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Extending Traditional Technology of Aquifer Characterization Through Numerical Models

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ABSTRACT

This is the final Technical Completion Report of Projects No. W-830 funded by the Water and Wildlands Resources Center of the University of California. This report consists of two parts. Part 1 entitled, *"Hydraulic Characterization of Aquifers, Reservoir Rocks and Soils: A History of Ideas"* is an integrated review of the development of hydraulic characterization methods in the fields of Civil Engineering, Soil Physics, Groundwater Hydrology and Petroleum Engineering. The narrative portion of this part is followed by a set of over 500 references pertaining to hydraulic characterization which represent our current knowledge of hydraulic characterization methodologies in the earth sciences and engineering. The second part entitled, *"A Numerical-Model/Spreadsheet Integration for Hydraulic Characterization of Aquifers, Reservoir Rocks and Soils"* presents a new interpretive tool that is under development for hydraulic characterization of groundwater systems, petroleum reservoirs and soils. Both the literature survey presented in Part 1 and the development of the interpretive tool presented in Part 2 are continuing research efforts. The narrative portion of Part 1, after informal peer review is expected to be submitted for publication in an archival journal. A systematic review of the more-than 500 references is a challenging, time-consuming task. Efforts will continue on a detailed review of the compiled literature for eventual publication. The development of the interpretive tool is part of a Masters research project of a graduate student. A prototype computer software, **AQTRUST** is expected to be ready by the time the M.S. research is completed by the summer of 1997. A preliminary demonstration of the software will take place during the Fall Annual meeting of the American Geophysical Union, San Francisco, in December, 1996. When future publications materialize from these continuing investigations, the support of the Water and Wildlands Resources Center will be appropriately acknowledged.

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PART 1

HYDRAULIC CHARACTERIZATION OF AQUIFERS, RESERVOIR ROCKS AND SOILS: A HISTORY OF IDEAS

With a Classified Bibliography

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ABSTRACT

Estimation of the hydraulic properties of aquifers, petroleum reservoir rocks and soil systems is a fundamental task in many branches of earth sciences and engineering. The transient diffusion equation proposed by Fourier early in the 19th century for heat conduction in solids constitutes the basis for inverting hydraulic test data collected in the field to estimate the two basic parameters of interest, namely, hydraulic conductivity and hydraulic capacitance. Combining developments in fluid mechanics, heat conduction and potential theory the civil engineers of the nineteenth century such as Darcy, Dupuit and Forchheimer solved many useful problems of steady-state seepage of water. Interest soon shifted towards the understanding of the transient flow process. The 1920s saw remarkable developments in several branches of the earth sciences; Terzaghi's analysis of deformation of water-saturated earth materials, the invention of the tensiometer by Willard Gardner, Meinzer's work on the compressibility of elastic aquifers and the study of the mechanics of oil and gas reservoirs by Muskat and others. In the 1930s, these led to a systematic analysis of pressure transients from aquifers and petroleum reservoirs through the work of Theis and Hurst. Over the past fifty years, many researchers have built on the the foundations laid in the 1930s. Notable among these are, Boulton, Bredehoeft, Cooper, Jacob, Hantush, Hubbert, Philip, Ramey, Warren and Root, and others. The response of a subsurface flow system to a hydraulic perturbation is governed by its geometric attributes as well as its material properties. In inverting field data to estimate hydraulic parameters, one makes the fundamental assumption that the flow geometry is known *a priori*. This approach has generally served us well in matters relating to resource development, primarily concerned with forecasting fluid pressure declines. Over the past two decades, earth scientists have become increasingly concerned with environmental contamination problems. The resolution of these problems requires that hydraulic characterization be carried out at a much finer spatial scale, for which adequate information on geometric detail is not forthcoming. Traditional methods of interpretation of field data have relied heavily on analytic solutions to specific, highly idealized initial-values problems. The availability of efficient numerical models and versatile spread-sheets offer promising opportunities to relax many unavoidable assumptions of analytical solutions and interpret field data much more generally, with fewer assumptions. Perhaps the time has come to look for a new conceptual foundation to quantitatively characterize subsurface systems to meet the emerging sophisticated needs.

INTRODUCTION

In order to solve practical problems of interest in the fields of groundwater seepage, hydrogeology, agricultural engineering, petroleum engineering, environmental engineering, soil physics and geophysics, it is necessary to have reliable estimates of hydraulic parameters such as permeability, hydraulic capacitance and porosity. Since the early work of Darcy, Dupuit, Forchheimer and others in Europe during the second half of the nineteenth century, a substantial body of literature has accumulated in diverse fields of earth sciences and engineering pertaining to methods for estimating hydraulic characteristics by inverting data collected from experiments conducted on field installations. For a student of the earth sciences, it is of considerable interest not only to gain an understanding of how the ideas relating to hydraulic characterization have evolved historically but also to decipher the fundamental notions which unite all these methods.

It is reasonable to state that all the hydraulic characterization methods in use today have two themes in common: an equation of motion, familiarly known as Darcy's Law, which gives formal identity to the notion of permeability and the equation of transient heat conduction, originally proposed by Fourier in 1807, which has established itself as the working model for diffusion-type processes in physical sciences. The equation of motion is imbedded in the diffusion equation.

Intrinsic to the transient diffusion equation (stemming from Fourier's equation of transient heat conduction) are the parameters hydraulic conductivity and hydraulic capacitance[1]. In turn, hydraulic capacitance includes, among other properties, the porosity of the porous medium. The transient diffusion equation provides the foundation for hydraulic characterization. Ultimately, all the hydraulic characterization methods consist of fitting the field data to the transient diffusion equation and finding the best combination of parameters which agree with the field data. Thus hydraulic characterization methods are "inverse" methods concerned with the estimation of parameters compatible with the diffusion model.

In the inversion venture outlined above, earth scientists and engineers have historically relied

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[1] The terms storativity and specific storage are often used in groundwater hydrology to denote hydraulic capacitance and specific hydraulic capacity of water-saturated geologic materials. For purposes of generality we shall prefer, in this work, the term hydraulic capacitance, which includes storativity as a special case. Hydraulic capacitance represents the quantity of water released from storage due to a unit change in potential due to a combination of three independent processes, namely, pore volume change, change in water saturation and expansion of water.

on the use of "analytic solutions" (also referred to as closed-form solutions). A variety of ingenious techniques (type-curve matching, early-time and late-time approximations) have been devised to back the parameters out from the field data. Taking advantage of developments in digital computers, researchers have, over the past two decades, been successfully experimenting with numerical models to estimate hydraulic parameters by way of "calibration" exercises. With the improvements in the reliability of solutions generated by numerical models and the increased availability of powerful "spreadsheets", there are indications that numerical models will soon become preferred tools of inversion of field data to estimate hydraulic parameters. Numerical models are especially attractive because they can help minimize many assumptions that enter into the idealizations which are essential for obtaining closed-form solutions.

At present, as the personal computer drastically changes our approach to analyzing field data from hydraulic tests, it is worth our while to summarize our current knowledge of hydraulic characterization in a systematized manner and to look ahead into the future. So motivated, the present work is an attempt to take an integrated view of concepts, ideas and methods developed in agricultural engineering, soil physics, hydrogeology, petroleum engineering, civil engineering, geophysics and related fields. This is a substantial task, considering the vast amount of literature that has accumulated on this topic over many decades. Under the circumstances, the goal of the present study is a modest one of generating an overall synthesized understanding of the field based primarily on literature from the U.S. Even in this regard, no claim is made that the literature compiled is comprehensive or complete. The hope is that the literature surveyed is adequate enough to capture the essential elements of the major ideas and concepts of relevance. Hall (1954) presented a well-reasoned review of literature on the topic of seepage towards wells. His survey is especially comprehensive in regard to the 19th century European literature. Hall's paper has been a valuable source of information in regard to the European literature discussed in the present work.

This work primarily focusses on field methods rather than laboratory methods. The hydraulic response of a subsurface flow system is governed by its geometric attributes as well as its material properties. In inverting field data to estimate hydraulic parameters, tradition is to assume that the geometric attributes of the flow system is known and the hydraulic parameters are assumed to be the unknowns to be estimated. This work is restricted to those methods in which geometric details (symmetry, layering) are assumed known *a priori*. Over the past two decades, an increasing body of literature has accumulated on the application of stochastic methods and probability concepts to the hydraulic characterization of heterogeneities (especially hydraulic conductivity) in subsurface flow systems. These methods are outside the scope of the present work.

The history of science is such that ideas are born and methods are fabricated in response to pure curiosity or practical needs. Integration of ideas to identify underlying unity among diversity comes later. Individual disciplines in the earth sciences have generally been focussed on problems of special interest to their needs. For example, until recently, soil physicists have devoted much of their attention to the process of infiltration into soils and the movement of water in the root zone. Thus, although the various earth disciplines have a common thread of unity in terms of physical processes governing hydraulic characterization, these disciplines have traditionally maintained distinct identities with very limited flow of ideas between themselves. A consequence is that when one attempts an integration of ideas as in the present work, the portrayal of the individual disciplines cannot be very even. This is unavoidable.

HISTORY OF IDEAS

It is now well recognized that our conceptual model for understanding the occurrence and movement of fluids in geological materials is based on treating fluid flow as a process mathematically analogous to heat conduction in solids. As a consequence, the working mathematical model for the flow of fluids in geologic materials is the partial differential equation of heat conduction, originally proposed by Fourier (1807)[2]. Fifty years later, Darcy (1856) described a simple equation of motion for the steady flow of water through sands, now widely known as Darcy's Law. Intrinsic to Darcy's Law is the parameter *hydraulic conductivity* which is a measure of the ability of a porous material to transmit water. Earlier, in 1842, Poiseuille had already studied the flow of fluids through capillary tubes, applying rigorous principles of fluid mechanics. Thus, it is reasonable to assume that in defining the mathematical form of the equation of motion and in defining the hydraulic conductivity parameter of earth materials, Darcy was

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[2] As described by Grattan-Guinness (1972), Fourier's 1807 monograph on the propagation of heat was not formally published. After much additional work to answer criticisms of the reviewers (Laplace, Lagrange, Monge and LaCroix), Fourier's classic, *Theorie Analytique de la Chaleur*, was published in 1822

influenced by Fourier's work on heat conduction as well as developments in fluid mechanics of engineered materials (capillary tubes) and open channels.

Immediately following Darcy's insightful contribution, analogy with heat conduction was actively used by engineers in Austria, France and Germany to solve practical problems of groundwater seepage which were of interest to civil engineers during the second half of the 19th century. Although Fourier's general equation addressed the transient heat conduction process, these civil engineers restricted themselves to the steady state fluid flow problem. Whereas the transient process involves two parameters (conductance and capacitance) the steady state problem involves only the conductivity parameter.

The following discussion of development of ideas in Europe during the 19th century is based on Hall (1954), who, as a civil engineer, reviewed the European literature in considerable detail. Julian Dupuit, a contemporary of Darcy was a theoretically oriented civil engineer who dealt with problems of open channel flow as well as seepage through soils. The chapter on seepage in his book on open channel flow (Dupuit 1863) later proved to be a standard reference on the subject. It is interesting that Dupuit, starting from the hydraulic principles of open-channel flow, derived an expression for movement of water through soils which proved to be equivalent to Darcy's empirical Law. By integrating the equation in a radial system, Dupuit derived solutions for steady flow in a confined aquifer (artesian well) and in an unconfined aquifer (gravity well). He idealized the well to be at the center of a circular island so as to satisfy the mathematical needs of a credible boundary conditions. The assumptions of horizontal flow he made in the case of a gravity well in an unconfined aquifer, while yet accounting for the variation in the saturated thickness of the aquifer is used even now and is referred to as the Dupuit assumption. To be mathematically consistent with the boundary conditions, Dupuit idealized the well as being located at the center of a circular island.

In Germany, Adolf Thiem and later, his son, Gunther Thiem, carried out pioneering work on groundwater seepage, especially in the study of flow of water to wells. They are also credited with the collection of extensive observational information on the subject. Although he later became aware of the contributions of Dupuit and Darcy, Adolph Thiem independently derived the expressions for steady radial flow of water in confined and unconfined aquifers. In the field of groundwater hydrology, Gunther Thiem (1906) is widely known for the equation describing the steady radial flow of water in a confined aquifer, although that solution was derived earlier by

Dupuit (1863). Gunther Thiem distinguished himself by systematizing and documenting the application of field methods, rather than creating new methods himself.

At this juncture it is appropriate to briefly digress and discuss terminologies. The word groundwater (grundwasser in german) appears in the literature by the early 1880s in the work of A. Thiem. The engineers of the late 19th century distinguished between "gravity wells" and "artesian wells". The former referred to wells in a phreatic aquifer whose upper boundary is a free surface or the water table over which the pressure is atmospheric. The latter referred to what is currently recognized as a confined aquifer. Although the possibility of a seepage face above the water level in a gravity well was recognized, the term "seepage face" had not yet been coined. Aquifers were commonly referred to as "groundwater streams" (Hall 1954).

Perhaps the most well-known researcher of this era was Phillip Forchheimer of Austria, whose distinguished career spanned nearly a half century and influenced the work of many researchers who followed him. He was among the earliest to recognize the concepts of isopotential lines and streamlines in regard to groundwater seepage and extended these concepts systematically to generate flownets as a means of quantitatively analyzing steady flow fields, including flow of water to wells under varying geometric conditions. Forchheimer formally wrote down the Laplace equation (Forchheimer 1898) to describe the steady flow of groundwater and went on to use mathematical techniques such as conformal mapping to solve problems. It appears (Hall 1954) that he was influenced by the work on conformal mapping of Holzmüller (1882) for the solution of heat conduction problems. In addition to formally explaining the results of earlier workers such as Dupuit and Thiem, Forchheimer presented new results for single wells as well as groups of wells and sloping aquifers.

