 21st century and has emphasized several important needs (education, relation with oil industry, databases, uncertainty, integration with other techniques). There will also be some unpredictable revolutions. However, such revolutions require a fight to preserve space for fundamental research in this field.

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