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Physical Measurements in Subsurface Hydrology

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Measurements needed to define the basic hydraulic properties of subsurface porous media constitute a fundamental problem. Complex mathematical flow models can only make realistic predictions if the "correct" values for the hydraulic properties are used. This paper reviews the physical measurements currently in use to determine flow related properties of subsurface porous media.

INTRODUCTION

In many ways, the measurement of physical properties of heterogeneous subsurface materials is the central challenge of modern subsurface hydrology. Due largely to the lack of practical measurement techniques, our ability to define parameters conceptually, often for computational purposes, has vastly outpaced methodology for measuring those parameters, especially in the field. Any physical parameter that has not been or can not be subjected to independent measurement can not be claimed to be "real." The need to deal with this problem when working with complex mathematical models causes the application of such models and the interpretation of the results to be less than straightforward (*Güven et al.*, 1990).

There are many classes of measurements within the purview of subsurface hydrology, including, in the broadest sense, all measurements related to physical, chemical and biological phenomena. In this paper, only those measurements needed to define the basic hydraulic properties of subsurface porous media that relate to the occurrence and movement of water will be discussed. One can argue that this constitutes the most fundamental measurement problem, because most near-surface chemical and biological phenomena occur in a water-based environment. There is little hope of developing a quantitative understanding of these processes if our ability to predict the occurrence and movement of water alone is severely limited.

In addition to the quoted papers, many readers will find it useful to consult books and symposia published during the past four years that deal to a significant extent with the measurement problem. A partial list of such contributions includes *Bear and Corapcioglu* (1988), *Boersma et al.* (1987), *Cushman* (1990), *Custodio et al.* (1988), *Keys* (1989), *Molz et al.* (1989a), and *Streltsova* (1988).

PHYSICAL MEASUREMENTS IN THE UNSATURATED ZONE

Most of the water and other liquids entering the land masses on the earth's surface flow through unsaturated soil from which they are either directly returned to the atmosphere through processes of evaporation and transpiration or indirectly by first traveling down to aquifers. To increase our understanding of unsaturated flow, it is imperative that we are able to measure variables such as the volumetric liquid content of the soil and the soil liquid potential. It is just as important, however, that we can determine the parameters that govern the flow in unsaturated porous media. Only if we have proper knowledge of the liquid-conductivity and liquid-retention properties of a porous medium can we make predictions of a liquid's flow. In this paper, a number of measurement techniques to obtain values for these variables and parameters will be reviewed, with emphasis placed on those techniques that have been developed or improved during the time period 1987-1990.

Although the emphasis will be on water (aqueous phase liquid, APL), measuring techniques related to nonaqueous phase liquids (NAPL) will also be discussed briefly.

Liquid Content

Field procedures. Although the neutron probe has been used to determine the volumetric water content in field soils for many years, it has continued to be the subject of study. *Amoozegar et al.* (1989a) pointed out that loosely fitted access tubes result in a loss of sensitivity with increasing hole size. Consequently, individual calibration curves, usually already a necessity for different soil types and sometimes even for different depths within the same soil type, are required if the access holes vary in diameter. However, there might be cases where the installation of tightly fitted access tubes is not practical, such as for the monitoring of water content to depths greater than a few meters. *Tyler* (1988) used the neutron probe (probe diameter = 5 cm) inside 15-cm steel casings up to depths of 100 m. Because of the large air gap between the detector and the surrounding soil and thermalization of neutrons at the casing, a nonlinear calibration curve was necessary. The most straightforward calibration technique consists of determining the volumetric soil water content of soil cores taken from around the access tube and relating these water content values to the count rates obtained with a rate meter. Transfer of calibration curves obtained in this manner to other, but similarly built, neutron probes was shown to be possible with the use of hollow plastic cylinders of different outside diameters (*Reginato and Nakayama*, 1988). The plastic cylinders also proved to be useful upon repair of the neutron probe equipment, avoiding the need for recalibration in the field.