In the United States, Slichter (1899) pioneered the study of groundwater systems by mathematically analyzing the steady flow of water through geologic media. In particular, he investigated mutual interference between artesian wells and the perturbation of the regional steady-state groundwater flow field by a producing water well. Slichter was unaware of Forchheimer's work and formulated the Laplace equation independently. He obtained solutions using the conformal mapping method. It appears that Slichter too, like Forchheimer, was influenced by the work of Holzmüller (1882). Another important contribution of Slichter was that he investigated the physical significance of hydraulic conductivity, which was merely treated as an empirical coefficient by Darcy. By studying the geometric properties of various spherical packs, Slichter (1899) identified the geometric component and the viscous drag components of hydraulic conductivity.

An important milestone relating to flow of water in geologic materials was the contribution of Buckingham (1907). Buckingham, a physicist, studied the flow of water in unsaturated soils and concluded that the moisture movement was proportional to spatial gradient of capillary potential. He further postulated that the "constant" of proportionality was in fact a function of the capillary potential itself in partially saturated soils. It is remarkable that Buckingham, who was probably not aware of Darcy's work (Sposito 1987), gave a theoretical basis for Darcy's empirical law and extended the law to the unsaturated zone. Buckingham's hydraulic conductivity, which is a function of capillary pressure, is central to the fields of soil physics and multi-phase flow analysis still in use today. Buckingham (1914) is also widely known for his seminal contribution on dimensional analysis. Most of the methods used to invert field data to obtain hydraulic parameters on the basis of analytic solutions routinely use dimensionless groups to minimize the number of variables which need to be handled. The rationale for defining these dimensionless groups stems from the "pi theorem" proposed by Buckingham in 1914.

The early Twentieth Century saw the simultaneous initiation of a profound concept in several earth science disciplines: soil science, soil mechanics, groundwater hydrology and petroleum engineering. This was the recognition of the importance of time (Narasimhan 1986; Narasimhan 1988). In their own field settings, researchers in these fields recognized that almost all subsurface fluid flow systems are dynamic in nature. In the field of soil physics, Green and Ampt (1911) proposed a simple approximation to quantify the vertical infiltration of water into an unsaturated soil. The Green and Ampt idealization assumes that as water infiltrates into a soil, a sharp, piston-like zone of saturation advances with time. This approximation is still used in interpreting field data from infiltrometer tests to estimate *in situ* hydraulic conductivity of soils.

Willard Gardner was among the earliest (Gardner and Widtsoe 1921) to quantify transient moisture movement in unsaturated soils in terms of a transient diffusion equation, analogous to Fourier's transient heat conduction equation. It is now known that his failure to achieve satisfactory agreement between experiment and theory was due to the fact that he did not account for the dependence of hydraulic conductivity on capillary potential, suggested a decade earlier by Buckingham. In other words, he tried to fit experimental data to a linear partial differential equation, when in fact, a non-linear parabolic equation should have been used.

The early 1920's saw the publication of the classic book, *Introduction to the Mathematical Theory of Conduction of Heat in Solids,* by Carslaw (1921). This book (and its revision, Carslaw and Jaeger, 1947) constituted a remarkably well-organized compendium of a variety of closed-form solutions to problems in steady state and transient heat conduction problems. The availability of these solutions and the methods used to derive these solutions have proved to be of great benefit to earth scientists and engineers over the past seventy-five years in solving a host of fluid flow problems of the earth's subsurface.

The 1920's saw the publication of two major contributions in the earth sciences. Terzaghi (1924) experimentally studied the deformation of water-saturated clays and established the relationships between external stresses, pore-fluid pressure and deformation. In the process, he introduced the notion of effective stress. Some would consider Terzaghi's paper to have founded the discipline of soil mechanics. Terzaghi proceeded to write down and solve the equation for transient movement of water in a one dimensional clay column by analogy with the heat conduction equation. In his paper, Terzaghi was meticulous in establishing the one-to-one correspondence between the attributes of the heat-conduction system and the porous-medium flow system. Probably he was the first to point out that the compressibility of a clay is analogous to specific heat of a solid.

A second major contribution of the 1920's was the paper by Meinzer (1928), whom many would consider to be the founder of the discipline of groundwater hydrology in the United States. Meinzer's descriptive paper was a careful synthesis of observations by many geologists of the U. S. Geological Survey of the early twentieth century who had studied the decline in water pressures in artesian aquifers such as the Dakota aquifer in North Dakota. Based on mass balance calculations these observations led to the inference that the decline in water pressures were correlated with the decrease in porosity and an increase in water volume which together accounted for the mass of water mined from the aquifer. Considering the fact that the strains so caused in the porous medium and the water are extremely small (less than one part in a million), it was remarkably perceptive of Meinzer and his coworkers to have drawn their inferences based on rough estimates of water balance. Meinzer (1937), in fact, had made rough estimates that the land should have subsided by 4 to 5 inches in the North Dakota artesian basin and this was viewed with skepticism by some contemporary geologists and engineers.

Contemporaneously with Terzaghi's new leadership in the field of soil mechanics, important developments were also taking place in analyzing seepage through soils. Forchheimer (1930) published his book *Hydraulik* and Dachler (1936) published his book on groundwater flow, containing a host of steady seepage problems, including flow to wells. For the first time, a successful attempt was made by Weber (1928) to analyze the non-steady flow of water to a gravity well (that is, non-steady flow to a fully penetrating well in an unconfined aquifer). The approach taken by Weber to analyze this problem is worth some discussion because it differs significantly from the more rigorous mathematical approach of Muskat, Hurst and Theis, who solved a parabolic partial differential equation.

Weber (1928) considered a well in which the water level is maintained constant (constant drawdown test). As pumping progresses, the radius of the cone of depression (also referred to as the radius of influence) increases with time. As a first step in the analysis of this problem, Weber derived an approximate expression for the radius of influence, assuming that water is released from storage by physical drainage of the volume of the aquifer through which the water table moves and that the volume of water so drained per unit volume is the "effective porosity" (the modern notion of specific yield). Mass balance requires that the volume of water so drained is equal to the cumulative production at the well. Once the effective radius is estimated, drawdown as a function of distance from the well is estimated from the steady-state solution of radial flow to a gravity well. About a decade later, similar results were obtained by Steinbrenner (1937) in Austria.

The 1930s witnessed important developments in the fields of soil physics, groundwater hydrology and petroleum engineering. By the late 1920s, the tensiometer had become well developed thanks to the efforts of Willard Gardner *et al.* (1922)[3] and his coworkers. Routine measurements of moisture content and its relation to capillary pressure had become possible (Richards 1928). Combining Buckingham's (1907) work on the equation of water motion in unsaturated soils with the newly available soil moisture retention curves, Richards (1931) formally wrote down, for the first time, the non-linear partial differential equation describing transient flow of water in unsaturated soils. The slope of the moisture content versus capillary pressure curve came

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[3] This Abstract is reportedly the first published reference (Wilford Gardner, personal communication, 1991) to the tensiometer, an instrument which has played a vital role in the evolution of modern soil physics

to be the hydraulic capacitance and was referred to as moisture capacity. Because of the difficulties of obtaining closed form solutions to non-linear differential equations, Richards equation remained unsolved for nearly two decades. It would be the early 1950s before Childs and Collis-George (1950) showed that the severity of nonlinearity of the parabolic equation could be lessened by using volumetric moisture content as the dependent variable, rather than capillary potential. Following this suggestion, Klute (1952), Philip (1955) and others began obtaining solutions for Richards equation under highly simplified conditions using numerical methods.

In the field of petroleum reservoir engineering, the 1930s was an eventful decade. The need for applying rigorous methods of mathematical physics to understanding the dynamics of oil and gas reservoirs had been recognized. The decade started with careful theoretical and experimental study of steady-state flow systems as a prelude to the study of transient systems which followed immediately thereafter. Muskat and Botset (1931) experimentally studied the steady flow of gases in geologic materials and verified that the mass flux of gas was proportional to the drop in the square of the pressure along the flow path. They then went on to formulate the non-linear parabolic equation for transient gas flow in a reservoir and solved the special case of steady radial flow in a circular reservoir with a well at the center and a constant pressure outer boundary. Wyckoff *et al.* (1932) experimentally studied, with the help of physical models, the radial flow of water in a sand body with a free surface (an unconfined aquifer) and verified the assumptions of Dupuit (1863). They also extensively discussed the importance of the seepage face, the capillary fringe and water movement in the unsaturated zone above the water table.

The work on estimating reservoir permeability from transient field tests was initiated by Moore *et al.* (1933). They clearly articulated a need for estimating, from field tests, important properties of reservoir rocks so that the drainage of oil reservoirs could be studied. This little-known work is very significant for many reasons. Although detailed mathematical derivations were not presented, the authors formally laid down the parabolic equation involving a slightly compressible fluid, obtained solutions for a well of finite radius producing at constant pressure from a finite cylindrical reservoir, calculated drawdown and buildup and demonstrated how the solution can be made use of to estimate reservoir permeability. Furthermore, the authors presented their results in terms of the two important dimensionless groups, dimensionless time and dimensionless drawdown. These dimensionless groups have since become part of the petroleum engineering and groundwater hydraulics literature. The mathematical details of this work were presented by Hurst (1934). At about the same time, Muskat (1934) presented a detailed analysis of transient flow of compressible fluids in oil and gas reservoirs. He derived solutions for wells of finite radius as well as vanishingly small radius in a circular reservoir with prescribed potential boundary or with prescribed flow rate at the well. He then went on to verify the veracity of his model with pressure decline data from an oil field in east Texas. Hurst (1934) formulated the parabolic equation in radial coordinates for slightly compressible fluids (liquids) and obtained solutions for production at constant pressure and at constant discharge from a well of finite radius, pumping a cylindrical reservoir of finite radius. Both Hurst and Muskat considered hydraulic capacitance arising purely from fluid expansion and neglected changes in porosity. In 1937 Muskat published his definitive work on the flow of homogeneous fluids through porous media in which he elucidated the fundamental problems of modern petroleum reservoir engineering and the mathematical methods for solving them.

In the field of groundwater hydrology, Theis (1935) set up and obtained a solution to the parabolic equation similar to that of Hurst (1934) and Muskat (1934) but considered a laterally infinite aquifer with a well of vanishingly small radius (line-source well) producing at a constant rate. He verified the credibility of his model by applying it to field data from an unconfined aquifer. Theis used the term *storage coefficient* to denote the hydraulic capacitance parameter in the parabolic equation, a term which still enjoys common usage. Although he was quite cognizant of the analogy between heat capacity and hydraulic capacitance (Freeze 1985) Theis did not explicitly discuss the physical meaning to storage coefficient in his paper. It appears that Theis took a fairly limited view of storage coefficient, restricted to the particular boundary value problem he was interested in, namely, a laterally infinite aquifer of finite thickness, in which water flows horizontally. Thus, Theis (1940) explains storage coefficient as the volume of water released from a vertical prism of the aquifer of unit cross sectional area in response to a unit change in hydraulic head. Moreover, Theis (1940) identifies the role of compressibility in regard to storage coefficient in an artesian aquifer but does not recognize expansion of water. This restricted view of storage coefficient came to enjoy popular usage among groundwater hydrologists in the U.S. Geological Survey in subsequent decades.

Theis' work has proved to be a milestone not only in groundwater hydrology, but in the earth sciences in general. In addition to constituting the basic and simplest technique used widely for interpreting data from transient aquifer tests, the Theis' model is also frequently used as the standard against which the transient behavior of more complex aquifers is studied for comparison. One of the factors contributing to the popularity of Theis' work appears to be the fact that hydrologists of the U.S. Geological Survey actively developed workable techniques for using Theis' solution to interpret field data from aquifer tests and widely communicated their results through publications of the Survey, readily available to field geologists. Also, the contributions provided a large scale regional perspective of hydraulic characterization in terms of earth processes in general while contributions in the fields of civil engineering, petroleum engineering and soil physics took a limited local view of the characterization venture. A landmark publication in this regard was U.S. Geological Survey Water Supply Paper No. 887 by Wenzel (1942), which elaborately described the various methods for interpreting pumping test data.

It is worth noting here that Moore *et al.* (1933), Muskat (1934) and Hurst (1934) were all concerned with laterally limited reservoirs , whereas groundwater hydrologists such as Theis (1935) were concerned, in general, with laterally infinite systems. Also, petroleum engineers concentrated on developing techniques for analyzing data from the production well whereas groundwater hydrologists devoted attention to pumped-well analysis as well as analysis of interference test data (that, is data from passive, observation wells which respond to the removal of water at the pumped well). More than one reason can be attributed to these differences in the styles of design and analysis of hydraulic tests between petroleum engineers and groundwater hydrologists. According to Brigham (1996) petroleum engineers had to work in general with active well-fields in which many wells were producing fluids at the same time. Under such conditions, planes of no-flow boundaries developed between producing wells, leading to the dynamic isolation of each well. Groundwater hydrologists, on the other hand did not often deal with well fields. Moreover, oil occurs very commonly associated with dissolved natural gas and, as the pressure drops during production, gas tends to come out of solution. A consequence is that the apparent compressibility of such oil may be order of magnitude higher than gas-free oil, leading to a great increase in the effective hydraulic capacitance. In turn, increased hydraulic capacitance contributes to small radius of influence around a production well and hence, the reduced need for interference analysis. Another possible explanation for the differences in styles between petroleum engineering and groundwater hydrology is that petroleum reservoirs often constitute closed systems while groundwater systems are in general open in nature.

Upon reflection, it is evident that the notion of capacitance is essential for describing the transient flow process. In the work of Gardner and Widtsoe (1921), hydraulic capacitance was purely governed by the rate of change of saturation with capillary pressure, referred to as moisture capacity in the soil physics literature. In Terzaghi's work, hydraulic capacitance was governed only by the compressibility of a relatively soft porous material for which one could reasonably neglect the compressibility of water. Meinzer's work combined porous medium compression and fluid expansion in giving form to hydraulic capacitance. Hurst (1934) and Muskat (1934) restricted hydraulic capacitance solely to expansion of the liquid (Narasimhan 1986; Narasimhan 1988). In general, in a saturated-unsaturated deformable porous medium, hydraulic capacitance includes all the three components, namely, pore-volume change, change in water saturation and expansion of water (Narasimhan and Witherspoon 1977).

At present, it is almost invariably assumed by hydrogeologists that the Theis method is applicable to confined aquifers in which water release from storage is due to the elastic properties of the porous medium and of water. However, it must be noted that in his classic paper Theis (1935) applied his method to an unconfined aquifer and stated, "the equation applies rigidly only to water bodies ....and applicable only to unconfined water bodies - in which the water in the volume of sediments through which the water table has fallen is discharged instantaneously with the fall of the water table." However, it had been recognized by previous workers that the drainage of water in an unconfined aquifer is an extremely complex physical process and therefore, as noted by Hall (1954), the instantaneous drainage assumption of Theis is a shortcoming of the Theis method as applied to unconfined aquifers.

Arthur Casagrande is a respected name in the field of soil mechanics. Although he did not publish many papers on the theory of flow to wells, Hall (1954) notes that commencing from 1934 Casagrande introduced his students at Harvard University to novel ideas in regard to seepage theory, including flow of water to wells. As part of his lectures, Casagrande had demonstrated that, for large values of time, the drawdown predicted by the Weber (1928) method and that predicted by the Theis' method are essentially the same.

In the field of civil engineering, a little known but major discovery was made in the early 1930s which was to influence the attention of earth scientists and engineers for the next half a century.

Rappleye (1933) of the U.S. Coast and Geodedic Survey carefully documented substantial "areal subsidence" of land in the Santa Clara Valley of California based on rerunning of first-order leveling surveys during 1931-32. He reported that between 1920 and 1933 a bench-mark in San Jose had subsided by 4.1 feet and that as much as 0.5 feet of that subsidence had occurred during 1932-33. Although heavy groundwater pumpage was suspected to be the cause of the subsidence (Tibbetts 1933), it was left to Meinzer (1937) to advance a rational physical mechanism correlating groundwater pumpage and observed land subsidence. Not only did Meinzer recognize the applicability of his North Dakota observations (Meinzer 1928) to the San Jose subsidence, but also conjectured that the substantial magnitude of subsidence observed was probably due to a preponderance of soft, fine-grained sediments in the Santa Clara basin. As we shall see later, Meinzer's conjecture was confirmed subsequently by meticulous field observations by Poland and coworkers in the Santa Clara Valley and the San Joaquin Valley of California.

The decade of the 1940s was quite eventful in the study of transient groundwater systems. Hubbert (1940) published the *Theory of Ground-water Motion*, a paper which still remains definitive. In this paper Hubbert elaborated the physical meaning of a fluid potential, formally defined permeability on the basis of balance between impelling forces and resistive forces, derived a tangent law for the refraction of flow lines and went on to establish the foundations for the study of regional groundwater systems and petroleum reservoirs.

We saw earlier that Theis (1940) took a restricted view of storage coefficient limited to horizontal flow in an elastic aquifer. However, Jacob (1940) took a much more fundamental view of storage coefficient in the sense of hydraulic capacitance and derived an expression combining the deformability of the porous medium (its bulk modulus) and the compressibility of water. He thus gave formal identity to the processes heuristically recognized by Meinzer (1928; 1937). He also went on, in this classic paper, to derive an expression for the change in water pressures in aquifers subjected to external stress changes such as those caused by passing railroad trains or barometric pressure changes and defined the parameter, *tidal efficiency.* Jacob's theoretical work paved the way for interpreting hydraulic parameters of aquifers by analyzing these responses. Jacob went on to make two other major contributions during the 1940s. In 1946 he published a paper on radial flow to a leaky aquifer, which opened up a fertile area of research relating to leaky aquifers and leaky caprocks of petroleum reservoirs. It is not quite clear as to how much Jacob was influenced by the land subsidence research of the 1930s. It is now well-established that the study of leaky aquifer systems and the study of land subsidence in sedimentary basins go hand in hand. Also, motivated by engineering issues of production efficiency, Jacob (1947) devoted attention to hydraulic efficiency of the well, as water dynamically flows from the aquifer. He defined the notion of effective well radius and the well-loss function. In accounting for well-losses, Jacob accounted for non-laminar flow conditions arising due to high flow-velocities in the vicinity of well-screen. Such flows are some times referred to as "non-Darcy" flow. In the field of petroleum engineering, van Everdingen and Hurst (1949) used the Laplace Transformation to quantify the effects of well-bore storage on pressure transients around a pumping well and also accounted for *skin effects* arising from formation damage in the immediate vicinity of the well.

These developments in the fields of hydrogeology and petroleum engineering occurred primarily because the researchers mentioned above were interested in aquifers and reservoirs with fairly large areal extent, lying at depths of a few hundred meters or more. In such formations, the region of pressure perturbation around the well often extended to several hundred meters or more. However, in the fields of soil physics and civil engineering, transient flow problems of interest were of a smaller spatial scale. Soil scientists and agronomists were primarily interested in the plant root zone of the soil above the water table, seldom exceeding a few meters from the land surface. Civil engineers and geotechnical engineers on the other hand were interested in seepage and ground settlement problems extending from a few meters to perhaps a few tens of meters. The nature of problems tackled by these researchers was such that they needed to estimate hydraulic parameters rather quickly and inexpensively. Soil physicists dealing with soils in the vadose[4] zone were confronted not only with significant spatial variability on the scale of their observation but also had to contend with a very difficult-to-solve highly non-linear diffusion process. Out of practical necessity, judicious compromise between mathematical rigor and practical need gave rise to greatly simplified models, resulting in field techniques based on infiltrometers, constant-head permeameters, auger-hole tests and variable-head permeameters.

The auger-hole methods and piezometer methods were pioneered by Kirkham (1946), Luthin

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[4] The phrase vadose zone denotes the region between the water table and the land surface within which water and air coexist in the pore spaces. It is also referred to as the zone of aeration or the unsaturated zone.

and Kirkham (1949) and van Bavel and Kirkham (1948). These methods are still being used and improved to estimate the hydraulic conductivity of the saturated soil below the water table. Essentially these are field adaptations of the variable-head permeameter. Although the experiment itself involves a non-steady flow process, the interpretation logic neglects the role of hydraulic capacitance. The time-dependant falling water level is treated as a function, among other factors, of the hydraulic conductivity of the soil and a shape factor dependent on the flow geometry. Because the flow geometry involved combinations of radial, hemispherical and vertical components of flow, a great deal of effort was spent by Kirkham and others to calculate shape factors for a variety of field conditions. Thus, calculating the shape factors using available mathematical techniques constituted an important part of developing these techniques.

As in the case of soil science, the variable-head permeameter was found to be adequately inexpensive and rapid to satisfy the hydraulic characterization needs in the field of civil engineering. Special efforts were made to systematize and standardize these methods. A widely used work in this regard was that of Hvorslev (1951), published under the auspices of the U.S. Army Corps of Engineers. In providing a set of shape factors for a number of field situations, Hvorslev drew upon earlier work of Dachler (1936) and others.

A significant contribution of the 1950's was the work of N.S. Boulton, a civil engineer from England. As was noted earlier, Theis (1935) illustrated the credibility of the transient groundwater flow equation by applying it to data gathered from an unconfined aquifer. Nevertheless, as Theis himself recognized, his method hinged on the assumption that water drained instantly from the zone through which the water table declined. However, it was recognized by many that the drainage of water, governed by the theory of capillary potential, was a time-dependent, non-instantaneous process[5]. A need was felt by some researchers to mathematically account for this non-instantaneous process. Boulton (1954) initiated investigation of the transient flow of water to a well in an unconfined aquifer. Instead of venturing to rigorously solve the highly complex flow process above the water table as embodied in Richards equation, Boulton (1954) simplified the effect of the unsaturated zone by introducing the approximation of *delayed yield* in conjunction with the notion

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[5] This time-dependent drainage is mathematically analogous to chemical disequilibrium processes such as precipitation or dissolution. Therefore, it is reasonable to term the non-instantaneous drainage of water from the zone through which the water table moves as kinetically-controlled drainage

of specific yield. The resulting governing equation was solved for potentials within the saturated domain, while yet approximately accounting for contribution from the unsaturated zone by means of a time-dependent source term. With minor modifications and extensions, Boulton's model still continues to be used by groundwater hydrologists as the basis for estimating parameters of an unconfined aquifer.

Another important contribution of the 1950's was the work by Skempton (1954). A soil mechanician, Skempton investigated the relations between external stress changes (including shear) and the changes in pore fluid pressure in water saturated soils. Skempton proposed pore pressure coefficients *A* and *B*, which are related in principle to the concept of tidal efficiency proposed earlier by Jacob but accounts for multi-dimensional deformation and pertain to the effects of mean principal stress (coefficient B) and the effects of shear stress (coefficient A). The foundations for estimating the hydraulic parameters of an aquifer from passive response of wells to barometric tides, earth tides and ocean tides are contained in the contributions of Jacob (1940) and Skempton (1954).

Soon after the publication of Theis' work, groundwater hydrologists developed several approaches to interpret drawdown data as well as data on water level recovery after cessation of pumping (Theis 1935). Although groundwater hydrologists were routinely using Theis' recovery method for over a decade, it was not until the 1950s that the petroleum engineers developed methods to analyze pressure build-up (or pressure recovery) data. Research in this direction was pioneered by Horner (1951) and Miller *et al.*, (1950). Incidentally, it appears that modern pressure transient analysis in petroleum engineering commenced during the 1950s, after the second world war.

By now, the field of groundwater hydrology had become well enough established and a definitive text book on groundwater hydrology was published by Todd (1959). This book devoted considerable attention to groundwater hydraulics and presented a comprehensive literature on the topic. Roger de Wiest brought to the western world some of the developments in the erstwhile Society Union by translating the book, Theory of Groundwater Movement by Polubarinova-Kochina (1952).

The decade of the 1960s witnessed many and varied developments of significance to hydraulic characterization. The monograph on Theory of Aquifer Tests by Ferris *et al.* (1962) provided a comprehensive description of pumping tests and slug tests under a variety of aquifer conditions, geometry, boundary conditions and flow rates. A group of groundwater hydrologists at the U.S.

Geological Survey, led by Hilton Cooper, elegantly extended the Theis approach to solve many well-defined initial value problems which have since enabled hydraulic characterization under test conditions which are more general than those of Theis (1935). Among these contributions one should take special notice of, the interpretation of data from slug tests (Cooper, *et al.* 1967), analysis of pressure transient data from an anisotropic aquifer (Papadopulos 1965), transient flow of water to a well of large diameter (Papadopulos and Cooper 1967), and response of a well to seismic waves (Cooper *et al.* 1965). The work on seismic response showed how a well could, under certain conditions, amplify a seismic signal. The theoretical developments related to anisotropy and seismic response of wells were verified by Papadopulos and by Bredehoeft with the help of electrical analog models involving the use of resistors, capacitors and harmonic oscillators. Following this work, Bredehoeft (1967) analyzed the response of aquifers to earth tides, giving consideration to multidimensional strains experienced by an aquifer and proposing a method for estimating the storage coefficient (hydraulic capacitance) of an aquifer. This work continues to be widely used to interpret passive response of aquifers to earth tides..

The study of leaky aquifers, pioneered by Jacob a decade earlier was continued with vigor by Hantush and Jacob through the 1960's. Because they were primarily concerned with groundwater as a resource, Hantush and Jacob focused attention on analysis of drawdown data from the aquifer itself and did not venture into obtaining solutions for changes in potential within the aquitards which constituted the source of leakage. Hantush provided a comprehensive summary of developments related to leaky aquifers as well as other aquifer configurations in the publication, *Hydraulics of Wells*, Hantush (1964).

The leaky aquifer problem attracted the attention of petroleum engineers from two different perspectives. On the one hand, they were aware of leakage of oil into reservoir rocks from leaky cap rocks. On the other hand, they were also interested in the role of leaky cap rocks in the context of artificial storage of natural gas in deep aquifers. In the latter case, it was critical that the "integrity" of the caprock and its ability to keep the gas trapped in the aquifer be known. This necessitated a knowledge of the pressure changes in the aquitard itself rather than just the aquifer. Accordingly, Neuman and Witherspoon (1969) extended the leaky aquifer model of Jacob and Hantush to hydraulically characterize the aquifer as well as the aquitard.

Following the discovery of land subsidence in the Santa Clara Valley (Rappleye 1933; Meinzer

1937) Poland started a systematic study of land subsidence in different parts of California. Over the next four decades Poland and coworkers of the U.S. Geological Survey collected a wealth of data confirming Meinzer's (1937) conjecture about the importance of fine-grained sediments in contributing to large subsidence magnitudes as well as the applicability of Terzaghi's one-dimensional consolidation theory to large-scale geologic systems. Poland and Davis (1969) documented these observations in a classic paper. Note that from a process point of view, land subsidence is a manifestation of the hydraulic capacitance parameter.