The time-domain reflectometry (TDR) technique is becoming increasingly popular to measure in situ volumetric water content (*Topp*, 1987). The method is based on the determina-

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tion of the composite, or apparent, dielectric constant of a porous medium, which is strongly related to its water content and influenced only slightly by other properties such as soil bulk density and texture. For many soils, a rather general relationship can therefore be used to obtain the volumetric water content from the apparent dielectric constant. If higher degrees of accuracy are required, the relationship can be improved by incorporating the dielectric constant of the dry medium in the calibration procedure (*Alharthi and Lange,* 1987). For media with constant porosity, this technique was also applied to the simultaneous measurement of immiscible liquid contents (*Alharthi et al.,* 1986). A thorough discussion of the dielectric response to frequencies in the range of 1 to 50 Mhz was presented by *Campbell* (1990), who noted a greater soil dependence of the real dielectric behavior at lower frequencies because of ionic conductivity. Most measurements are, however, taken at higher frequencies and are not affected by this dependency. The time-domain reflectometry method can also be automated to obtain water content measurements at multiple points in space and time, using the automation and multiplexing system described by *Baker and Allmaras* (1990). Such a system is particularly useful to obtain measurements during transient flow conditions, because TDR is not subject to long measurement times as, e.g., the neutron radiation technique. Water content values obtained by TDR represent average values over the length of the probes. *Baker and Lascano* (1989) showed that the cross-sectional area over which the soil water content is being measured is approximately 10 cm^2 per wave guide (probe).

Although not widely used to explicitly determine the soil water content, another method based on variations of the dielectric constant with water content is ground-penetrating radar (*Davis and Annan,* 1989). In soils, the method is mainly used to identify horizons or layers where large discontinuities in texture and, therefore, in water content occur. Since these discontinuities are often the cause of preferential flow, the method also seems to be a valuable tool in selecting locations for suction cup samplers in studies of solute transport (*Donohue and Kung,* 1991).

Porous blocks with embedded electrodes continue to be used to determine water contents of the vadose zone (*Frohlich and Parke,* 1989; *Kean et al.,* 1988; *Reynolds et al.,* 1987).

Little information has been published about the distributions of simultaneously occurring APLs and NAPLs under field conditions. Based on measured saturation-pressure relationships, both *Farr et al.* (1990) and *Lenhard and Parker* (1990) were able to predict LNAPL (light NAPL) volumes from APL and LNAPL levels in monitoring wells. *Farr et al.* pointed out that the water table, being the surface on which the water pressure is zero gage, is located above the LNAPL-water interface in the well, and that LNAPL in the porous medium resides below the water table.

Laboratory procedures. The relatively new application of real-time neutron radiography (*Von der Hardt and Rottger,* 1981) was demonstrated by *Brenizer and Gilpin* (1987), who were able to accurately follow the infiltration of water into a dry soil column. The method is based on creating a "shadowgraph" image on photographic film, using neutrons as the radiation source. The radiographic image is formed by various degrees of neutron attenuation, referred to as relative density, which depends on the soil water content. *Brenizer and Gilpin* (1987) were able to obtain real-time measurements by updating the images every 1/30 of a second. Although the neutron density, as observed on a radiograph, was assumed to be directly related to the density of the medium and, therefore, to the volumetric water content, no attempt was made to experimentally correlate neutron attenuation to water content values.

New applications continue to be found for the use of gamma radiation to measure variables in a porous medium. The method has evolved from only determining the soil bulk density or its volumetric water content, with the use of a single gamma radiation source, to the simultaneous determination of either (i) dry bulk density and volumetric water content (*Corey et al.,* 1971; *Hopmans and Dane,* 1986), (ii) volumetric NAPL and volumetric water content (*Ferrand et al.,* 1986; *Ferrand et al.,* 1989; *Lenhard et al.,* 1988), or (iii) volumetric water content and salt concentration (*Grismer et al.,* 1986), with the use of dual-energy sources, usually ^{137}Cs and ^{241}Am. If the dual-energy sources are lined up behind the same collimator, a correction due to Compton scattering in the Americium window needs to be made. This correction method was improved by *Stillwater and Klute* (1988), who also offered a better way of determining dead time. An overview, including theory, instrumentation, automation, calibration, and an error analysis for each of the above mentioned applications was presented by *Oostrom and Dane* (1990).

Measurement of soil-water content and bulk density at or near the microscopic level offers the potential of increasing our understanding of flow and transport through porous media. Recent advances in x-ray technology have allowed the development of computed tomography (CT) methods for rapid, nondestructive, three-dimensional analysis of water flow in porous media (*Crestana et al.,* 1985; *Anderson et al.,* 1988). The smallest resolution of current CT scanners, also referred to as CAT (computer assisted tomography) scanners, is approximately 1x1x3 mm. The method was evaluated by *Brown et al.* (1987), who found a significant linear relationship between gravimetric water content values and those determined by the CAT scanner for porous foam media. *Anderson et al.* (1988) indicated that the information obtained by CT can be greatly influenced by certain minerals present in porous media and by swelling and shrinking. Tomography is not limited to obtaining information at a very small scale. *Daily and Ramirez* (1989) were able to use the technique to measure in situ drying and wetting in a densely welded tuff when subjected to heating and cooling cycles. They referred to this technique as geophysical tomography.