During the 1960s the movement of oil in fractured reservoirs attracted the attention of petroleum engineers for two different reasons; the depletion of naturally fractured reservoirs and the pressure response of reservoirs stimulated by hydraulic fracturing. The analysis of flow in naturally fractured reservoirs received significant impetus from the work of Barenblatt and others (Barenblatt *et al.* 1960) in the former Soviet Union who proposed a model for the dynamic, macroscopic interactions between a pervasive high diffusivity continuum (fracture network) embedded in which are islands of low-diffusivity continua (porous rock-matrix). The work of Barenblatt *et al.* (1960) was extended formally to the study of petroleum reservoirs with idealized fracture networks by Warren and Root (1963). The conceptual basis provided by Warren and Root is still widely used in the fields of petroleum engineering and hydrogeology. The frequently referred to phrases: *double-porosity systems*, *dual-porosity systems* and *multiple-interacting continua*, derive their existence from the work of Barenblatt *et al.* (1960) and Warren and Root (1963).

By the 1960s stimulation of low-permeability reservoirs by hydraulic fracturing had become commonplace in petroleum production engineering. Through an elegant analysis of the mechanics of hydraulic fracturing in an elastic rock, Hubbert and Willis (1957) showed that massive hydraulic fractures tend to manifest themselves as planar vertical fractures or horizontal fractures depending on ambient tectonic stress conditions. It became immediately clear that such high permeability planar fractures will profoundly perturb the radial flow field around the production well. Prats (1961) was among the earliest workers to investigate the effects of discrete vertical fractures on the steady flow of oil into a well. Soon the analysis was extended to transient flow conditions by Scott (1963) and subsequently many others.

In the field of geophysics, the technique of hydraulic fracturing, originally developed for petroleum reservoir stimulation, was perceived as a means of estimating *in situ* rock stresses through "min-frac" experiments. Drawing upon the theoretical foundations of Hubbert and Willis (1957), Kiehle (1964), Haimson and Fairhurst (1969) and others pioneered work in this direction.

The 1960s saw many text books, monographs and articles published indicating the extensive interest among earth scientists on the topic of subsurface hydraulic characterization. The text books by Davis and de Wiest (1966) and de Wiest (1967) addressed issues of hydraulic characterization, among other topics. Narasimhan (1969) provided an overview of contemporary methods available for analyzing pumping test data. Walton (1970) and Kruseman and de Ridder (1970) described various field techniques for groundwater resource evaluation by means of aquifer tests. In the field of petroleum engineering, Matthews and Russell (1967) published their definitive monograph on pressure buildup and flow test analysis. Witherspoon *et al.* (1967) described aquifer characterization methods pertinent to underground storage of natural gas. In the field of civil engineering, Harr (1962) and Cedergren (1967) published authoritative texts on groundwater, seepage and flownets. An excellent practical guide for water-well drilling engineers, including details of aquifer tests was published in 1966 by the Johnson Division of UOP Inc. of Minnesota, a firm known for the manufacture of well-screens and other equipment. Another notable publication of the 1960s was the book dealing with the physical principles of percolation and seepage by Bear *et al.* (1968) sponsored by UNESCO under its Arid Zone Research Programme.

In the field of geophysics, the technique of hydraulic fracturing, originally developed for reservoir stimulation, was perceived as a means of estimating in situ rock stresses through "mini-frac" experiments. Drawing upon the theoretical foundation of Hubbert and Willis (1957), Kiehle (1964), Haimson and Fairhurst (1969) and others pioneered work in this direction.

Perhaps the most significant research direction of the 60s was the development of numerical models. The era of the digital computer had dawned and computer development was advancing with incredible rapidity. The digital computer provided the possibility of solving transient fluid flow problems in complex geological systems which are far beyond the reach of closed form solutions. The finite element method (Clough 1960) which was initially designed for solving structural engineering problems, was soon adapted to solve steady state and transient problems of groundwater flow (Javandel and Witherspoon 1968). In the field of petroleum engineering, Fayers and Sheldon (1963) illustrated the use of a digital computer to solve fluid flow problems in three dimensions using the classical finite difference approximations. In the field of civil engineering

Tyson and Weber (1964) presented an integral form of the finite difference method which could efficiently handle groundwater systems with complex geometry. One of the important upshot of the development of the numerical model was the effort to hydraulically characterize the field system on the basis of observed water levels in numerous wells. Hydraulic characterization is achieved by a process of trial and error adjustment of hydraulic parameters in a numerical model to best match the field data. This approach to hydraulic characterization is popularly referred to as the *inverse method.* Inverse methods, stemming from this approach, continue to engage the attention of researchers today.

The 1970s witnessed a shift in research emphasis among earth scientists from issues based on resource development to issues related to environmental degradation. Research on topics introduced in the previous decades was continued but new issues pertaining to chemical contamination began to be introduced. The delayed drainage concept of Boulton (in relation to unconfined aquifers) was questioned by Neuman (1972), who invoked vertical anisotropy instead of delayed drainage to account for the pressure transient behavior of unconfined aquifers. In keeping with emerging interest in environmental issues, strong research interests continued in improving methods for characterization of shallow groundwater systems and the vadose zone, in particular, slug tests, permeameters and infiltrometers. In the field of petroleum engineering, considerable interest continued on the characterization of naturally fractured reservoirs. In order to better understand hydraulic properties of the vadose zone, Weeks (1978) devised a field method for evaluating pneumatic conductivity and diffusivity of the vadose zone based on transmission of barometric pressure changes from the land surface to the water table.

Among the publications of the 1970s dealing with the general topic of field characterization methods the following may be mentioned. Glover (1974) discussed a variety of analytical solutions pertaining to transient groundwater hydraulics from the perspective of irrigation and drainage; Lohman (1972) surveyed the topic of groundwater hydraulics; and text books by Bouwer (1978), Bear (1979) and Freeze and Cherry (1979) appeared in the field of groundwater hydrology. The U.S. Bureau of Reclamation (1977) published a manual on ground-water hydrology to aid practically in the investigation, development and management of groundwater systems. In the field of petroleum engineering, Earlougher (1977) reviewed advances in well test analysis and Ramey (1976) provided fresh insights into the practical aspects of well test analysis. Strelsova (1978), combined ideas from Boulton, Barenblatt and others and analyzed their relevance to well tests in heterogeneous hydrogeological systems.

During the 1980s, groundwater contamination arising from leaky gasoline tanks from gas stations and contamination arising from the uncontrolled disposal of industrial hydrocarbons such as lubricants, transformer oils and cleaning fluids came into unexpectedly sharp focus. Also, as a potentially serious health hazard, attention was given to the entry of radon gas into human dwellings in regions of the United States underlain by granitic rocks. In late 1987 the Congress of the United States decided that unsaturated zone disposal of high-level radioactive wastes at Yucca Mountain in Nevada would be the preferred geologic disposal alternative and that detailed site characterization studies should be carried out there before licensing. As a result, there has been a great impetus among researchers to develop techniques for characterizing the hydraulic properties as well as the pneumatic properties of the vadose zone.

Until the 1980s hydraulic characterization of soils by soil physicists and agricultural engineers was by and large limited to measuring the saturated hydraulic conductivity below the water table using auger hole tests, piezometer tests and permeameter tests pioneered by Kirkham, Bouwer and others. The 1980s saw notable effort among soil physicists to estimate, in the field, hydraulic characteristics of unsaturated soils. The theoretical basis for these efforts was largely provided by the work of Philip (1969), Wooding (1968) and others in Australia. The Guelph Permeameter (Reynolds and Elrick 1985) was a constant-head permeameter designed for small unlined bore holes a few meters deep, designed to estimate saturated hydraulic conductivity as well as the matrix flux potential. The latter is an integral of the unsaturated hydraulic conductivity, between the limits of ambient pressure head in the vicinity of the bore hole and zero pressure head. The 1980s also saw the development of Disc Tension permeameters (Clothier and White 1981; White and Perroux 1987; Perroux and White 1988). Designed for measuring the vertical hydraulic conductivity of the soil at the land surface, this instrument was especially designed to apply a constant moisture tension boundary condition at the land surface to enable infiltration at a water potential less than atmospheric. Based on theoretical analysis of infiltration from circular ponds, the disc permeameters involved infiltration experiments carried out under prescribed moisture suctions imposed at the disc at the land surface and measuring the infiltration rates. In essence, these are constant-head permeameters, except that a constant moisture suction is imposed. Interpretation of data is incumbent on several idealizations; for example, it is often assumed that hydraulic conductivity is exponentially related to moisture suction. In addition to saturated hydraulic conductivity, the disc permeameters enabled the estimation of sorptivity. In systems involving one-dimensional infiltration, sorptivity is related to the square root of matric flux potential mentioned earlier. Although the physical meaning of sorptivity is not very clear, it has proved to be of practical utility as a quantifiable mathematical parameter.

The 1980s also saw active research designed to understand the role of water in influencing natural earthquakes. To aid in the interpretation of these field experiments, researchers extended Bredehoeft's (1967) work to interpret the response of aquifers to barometric tides, earth tides, ambient changes in tectonic stresses and earthquakes.

Among publications of the 1980s concerned in general with characterization of groundwater systems, mention must be made of the text books by de Marsily (1986) and Fetter (1980). In the field of soil science, Klute (1982) edited a comprehensive two-volume work concerned with methods of soil analysis. Part 1 of this series included several invited articles dealing with infiltrometers, permeameters, auger-hole methods and other field techniques. Another useful publication summarizing methodologies relating to permeameters and infiltrometers was the special publication of the Soil Science Society of America edited by Topp *et al.* (1992). Books devoted to the topic of well-test analysis were published by Strack (1989) and Dawson and Istok (1991) in groundwater hydrology and Sabet (1991) in petroleum engineering.

The past twenty-five years, commencing from the early 1970s, have witnessed significant changes in the motivation for hydraulic characterization as well as the approaches used for the purpose. Interest in resource development has been accompanied by an increasing interest in mitigating and preventing the contamination of natural resources. There has been a growing desire to identify geological formations of very low hydraulic conductivity in which toxic wastes can be safely disposed. As a consequence, topics such as leaky aquifers and unconfined aquifers have gradually receded from the focus of attention of researchers. Interest has been steadily growing in characterizing flow processes in the vadose zone, which mediates between the wastes deposited at the land surface and the water table at depth. Methods are being developed to quantify the movement of air, gases and vapor through the vadose in addition to moisture movement. The dynamic coupling between gases in the vadose zone and atmospheric pressure changes is proving to be of considerable practical interest.

Major multimillion dollar hydraulic characterization ventures have been supported by the U.S. Department of Energy (DOE), the U.S. Nuclear Regulatory Commission (NRC), the U.S. Environmental Protection Agency (EPA) and others to hydraulically characterize heterogeneities in simple aquifers, in fractured rock systems and in unsaturated media. Current emphasis is on characterizing the details of heterogeneity at different scales because such detailed information is necessary for quantifying the migration of contaminant plumes. As attempts are made to physically describe the heterogeneities in greater and greater detail, it is being realized that the traditional methods based on the differential equation are inadequate. For example, attempts to characterize fractured rock systems through interference tests and tracer tests have shown that on the scale of observation carried out, these systems can hardly be treated as homogeneous media.

THE PRESENT

At the present time we have access to field instruments (*e.g.* pressure transducers, flow meters) of unprecedented precision. Automatic data loggers enable us to acquire data at frequencies of less than a second. Powerful desk-top computers enable us to collect, store, retrieve and manipulate enormous amounts of data. Yet we are confronted with peculiar limitations of data interpretation. The paradigm of our data interpretation is the partial differential equation. Concepts of homogeneity and continuity are prerequisites for applying the differential equation to a given system. Consequently, one has to set up one separate differential equation for each of the components in a heterogeneous system and couple them together at their interfaces. Thus we must have an appropriate macroscopic scale in which a differential equation is physically meaningful and the hydraulic parameters have physical significance. Yet attempts are frequently made to apply the differential equation on a scale smaller than an appropriate macroscopic scale to estimate hydraulic parameters. We are also challenged by another problem of scale. Each experiment provides us with parameter estimates on its own scale, varying from perhaps less than a meter in the case of disk tension permeameters of the shallow subsurface to perhaps hundreds of meters in the case of interference test of deep aquifers.

Upon reflection it is clear that the hydraulic response of a transient subsurface flow system is governed by two major attributes; geometry and material properties. To estimate hydraulic properties, we must assume *a priori* knowledge of geometry. All our traditional methods of hydraulic parameter estimation are based on this recognition. Thus, our ability of hydraulic characterization is constrained by this need. Yet, to meet the needs of solving contaminant transport problems, we actively seek information on the nature of heterogeneities within the formation being tested. Unfortunately, we do not have adequate geometric details of these heterogeneities. As a consequence, the task of inverting data from field hydraulic tests such as those involving permeameters, slug tests and aquifer tests to say something about small-scale heterogeneities is neither simple nor unique. Some researchers have resorted to using stochastic methods to overcome this constraint. How effectively these methods are in this regard remains to be seen.

It appears that we are philosophically in a state of transition. We are finding our traditional paradigm to be limited in its ability to provide us the types of answers we need. We have unprecedented abilities to collect data. Nonetheless, we are in search of a new paradigm to enable us to do justice to vast amounts of data gathered by way of interpretation. The new paradigm must reconcile with the fact that although the laws of physics are applicable to fluid-flow systems of the earth's subsurface, the parameters linking cause and effect can never be precisely quantified because we do not have the ability (nor will we ever have the ability) to fully describe the geometry of the system. Without a full description of the geometry, cause and effect cannot precisely be related to each other.

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PART 2

A NUMERICAL-MODEL/SPREADSHEET INTEGRATION FOR HYDRAULIC CHARACTERIZATION OF AQUIFERS, RESERVOIR ROCKS AND SOILS

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ABSTRACT

Analytic solutions have traditionally formed the basis for estimating hydraulic parameters from field data pertaining to aquifers, soils and petroleum reservoirs. We make a departure from this tradition by developing a methodology based purely on a numerical model. Crucial to this development has been the recent availability of powerful spreadsheets which enable efficient interfacing between the interpreter and the generic numerical model. Accordingly we have integrated the QuatroPro™ spreadsheet with a numerical model, TRUST, to generate a tool of interpretation (AQTRUST) for analyzing data from a variety of field tests including: the vadose zone, confined and unconfined aquifers, fully or partially penetrating wells, slug tests, pumping tests, variable flow rates, effects of well-bore storage and skin, and so on. In this report we present a description of this model/spreadsheet integration and demonstrate the usefulness of this methodology with practical examples. The credibility of the numerical model is also demonstrated by comparison with existing analytic solutions. The hope is that this tool can be made available to researchers in different disciplines to further their research through the availability of a reliable methodology of hydraulic characterization

MOTIVATION

Field methods are essential for estimating hydraulic characteristics of aquifers. These characteristics include hydraulic conductivity, *K*, hydraulic capacitance (also referred to as storativity), and porosity, *n*. Since the 1930's, following the work of Theis in groundwater hydrology and Hurst, Muskat and others in petroleum engineering, a vast amount of literature has accumulated on methodologies to conduct transient field experiments and estimate hydraulic conductivity and hydraulic capacitance. In parallel, similar methods were also developed in fields of soil science and civil engineering to estimate hydraulic conductivity in soils.

All these methods are based on the analogy between transient flow in porous media and transient heat conduction in solids. In particular, the partial differential equation (the parabolic equation or its special forms, the Laplace or Poisson equations) form the basis of analyzing the field data to back out the hydraulic parameters. The traditional practice, still widely followed, is to "solve" the partial differential equation for a particular set of forcing conditions and to use the resulting analytic solutions (also referred to as closed-form solutions) to invert the field data-set and estimate the parameters of interest.

With recent developments in computing technology, the data are now being inverted using computers. Along these lines, it is a common practice to directly program the analytic solutions into the computer and then to match field data against the programmed analytic solutions to estimate the parameters of interest. Although this approach has been helpful, it is constrained by the limitations inherent to the analytical solutions themselves. In particular, analytical solutions often depend on many simplifying assumptions in relation to system geometry, material properties and forcing functions. In contrast, personal computers, offer powerful possibilities of data inversion without depending on the analytical solution. This can be achieved through numerical models.

Although the advantage of numerical models has been known for some time, it's practical use in hydraulic characterization has been somewhat limited, because it is often cumbersome to prepare the input files for specific field situations to be fed into the computer program. Over the last few years, with the development of spreadsheets, the interface with the numerical model has become more efficient. Spreadsheets of increasing sophistication allow for an ease of handling large amounts of data from field tests. Graphing capabilities aid in the interpretation and representation of the field data and to compare estimated hydraulic parameters and numerical model results.

The motivation of this research is to develop a comprehensive tool for interpreting aquifer test data with fewer simplifying assumptions, which is easy to use by Earth Scientists and Engineers. We are developing a menu-driven tool that can be customized to account for specific attributes of field test configurations and well installations. We are combining an already existing subsurface fluid flow model (water, oil, gas) written in Fortran computer code with QuatroPro™, a commercially available spreadsheet.

LOGICAL BASIS

Traditionally in the fields of hydrogeology, petroleum engineering, soil science and civil engineering, the statement of the physics of subsurface fluid flow has been in terms of a partial differential equation, subject to a set of initial conditions, boundary conditions, sources, and sinks. Simplifying assumptions are necessary to render the partial differential equation amenable to obtaining analytic solutions. These assumptions include simple geometry, time-invariant material properties, constant flow rate, non-periodic boundary conditions and so on.

We depart from this tradition by viewing the physical problem of transient fluid flow as one of mass conservation over discrete elemental volumes, subject to mass transfer between adjoining volume elements through constraints of the equation of motion (Darcy's Law). The resulting integral equations of individual elements linked to each other are conveniently solved in the high-speed digital computer. This is inherently a forward problem. To achieve the inverse solution, we use a trial and error calibration process, in which one first uses an estimated set of hydraulic parameters (hydraulic conductivity and hydraulic capacitance), obtains the numerical solution, and then compares the numerical solution with the observed field data. If the comparison is not acceptable, the estimates for the parameters are revised and the process is repeated until the refined, estimated parameter leads to a solution that closely agrees with the field data.

THEORETICAL BASIS

We consider transient or steady-state, isothermal flow of fluids in geologic materials of the earth's subsurface. The fluids of interest could be liquid or gas. The discussion presented below is divisible into three parts: flow of liquids, flow of gases and the transport of a single dissolved chemical species.

In presenting a unified description of the governing equations, one has to contend with the different conventions used by researchers in different disciplines. For example, petroleum engineers use fluid pressure, p, as the dependent variable while groundwater hydrologists, soil physicists and civil engineers prefer to use potentiometric head as the dependent variable. For purposes of elucidation and comparison we will present the forms used in more than one convention.

Flow of Liquids

The partial differential equation governing the transient flow of a liquid stems from the general statement,

$$- div \cdot q = C_r \frac{\partial \phi}{\partial t} , \tag{1}$$

where q is Darcy velocity given by,

$$q = - K \nabla \phi , \tag{2}$$

in which K is hydraulic conductivity, C is specific hydraulic capacity (analogous to specific hear capacity) and ϕ is fluid potential. In water saturated geologic materials (2) takes the familiar form,

$$\nabla \cdot K \nabla \phi = S_s \frac{\partial \phi}{\partial t} , \tag{3}$$

where $\phi = z + \psi$ is the potentiometric head in which z is elevation and ψ is pressure head, K is hydraulic conductivity and S_s is *specific storage.* Specific storage is defined as the change in volume of water per unit bulk volume of the material per unit change in potentiometric head. Physically,

$$S_s = \rho_w \, g \, [\alpha + n \, \beta_w] \; , \tag{4}$$

where α is the compressibility of the porous matrix defined as,

$$\alpha = \frac{1}{V_B} \, \frac{\Delta V_w}{\Delta p} \; , \tag{5}$$

where ΔV_w is change in volume of water, ρ is density of water, n is porosity, and β is compressibility of water. We recognize that water is a slightly compressible fluid and β_w is a constant.

In the field of petroleum engineering, (3) is written with pressure as the dependent variable as,

$$\nabla \cdot \frac{k}{\mu} \, (\rho_w \, g \, \nabla z + \nabla p) = n c_t \, \frac{\partial p}{\partial t} \; , \tag{6}$$

where k is absolute permeability, μ is the dynamic coefficient of viscosity, p is pressure, and c_t is *total compressibility*, defined as,

$$c_t = n \, (\frac{\alpha}{n} + \beta_{oil}) \; . \tag{7}$$

Note that the left hand sides of (3) and (5) include the effects of gravity in the form of the elevation term z.

It is not uncommon to see (5) frequently written as,

$$\nabla \cdot \frac{k}{\mu} \, \nabla p = n \, c_t \, \frac{\partial p}{\partial t} \; . \tag{8}$$

Note that in (8) we have dropped the gravity term from the left hand side. Equation 7 is meaningful only under certain special conditions. For example, when flow is purely horizontal, (7) is valid. Equation (7) is inappropriate for systems in which vertical components of flow are known to exist.

Because most of the field methods of hydraulic characterization involves wells, boreholes or piezometers, it is convenient to express (3) in cylindrical coordinates as,

$$K \left[\frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r} \frac{\partial \phi}{\partial r} + \frac{\partial^2 \phi}{\partial z^2} \right] = S_s \frac{\partial \phi}{\partial t} , \tag{9}$$

If one restricts attention to purely horizontal flow, (9) reduces to,

$$K \left[\frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r} \frac{\partial \phi}{\partial r} \right] = S_s \frac{\partial \phi}{\partial t} . \tag{10}$$

For purely horizontal flow, (9) takes on an equivalent form,

$$\frac{k}{\mu} \left[\frac{\partial^2 p}{\partial r^2} + \frac{1}{r} \frac{\partial p}{\partial r} \right] = n \, c_t \frac{\partial p}{\partial t} . \tag{11}$$

Equations (3), (5), (9), (10) and (11) are often referred to as parabolic equations. When one restricts attention to a steady state flow system, the time derivatives in the above equations vanish and they reduce to the Laplace equation. For example, in cylindrical coordinates, the Laplace equation has the form,

$$\frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r} \frac{\partial \phi}{\partial r} + \frac{\partial^2 \phi}{\partial z^2}] = 0 . \tag{12}$$

A steady state flow system with sources or sinks at a finite number of points (*e.g.* production wells and injection wells in an aquifer) is described by the Poisson equation. In Cartesian coordinates pertaining to two-dimensional horizontal aquifers, the Poisson equation has the form,

$$\nabla \cdot K \, \nabla \phi = Q(x,y) . \tag{13}$$

It is a common convention to assume that the subsurface flow system is initially under hydrostatic conditions. When this assumption is made, one can conveniently neglect effects of gravity and write the parabolic equation in terms of drawdown of potentiometric head. Thus, for example,

$$K \left[\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r} + \frac{\partial^2 s}{\partial z^2} \right] = S_s \frac{\partial s}{\partial t} , \qquad (14)$$

where $s(r,z,t)$ is the drawdown defined as,

$$s(r,z,t) = \phi_o - \phi(r,z,t) , \qquad (15)$$

in which ϕ_o is the initial potentiometric head representing hydrostatic conditions.

These equations need to be augmented by appropriate boundary conditions. Under conditions of purely saturated flow, the relevant boundary conditions are of two kinds: prescribed potential (Dirichlet condition) and prescribed flux (Neumann condition). An impermeable boundary is a Neumann boundary with zero flux. The well is also generally treated as a prescribed flux boundary.

Note that in the equations described above, the parameters k, K, and S_s are all assumed to remain constant in time in order that the equations are amenable to being solved. Under this condition the equations are said to be linear.

It is worth recognizing here that a differential equation represents conservation of mass at a location within a single homogeneous material. If the flow domain of interest comprises more than one material (that is, if it is a heterogeneous system) one differential equation must be set up for each material component and their solutions made to agree at the appropriate material interfaces.

To obtain mathematical solutions to the aforesaid partial differential equations and to interpret the significance of the solutions in a systematic way, the use of dimensionless groups is extremely useful. The rationale for defining these groups stems from the Pi Theorem of Buckingham (1914). Two dimensionless groups which are fundamental to many interests in many systems relating to hydraulic characterization are,

dimensionless time, t_D

and dimensionless pressure, P_D .

Although the equation governing transient fluid flow in geologic media is mathematically similar to Fourier's transient heat conduction equation, the physical processes of fluid flow and heat conduction are vastly different in nature. Heat conduction has no attribute analogous to external stresses. In heat conduction, temperature (analogous to pressure) is a function only of heat (analogous to quantity of water); in transient fluid flow in porous media, however, pressure is a function of quantity of water as well as of external stresses acting on the material. Thus, in such a system, fluid pressure is a function of two state variables, quantity of water, M_w and external stresses, σ. Therefore, the total differential (or simply, the total change) in pressure has two components,

$$dp = (\partial p)_\sigma + (\partial p)_{M_w} . \tag{16}$$

On the right hand side of (16), the first term represents change in pressure caused by change in quantity of water with the external stresses remaining unchanged. Indeed, the parabolic equation of transient groundwater flow involving Darcy's Law stems from this partial differential. The second term on the right hand side of (16) relates to change in pressure caused by changes in fluid pressure induced by changes in barometric pressure, effects of earth tides and the like. In order to describe the change in pressure caused by all effects (that is, groundwater movement governed by Darcy's Law as well as effects of external stress change) we need to expand (10) and (11) to read,

$$\frac{K}{S_s}\left[\frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r}\frac{\partial \phi}{\partial r}\right]_\sigma + \frac{T_E}{\rho_w g}\left(\frac{\partial \sigma}{\partial t}\right)_{Mw} = \frac{\partial \phi}{\partial t} , \tag{17}$$

and,

$$\frac{k}{\mu n c_t}\left[\frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r}\right]_\sigma + T_E\left(\frac{\partial \sigma}{\partial t}\right)_{Mw} = \frac{\partial p}{\partial t} , \tag{18}$$

where T_E is tidal efficiency. Depending on the nature of the external stress changes, one could use Skempton's coefficients in place of T_E in (17) and (18). Equations (17) and (18) provide a basis for interpreting passive response of aquifers to barometric changes, effects of earth tides and related effects.

Unsaturated Flow

The linear partial differential equations given above relate to the flow of oil or water under conditions of full saturation of the respective fluid. When the flow system has more than one fluid present in the pores, the system is said to be unsaturated. Capillary pressure at fluid-fluid interfaces play a major role in the physical behavior of such systems and the governing differential equation becomes non-linear. In the field of soil physics, one is interested in systems with water and air as the permeating fluids. The non-linear differential equation describing transient flow in such systems is Richard's equation,

$$\nabla \cdot K(\psi)\ \nabla(z+\psi) = C_h(\psi)\frac{\partial\psi}{\partial t}\ , \tag{19}$$

where $K(\psi)$ denotes the dependence of hydraulic conductivity on ψ, and $C_h(\psi)$ denotes the dependence of hydraulic capacitance on ψ. Also, ψ in (19) denotes the gage pressure head so that $\psi>0$ in the domain with water and $\psi<0$ in the unsaturated domain. Implicit in (19) is the assumption that air pressure in the unsaturated domain remains constant at 0 and that (19) relates only to the flow of water.