Although the TDR method has been used mainly for field studies, it is also beginning to find applications in the laboratory.

Tensiometry and Pressure Transducers

To measure liquid pressures in the unsaturated zone, one depends on tensiometers. Good contact between the porous cup of the tensiometer and the surrounding porous medium is essential to obtain reliable information. *Gee and Campbell* (1990) designed a water potential measuring tensiometer with a flexible wick, which allows for good contact in coarse sand and gravel. Information about porous plastics that can be easily cut into any desired shape can be found in *McCoy* (1989). An automated tensiometer - pressure transducer system was described by *Nyhan and Drennon* (1990). It should be mentioned that over the last decade a number of inexpensive pressure transducers ($50) have become available, which makes their use economical for field applications.

When an APL and a NAPL occur concurrently in a porous medium, the porous cups to be used for measuring the NAPL pressure must be made hydrophobic. *Lenhard et al.* (1988) outlined such a procedure based on the use of chlorotrimethylsilane, which forms durable bonds with the ceramic surface, while attached trimethyl groups repel water molecules in preference to the NAPL.

Hydraulic Properties

Most methods for measuring the soil's hydraulic properties, both in the laboratory and in situ, have been described in *Klute* (1986). No new or improved laboratory methods have been developed over the last four years to directly determine liquid retention curves of porous media. Exceptions are the determination of NAPL retention curves. For NAPL curves with respect to air, the hydrophilic plate in the pressure cell must be replaced with a hydrophobic plate. For NAPL curves with respect to water, the pressure cell needs both a hydrophilic and a hydrophobic plate. Most of the experimental procedures and development of the capillary pressure - liquid content relationships have been discussed by *Lenhard and Parker* (1987a), *Parker and Lenhard* (1987), *Lenhard and Parker* (1987b), *Lenhard et al.* (1988), and *Lenhard et al.* (1989). These discussions include hysteresis and the determination of retention relationships for different combinations of fluids based on their surface tensions if one relationship is known.

The emphasis in this section will be on indirect methods and on improved direct field measurements.

Soil texture. Since the determination of hydraulic properties is relatively time consuming and expensive, various efforts have been made to relate hydraulic conductivity and water retention characteristics to easily determined soil physical properties such as soil texture. *Puckett et al.* (1985) were able to successfully predict water retention curves from textural data for soils covering approximately 35,000 km^2 in the Lower Coastal Plain of Alabama. The same prediction equations were later applied successfully to similar soils covering large areas in Florida (*Dane and Puckett*, 1990). *Ahuja et al.* (1985) tested a number of models that relate water retention to texture, structure, bulk density, and organic matter content using published coefficients for their relationships. They found that the calculated water content values were generally greater than the measured ones, but that considerable improvement could be gained by including two measured water content values into the relationships. *Puckett et al.* (1985) stressed the point that useful relations should only be expected for areas in which soils have similar mineralogy and genesis. This viewpoint was later supported by *Schuh et al.* (1988), who found the constant α = 1.38 of the *Arya and Paris* (1981) model to vary from 0.8 to 2.0 depending on the texture and water content of their soil samples. *Tyler and Wheatcraft* (1989) used fractal mathematics to demonstrate the physical significance of the α parameter in the Arya and Paris model. Using the fractal dimension from the particle size distribution, their estimated water retention data closely matched the measured data, except for the coarser soils. In a later paper, *Tyler and Wheatcraft* (1990) showed that the water retention equations of *Brooks and Corey* (1964) and *Campbell* (1974) are based on fractal concepts of pore distribution. The fractal model of water retention could subsequently be used to estimate the hydraulic conductivity (K) based on the models of Burdine and Mualem. Observed power-law behavior in the pressure head (h) versus water content (θ) and in the K(θ) relationships, at low values of θ, was explained by *Toledo et al.* (1990) based on theories of fractal geometry and thin film physics. *Mishra et al.* (1989) investigated the uncertainty in soil hydraulic properties estimated from particle size distributions of 250 soil samples. They concluded that the large degree of uncertainty in their estimated saturated hydraulic conductivity values made it very desirable to determine these values by direct measurements.