The hydraulic capacitance term on the right-hand side of (19) includes three components, namely, compressibility of porous medium, compressibility of water and rate of change of saturation with ψ. The hydraulic capacitance is a strong function of ψ. Moreover, in order to account for matrix compressibility under unsaturated conditions, one has to consider the complex relationships between pressure head and stresses (Bishop, 1955; Narasimhan and Witherspoon, 1977).

Equation (19) is generally extremely difficult to solve. Many of the solutions available relate to one-dimensional flow domains with K assumed to be an exponential function of ψ. In the capacitance term, it is customary to neglect matrix compressibility and water compressibility and restrict consideration to the rate of change of saturation with ψ.

Gravity and capillary pressure effects combine to give rise to a boundary condition known as the seepage face which is peculiar to unsaturated, gravity-drainage systems. On the seepage face $\psi=0$ (a constant potential boundary), water can only get out of the seepage face when the gradient of potential is directed outward. The seepage face acts as an impermeable boundary when the gradient of potential is directed inward, towards the flow domain.

NUMERICAL MODEL

The numerical model used as the tool of interpretation in this study is TRUST (Narasimhan et al., 1978) which uses the Integral Finite Difference Method (Narasimhan and Witherspoon, 1976). In this algorithm, the flow domain is discretized into elemental volumes of arbitrary shape and mass conservation is implemented through a set of interlinked algebraic equations. The hydraulic capacitance of individual volume elements is a function of its ability to deform, its ability to desaturate and the ability of water to expand in response to changes in fluid pressure. The transfer of water between adjoining elemental volumes depends on the hydraulic resistance between the volume elements. In order to compute the hydraulic resistance one has to have knowledge of the local flow geometry in addition to the hydraulic properties of the materials contained in the elemental volumes. Although the calculation of hydraulic resistance is a difficult task in the case of heterogeneous media in which flow geometry may change arbitrarily with time, the task becomes greatly simplified in those systems in which the flow geometry is *a priori* known. In the present work, we restrict attention to flow systems in which either radial flow (with or without flow in the vertical direction) can be assumed to be a reasonable idealization of the field conditions. Consequently, in calculating hydraulic resistances and mass transfer between elements, flow geometry is assumed known in the manner suggested by Narasimhan (1985). The applicability and the usefulness of the TRUST model has been illustrated through previous publications (Narasimhan and Witherspoon, 1978; Narasimhan, 1982).

In general, the algorithm handles spatial variations in material properties (heterogeneity), anisotropy, dependence of material properties on fluid pressure (saturated-unsaturated flow, pressure sensitive material properties), time dependent boundary conditions and arbitrary initial conditions. Because of the generality of this model in regard to system geometry, material properties, forcing functions and initial conditions, it is in principle, a powerful tool for analyzing data from field hydraulic tests involving complex geometry and material attributes. However, traditionally a practical limitation has been that providing the necessary information input to the algorithm by the interpreter has been a cumbersome task. Furthermore, the processing of the model output by comparison with observed data to back out the hydraulic parameters by way of iterative adjustment has also been a non-trivial task. Fortunately, the traditional limitations have become amenable to a great deal of simplification through the availability of commercially available spreadsheets. Essentially, then, we can conveniently use the spreadsheet (a) as a preprocessor for generating the input to the numerical model, and, (b) use the graphics in the spreadsheet as a means of comparing the output generated by the numerical model with the observed data.

In order to understand how the spreadsheet may be used as a preprocessor, it is useful to briefly describe the input data organization of the TRUST algorithm. In the algorithm, input information is organized into the following categories: problem control parameters (Block 1), material properties (Block 2), properties of the fluid (Block 3), volumetric properties of the elemental volumes (Block 4), properties of inter-volume flow connections (Block 5), boundary conditions (Block 6 and Block 7), time-dependent sources and sinks (Block 8) and initial conditions (Block 9). In AQTRUST, these blocks of information are handled through a set of interlinked "pages" of the spreadsheet, along with an input "page" to describe the anatomy of the field test. Perhaps the most cumbersome part of this description is the development of the information relevant to Block 4 and Block 5, where the geometry of the problem is systematically described. To minimize this difficulty we make use of the axisymmetric flow assumption. This assumption greatly simplifies the generation of the geometric information from the minimal information provided in the "input" page by way of well radius, screen length, aquifer thickness and so on. In addition, the axisymmetric assumption also enables us to design the computational grid in such a fashion that nodal points are generated to correspond exactly to the locations of observation wells or piezometers from which the data have been collected. This enables, int he interpretation process, the simultaneous comparison of calculated and observed data in backing out the hydraulic parameters. This process avoids the need for interpolation between solution points. In this process, the logic presented in Narasimhan (1985) is used.

THE MODEL-SPREADSHEET INTERFACE

The input page is used to describe the various attributes of the field test conditions. An example is shown in Figure 1. As the attributes are entered they are automatically translated via appropriate links into information compatible with the TRUST Fortran statements. In addition, the observed data from the various observation wells or piezometers are also entered. In addition to the test attributes, the interpreter also enters a set of estimates for the hydraulic parameters that are to backed out (e.g. hydraulic conductivity, specific storage). In the next step, a "macro" is implemented to convert the spreadsheet pages into a set of input files for the numerical model to read.

Following this the numerical model is executed. For convenience, the output information is written into separate files. One of these files contains the time history of change in fluid potential (or hydraulic head or drawdown) at locations corresponding to the locations of the one or more observation wells. This file is then imported into the spreadsheet and formatted appropriately with the help of macros and graphically portrayed along with the observed data. If the "match" between the observed data and the computed values is acceptable, the estimated hydraulic parameters used in the simulation is taken to be the desired estimates. If, not, the estimates used in the input page are suitably revised and the whole process repeated once again.

Application of the Tool

At the present stage of development, we have implemented the methodology described above to generate the numerical solutions for the types of field situations given in Table 1. That is, we describe the field set up in the input page along with estimates of relevant hydraulic parameters of interest. Based on the information of the input page, the numerical solution is obtained and the results are ready to be compared with field data or with analytic solutions. We have been successful in obtaining excellent agreement with the analytical solutions, so much so, we believe that the numerical model and the proposed methodology are reasonable and sound. We will soon be testing the method against field data.

Two Illustrative Examples

Finite Radius Well, with Finite Skin and Constant Flow Rate

The first illustration pertains to steady pumpage of water from a well with a finite casing radius of 0.1 m, piercing a confined aquifer of thickness 10 m (screen length). The well screen resides in a bore-hole of radius 0.125 m, the annulus acting either as a gravel-pack or as a skin. The scenario consists of a pumping test conducted for 11 days with a constant flow rate of 0.01 m^3/s. The initial, static water level is 100 m above datum, and the aquifer is fully screened. The relevant input data along with other field properties were entered into the input page shown in figure 2.

We use this illustration to evaluate the accuracy of the numerical solution as compared to an analytical solution presented by Agarwal *et al.* (1970). Accordingly, we chose $K_{aquifer}$, K_{skin}, and $S_{s,aquifer}$ in such a fashion that the dimensionless well-bore capacitance, C_D was 100. We generated the solution for this particular case and compared the results with the analytic solution corresponding to C_D=100 of Table 3 of Agarwal *et al.* (1970).

As can be seen from the graph in figure 3, the comparison is quite good. If, instead of the analytical solution we had field data, then we would have iteratively adjusted the estimated hydraulic parameters of the input page until the corresponding numerical solution matched with the field data in an acceptable manner.

Partial Penetration Pumping Test with Anisotropy (Screened Mid-Aquifer)

In the second illustration we present the case of a partially penetrating well with a finite well-bore radius and anisotropy. For this case we do not present an analytical solution. This case simply shows that the methodology has the ability to handle complex flow geometries. This scenario consists of a pumping test conducted for 11 days in a ten meter thick confined aquifer which is partially screened mid-way over a five meter interval. There are three observation wells located at 2, 10, and 20 meters from the pumped well, and the vertical hydraulic conductivity is one tenth the horizontal hydraulic conductivity. The input parameters used are shown in figure 4.

The varying distances of observation wells from the pumping well indicated the influence of anisotropy on the resultant hydraulic head with time. Using the same parameters, the isotropic case (shown as symbols in figure 5) was also solved numerically and compared with the anisotropic case. The graph (figure 5) of the numerical results for the pumping test demonstrates the stronger effect of anisotropy (shown as solid lines) closer to the pumping well. This is to be expected because in an aquifer that is partially penetrated by a well, three dimensional flow patterns exist close to the pumping well, whereas beyond a distance equal to about 1.5 to 2.0 times the aquifer thickness (Todd, 1980), the vertical flow resulting from partial penetration no longer influences the flow paths.

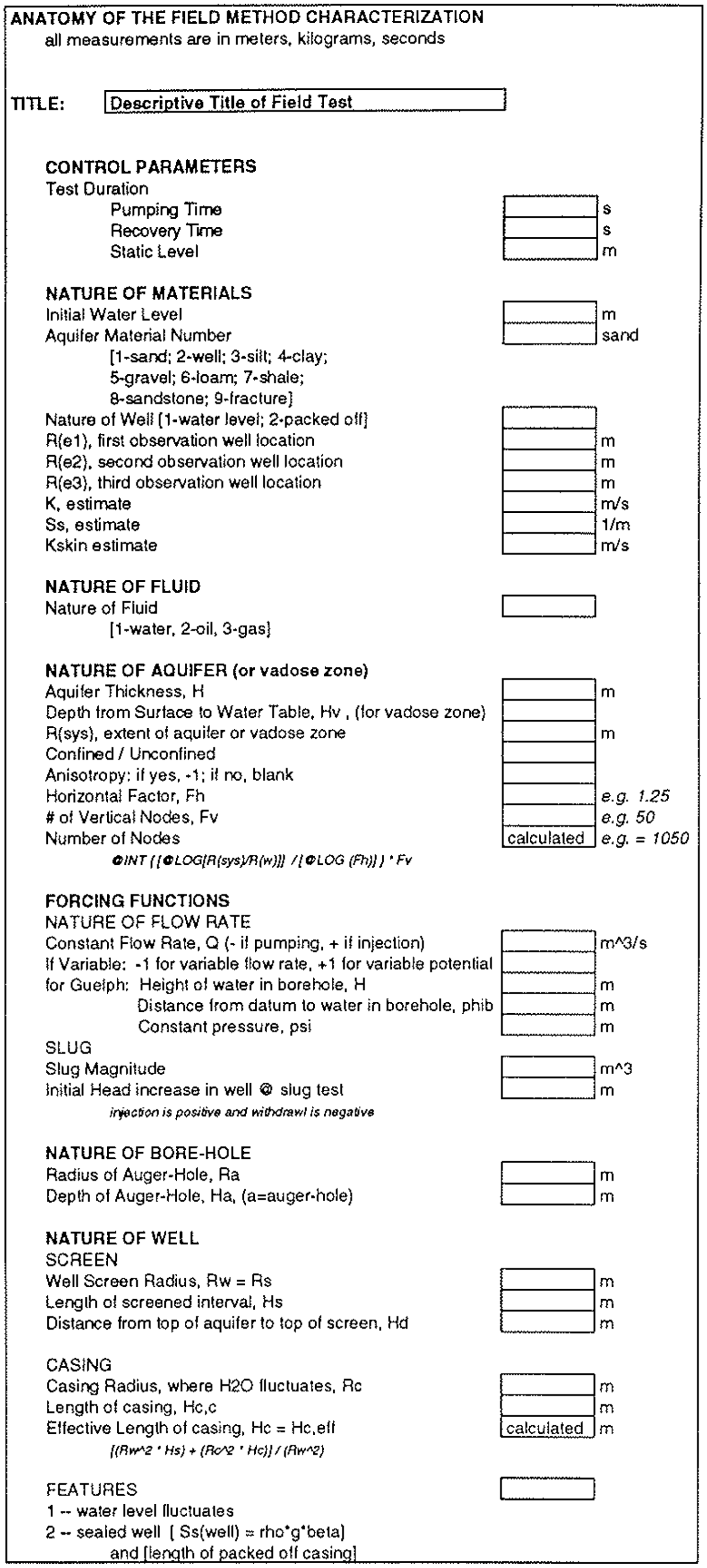
If this had represented an actual pumping test, the field data from each of the wells would have been compared to the values obtained from the numerical solution. If the match between the observed data and the computed values was acceptable, the estimated hydraulic parameters used in the simulation would be taken as the desired estimates. If not, the interpreter would revise the values on the input page and repeat the process until suitable matches were made.

Current Status

We are in the process of developing a set of macros to efficiently compare the output information from the numerical model with field data to facilitate the iterative process. As already indicated, at present we have addressed the cases included in Table 1. Our goal is to extend this capability to systems involving saturated-unsaturated flow, fluids with prescribed properties (water, oil, air), double porosity systems, leaky aquifer systems, multi-aquifer wells and so on. This numerical-model/spreadsheet interface will be used to analyze field test data and become part of a M. S. Thesis.

ACKNOWLEDGMENTS

We are grateful for the financial support by the Director, Center for Water and Wildland Resources of the University of California. This support has allowed us to extend the traditional technology of aquifer characterization through numerical models.



ANATOMY OF THE FIELD METHOD CHARACTERIZATION
all measurements are in meters, kilograms, seconds

TITLE: Descriptive Title of Field Test

CONTROL PARAMETERS

Test Duration		
Pumping Time		s
Recovery Time		s
Static Level		m

NATURE OF MATERIALS

Initial Water Level		m
Aquifer Material Number [1-sand; 2-well; 3-silt; 4-clay; 5-gravel; 6-loam; 7-shale; 8-sandstone; 9-fracture]		sand
Nature of Well [1-water level; 2-packed off]		
R(e1), first observation well location		m
R(e2), second observation well location		m
R(e3), third observation well location		m
K, estimate		m/s
Ss, estimate		1/m
Kskin estimate		m/s

NATURE OF FLUID

Nature of Fluid [1-water, 2-oil, 3-gas]		

NATURE OF AQUIFER (or vadose zone)

Aquifer Thickness, H		m
Depth from Surface to Water Table, Hv , (for vadose zone)		
R(sys), extent of aquifer or vadose zone		m
Confined / Unconfined		
Anisotropy: if yes, -1; if no, blank		
Horizontal Factor, Fh		*e.g. 1.25*
# of Vertical Nodes, Fv		*e.g. 50*
Number of Nodes	calculated	*e.g. = 1050*

*@INT ([@LOG[R(sys)/R(w)]] /[@LOG (Fh)]) * Fv*

FORCING FUNCTIONS

NATURE OF FLOW RATE

Constant Flow Rate, Q (- if pumping, + if injection)		m^3/s
If Variable: -1 for variable flow rate, +1 for variable potential		
for Guelph: Height of water in borehole, H		m
Distance from datum to water in borehole, phib		m
Constant pressure, psi		m

SLUG

Slug Magnitude		m^3
Initial Head increase in well @ slug test		m

injection is positive and withdrawl is negative

NATURE OF BORE-HOLE

Radius of Auger-Hole, Ra		m
Depth of Auger-Hole, Ha, (a=auger-hole)		m

NATURE OF WELL

SCREEN

Well Screen Radius, Rw = Rs		m
Length of screened interval, Hs		m
Distance from top of aquifer to top of screen, Hd		m

CASING

Casing Radius, where H2O fluctuates, Rc		m
Length of casing, Hc,c		m
Effective Length of casing, Hc = Hc,eff	calculated	m

*[(Rw^2 * Hs) + (Rc^2 * Hc)] / (Rw^2)*

FEATURES 1 -- water level fluctuates 2 -- sealed well [Ss(well) = rho*g*beta] and [length of packed off casing]		

Figure 1. Input page for AQTRUST, a numerical-model/spreadsheet integration.

Table 1. AQTRUST Scenario Titles.

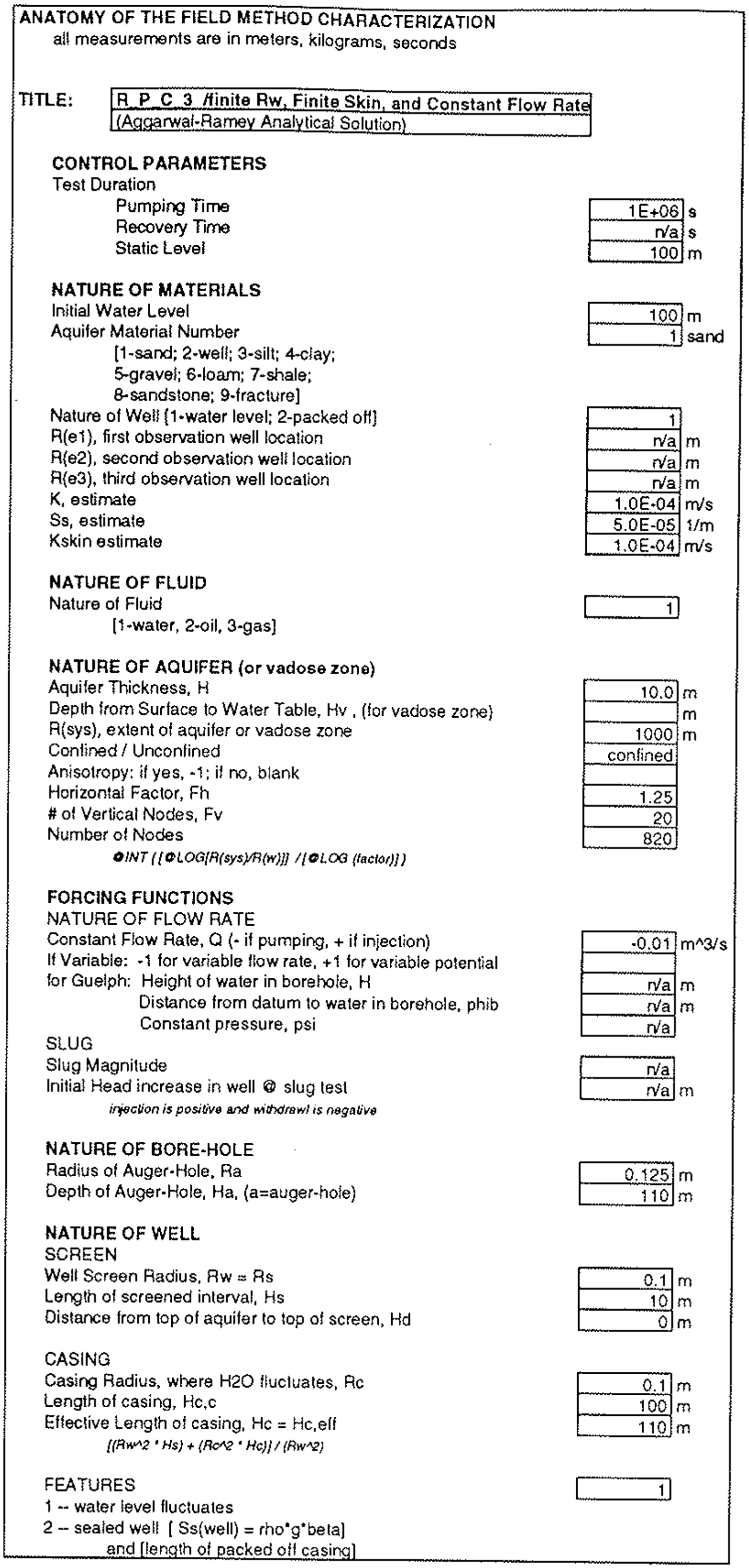
Geometry:
R: radial
C: cylindrical

Forcing Function:
P: pumping
S: slug
I: infiltrometer

Aquifer Type:
C: confined
U: unconfined
V: vadose zone

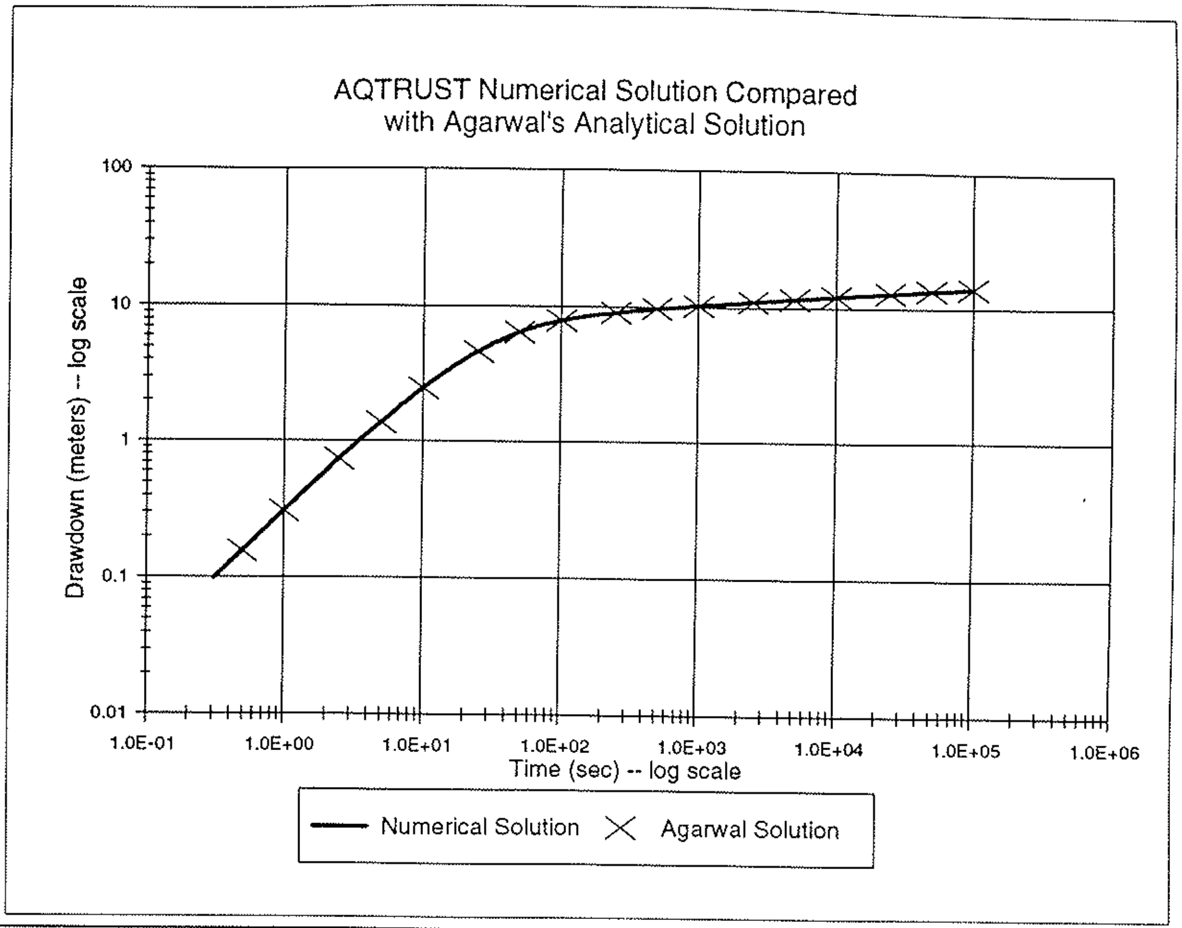
Geometry_ForcingFunction_AquiferType_ScenarioNumber

Radial Flow Geometry	
R_P_C_1	Line Source with Constant Flow Rate (Theis Solution)
R_P_C_2	Finite Rw, No Skin, and Constant Flow Rate (Agarwal-Ramey Analytical Solution)
R_P_C_3	Finite Rw, Finite Skin, and Constant Flow Rate (Agarwal-Ramey Analytical Solution)
R_P_C_4	Finite Rw, No Skin, and Variable Flow Rate
R_P_C_5	Finite Rw, No Skin, and Constant Drawdown
R_P_C_6	Finite Rw, No Skin, Constant Flow Rate, and Shut In
R_S_C_1	Slug Test with No Skin (Cooper Analytical Solution)
R_S_C_2	Slug Test with Skin
R_S_C_3	Pressure Pulse Slug Test
Cylindrical Geometry	
C_P_C_1T	Finite Rw, Partial Penetration with Top of Aquifer Screened
C_P_C_1M	Finite Rw, Partial Penetration with Middle of Aquifer Screened
C_P_C_1B	Finite Rw, Partial Penetration with Bottom of Aquifer Screened
C_S_C_1T	Partial Penetration Slug Test with Top of Aquifer Screened
C_P_C_1	Full Penetration Pumping Test with Anisotropy
C_P_C_2T	Partial Penetration Pumping Test with Anisotropy with Top of Aquifer Screened
C_S_C_1	Slug Test with Full Penetration and Anisotropy
C_S_C_2T	Slug Test with Partial Penetration at Top of Aquifer and Anisotropy
C_I_V_1	Guelph Permeameter with Hydrostatic Initial Conditions
C_I_V_2	Guelph Permeameter with Constant Psi Initial Conditions



ANATOMY OF THE FIELD METHOD CHARACTERIZATION		
all measurements are in meters, kilograms, seconds		
TITLE:	R_P_C_3 /finite Rw, Finite Skin, and Constant Flow Rate (Aggarwal-Ramey Analytical Solution)	
CONTROL PARAMETERS		
Test Duration		
Pumping Time	1E+06	s
Recovery Time	n/a	s
Static Level	100	m
NATURE OF MATERIALS		
Initial Water Level	100	m
Aquifer Material Number [1-sand; 2-well; 3-silt; 4-clay; 5-gravel; 6-loam; 7-shale; 8-sandstone; 9-fracture]	1	sand
Nature of Well [1-water level; 2-packed off]	1	
R(e1), first observation well location	n/a	m
R(e2), second observation well location	n/a	m
R(e3), third observation well location	n/a	m
K, estimate	1.0E-04	m/s
Ss, estimate	5.0E-05	1/m
Kskin estimate	1.0E-04	m/s
NATURE OF FLUID		
Nature of Fluid [1-water, 2-oil, 3-gas]	1	
NATURE OF AQUIFER (or vadose zone)		
Aquifer Thickness, H	10.0	m
Depth from Surface to Water Table, Hv , (for vadose zone)		m
R(sys), extent of aquifer or vadose zone	1000	m
Confined / Unconfined	confined	
Anisotropy: if yes, -1; if no, blank		
Horizontal Factor, Fh	1.25	
# of Vertical Nodes, Fv	20	
Number of Nodes *@INT ([@LOG[R(sys)/R(w)]] /[@LOG (factor)])*	820	
FORCING FUNCTIONS		
NATURE OF FLOW RATE		
Constant Flow Rate, Q (- if pumping, + if injection)	-0.01	m^3/s
If Variable: -1 for variable flow rate, +1 for variable potential		
for Guelph: Height of water in borehole, H	n/a	m
Distance from datum to water in borehole, phib	n/a	m
Constant pressure, psi	n/a	
SLUG		
Slug Magnitude	n/a	
Initial Head increase in well @ slug test *injection is positive and withdrawl is negative*	n/a	m
NATURE OF BORE-HOLE		
Radius of Auger-Hole, Ra	0.125	m
Depth of Auger-Hole, Ha, (a=auger-hole)	110	m
NATURE OF WELL		
SCREEN		
Well Screen Radius, Rw = Rs	0.1	m
Length of screened interval, Hs	10	m
Distance from top of aquifer to top of screen, Hd	0	m
CASING		
Casing Radius, where H2O fluctuates, Rc	0.1	m
Length of casing, Hc,c	100	m
Effective Length of casing, Hc = Hc,eff *[(Rw^2 * Hs) + (Rc^2 * Hc)] / (Rw^2)*	110	m
FEATURES 1 -- water level fluctuates 2 -- sealed well [Ss(well) = rho*g*beta] and [length of packed off casing]	1	

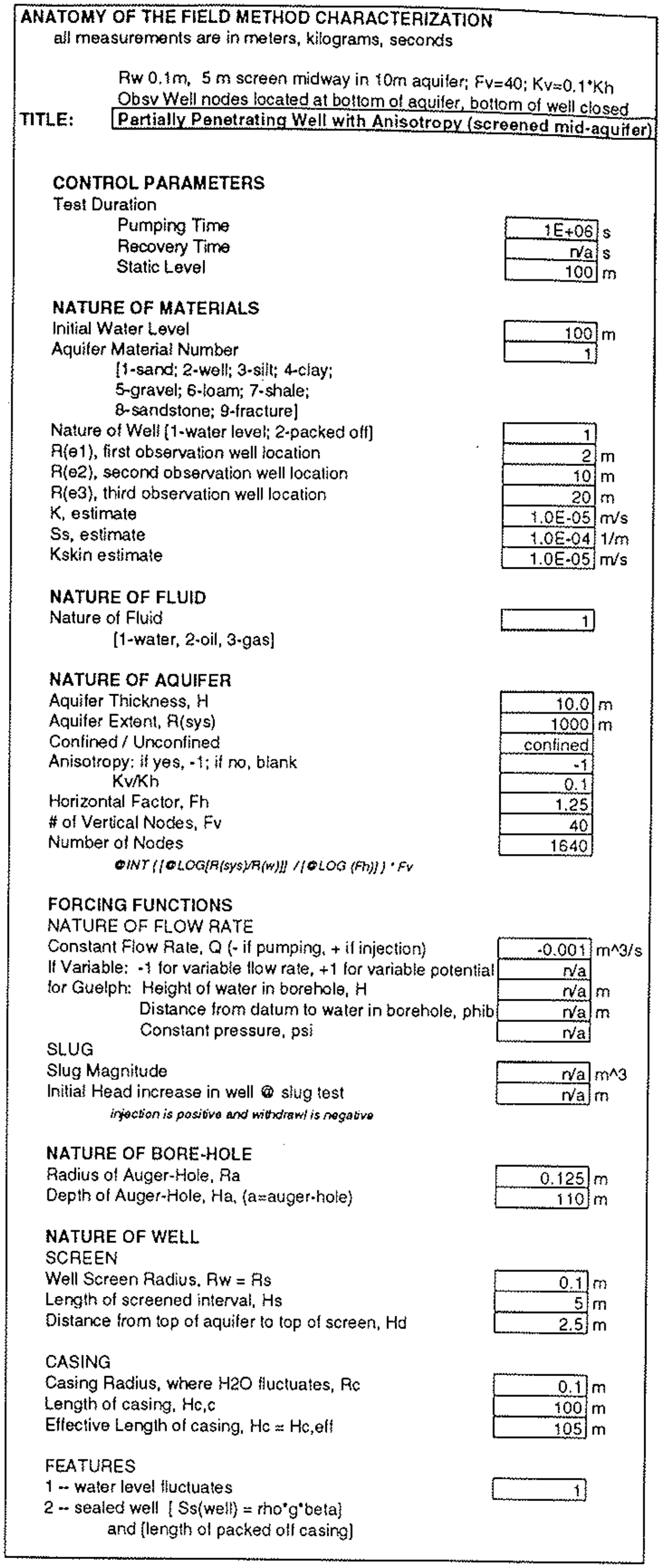
Figure 2. Input page for first illustration: Finite radius well with finite skin and constant flow rate.



AQTRUST Solution							
Time (s)	dwdwn(m)	Time (s)	dwdwn(m)	Time (s)	dwdwn(m)	Time (s)	dwdwn(m)
1E-12	0.000	18.77	3.840	79.17	7.433	1409.6	10.591
0.63088	0.195	19.487	3.935	82.86	7.520	1556.2	10.674
1.2814	0.388	20.978	4.125	86.822	7.607	1898.7	10.838
1.6162	0.484	21.754	4.219	95.689	7.779	2098.3	10.920
2.3056	0.676	23.374	4.408	100.67	7.865	2319.5	11.002
2.6604	0.773	24.219	4.503	106.07	7.950	2836.8	11.167
3.0221	0.869	25.089	4.597	111.94	8.035	3472.4	11.331
3.7662	1.061	25.986	4.691	125.33	8.203	3842.9	11.413
4.149	1.158	27.865	4.879	132.98	8.287	5213.9	11.660
4.9367	1.350	28.849	4.973	141.38	8.370	6394.1	11.824
5.342	1.447	29.866	5.067	160.81	8.536	7082.1	11.906
5.7551	1.543	30.918	5.160	184.47	8.701	8690.5	12.070
6.1762	1.639	33.131	5.347	198.21	8.784	9628.1	12.152
7.0436	1.831	34.298	5.440	213.43	8.866	10668	12.235
7.4902	1.928	35.508	5.533	248.97	9.030	13098	12.399
7.9459	2.024	38.069	5.718	292.66	9.194	14515	12.481
8.4108	2.120	40.837	5.903	318.13	9.277	17827	12.645
9.3694	2.312	42.309	5.995	377.67	9.441	19759	12.727
9.8638	2.408	43.844	6.087	412.37	9.523	21900	12.809
10.369	2.504	47.123	6.270	450.84	9.605	29824	13.056
11.411	2.695	50.717	6.452	540.74	9.770	33059	13.138
12.5	2.887	52.648	6.543	593.11	9.852	36647	13.220
13.063	2.982	56.816	6.723	715.5	10.016	40625	13.302
13.639	3.078	59.071	6.813	786.81	10.098	49925	13.467
14.83	3.269	61.452	6.903	865.84	10.181	55347	13.549
16.08	3.460	66.645	7.081	953.43	10.263	75414	13.795
16.728	3.555	69.483	7.170	1158.1	10.427	92693	13.959
18.072	3.745	75.726	7.346	1277.4	10.509	100000	14.020

Agarwal, et al. Solution	
Time (s)	Dwdwn(m)
0.5	0.155
1	0.305
2.5	0.730
5	1.366
10	2.435
25	4.589
50	6.418
100	7.854
250	9.034
500	9.699
1000	10.303
2500	11.064
5000	11.626
10000	12.183
25000	12.916
50000	13.469
100000	14.021

Figure 3. Comparison of a numerical solution (solid line) and Agarwal's analytical solution (symbols) for a finite radius well with finite skin and constant flow rate.



ANATOMY OF THE FIELD METHOD CHARACTERIZATION		
all measurements are in meters, kilograms, seconds		
Rw 0.1m, 5 m screen midway in 10m aquifer; Fv=40; Kv=0.1*Kh		
Obsv Well nodes located at bottom of aquifer, bottom of well closed		
TITLE:	Partially Penetrating Well with Anisotropy (screened mid-aquifer)	
CONTROL PARAMETERS		
Test Duration		
Pumping Time	1E+06	s
Recovery Time	n/a	s
Static Level	100	m
NATURE OF MATERIALS		
Initial Water Level	100	m
Aquifer Material Number [1-sand; 2-well; 3-silt; 4-clay; 5-gravel; 6-loam; 7-shale; 8-sandstone; 9-fracture]	1	
Nature of Well [1-water level; 2-packed off]	1	
R(e1), first observation well location	2	m
R(e2), second observation well location	10	m
R(e3), third observation well location	20	m
K, estimate	1.0E-05	m/s
Ss, estimate	1.0E-04	1/m
Kskin estimate	1.0E-05	m/s
NATURE OF FLUID		
Nature of Fluid [1-water, 2-oil, 3-gas]	1	
NATURE OF AQUIFER		
Aquifer Thickness, H	10.0	m
Aquifer Extent, R(sys)	1000	m
Confined / Unconfined	confined	
Anisotropy: if yes, -1; if no, blank	-1	
Kv/Kh	0.1	
Horizontal Factor, Fh	1.25	
# of Vertical Nodes, Fv	40	
Number of Nodes	1640	
*@INT ([@LOG[R(sys)/R(w)]] /[@LOG (Fh)]) * Fv*		
FORCING FUNCTIONS		
NATURE OF FLOW RATE		
Constant Flow Rate, Q (- if pumping, + if injection)	-0.001	m^3/s
If Variable: -1 for variable flow rate, +1 for variable potential	n/a	
for Guelph: Height of water in borehole, H	n/a	m
Distance from datum to water in borehole, phib	n/a	m
Constant pressure, psi	n/a	
SLUG		
Slug Magnitude	n/a	m^3
Initial Head increase in well @ slug test	n/a	m
injection is positive and withdrawl is negative		
NATURE OF BORE-HOLE		
Radius of Auger-Hole, Ra	0.125	m
Depth of Auger-Hole, Ha, (a=auger-hole)	110	m
NATURE OF WELL		
SCREEN		
Well Screen Radius, Rw = Rs	0.1	m
Length of screened interval, Hs	5	m
Distance from top of aquifer to top of screen, Hd	2.5	m
CASING		
Casing Radius, where H2O fluctuates, Rc	0.1	m
Length of casing, Hc,c	100	m
Effective Length of casing, Hc = Hc,eff	105	m
FEATURES		
1 -- water level fluctuates 2 -- sealed well [Ss(well) = rho*g*beta] and [length of packed off casing]	1	

Figure 4. Input page for second illustration: Partially penetrating well with anisotropy.

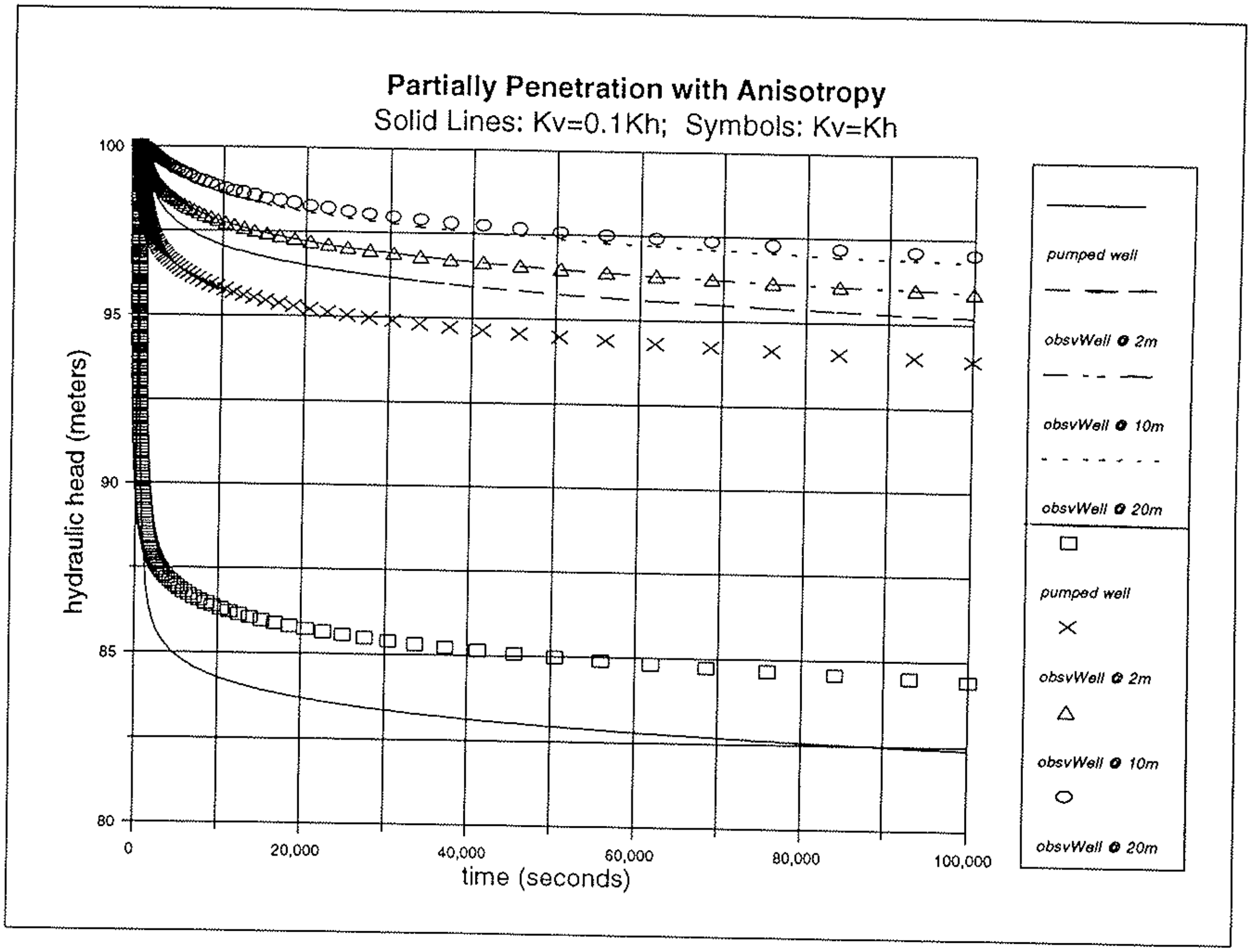


Figure 5. Comparison of an anisotropic, Kv=0.1Kh (solid line), and an isotropic, Kv=Kh (symbols), for a partially penetrating well.

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APPENDIX A

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