Functional relationships. The emphasis in determining hydraulic properties has been on the θ(h) characteristics. Once these characteristics are known and represented by functional relationships, they can be used to predict relative hydraulic conductivity values. These relative values can then be converted to real values if a matching point on the hydraulic conductivity function, either K(θ) or K(h), is known. This point is usually the saturated hydraulic conductivity (Ksat) value. The selection of Ksat as the matching point might be questioned, however, especially for soils with well developed structures and/or cracks that allow the majority of water to flow through large channels, rather than through the general soil matrix, if soil water pressure head values are positive. The most widely used functional relationships to represent soil water characteristics and hydraulic conductivity functions are probably those of *Brooks and Corey* (1964) and *van Genuchten* (1978). *Milly* (1987) proposed an improved procedure to determine the parameter values in the Brooks and Corey model. As was pointed out by *Hills et al.* (1989), measurement of the hydraulic properties over the full range of soil water content values is nearly impossible. Existing hydraulic models are therefore often extrapolated outside the range of measured values, resulting in uncertainties in the predictions. *Nimmo et al.* (1987) were able to extend the water content range over which unsaturated hydraulic conductivity values are usually obtained by making use of centrifugal forces. The main limitation of this method is that it only applies to compacted samples. An analysis of the effects of parameter uncertainty on predictions of unsaturated flow was given by *Mishra and Parker* (1989a). *Hills et al.* (1989) found the values for the model parameters to be very sensitive to the laboratory and field techniques used to estimate them. The value of laboratory-determined hydraulic properties in field studies is therefore debatable. The best approach, whether it be a direct or an indirect method, should be based, at least in part, on field measurements.

Inverse procedures. The inverse approach to determine hydraulic properties of unsaturated porous media was first presented by *Zachmann et al.* (1982) and *Kool et al.* (1985, 1987) for laboratory soil samples and by *Dane and Hruska* (1983) for a presumed homogeneous soil profile. In the latter case, water content profiles obtained with a neutron probe during drainage, a zero flux boundary condition at the soil surface, and pressure head values at the bottom of the soil profile measured as a function of time, were used to solve the flow equation numerically. The method uses an initial estimate for the parameters contained in the van Genuchten model (other models are applicable as well). The resulting approximations for the water content values are compared to the measured data. The parameter values are then adjusted and the process is repeated iteratively until reasonable agreement is found between measured and calculated water content values. The method was later improved by *Kool and Parker* (1988), who included hysteresis in the description of water retention. The authors concluded, however, that the effect of hysteresis is easily overwhelmed by other sources of error. They also showed a consistently low sensitivity to Ksat, as previously shown by *Dane and Hruska* (1983), and the parameter n in the van Genuchten model. If both hydraulic and transport parameters need to be estimated, substantially lower estimation errors occur for a simultaneous than for a sequential solution of the inverse problem (*Mishra and Parker,* 1989b). A direct approximate method to the inverse problem was presented by *Mathis* (1985), who used the measured data to obtain directly a smooth approximation to the actual solution of the flow equation. The parameter values were then selected to fit the differential equation. Results of this method, which has a much shorter computational time, compared favorably with the iterative inverse procedure.

Direct field methods. A simple field method to estimate the soil hydraulic properties for assumed relationships was proposed by *Shani et al.* (1987). The only measurements required are the water application rates to the soil surface from a dripper (point source) and the radii of the ponded zones corresponding to these application rates once these radii have reached a constant value. The method requires a homogeneous soil with uniform initial water content and is more or less limited to measurements at the soil surface. The latest in a series of tension infiltrometers was designed by *Ankeny et al.* (1988). It operates over a tension range from 2 to 50 cm of water, provides for automatic data collection, and can be used with very low infiltration rates. A compact constant-head well permeameter, capable of determining Ksat in the vadose zone to large depths, was designed by *Amoozegar* (1989b), who recommends the Glover solution instead of the simultaneous-equations approach to calculate Ksat (*Amoozegar,* 1989c). Theoretical developments by *Parlange et al.* (1988) for falling head infiltrometers led to improved determinations of Ksat. A regression model, which included capillary effects, to determine Ksat in the vadose zone with a borehole permeameter was developed by *Stephens et al.* (1987). These authors pointed out that short-duration tests significantly underestimate infiltration rates unless a correction is made for entrapped air. *Ahuja et al.* (1988a) successfully determined K(h) with a simplified functions approach, which only required tensiometric data. Their method allowed them to obtain K(h) relationships to depths of 1.9 m. Several methods have assumed a unit hydraulic gradient over space and time to facilitate the collection of data and the calculations of unsaturated K-values. Based on data collected over large areas in the southeastern United States, *Ahuja et al.* (1988b) showed that hydraulic gradients were at times two to five times smaller or greater than unity, with the largest deviations being found in the top soils. Results from unit gradient methods are therefore suspect. Soil layering complicates the in-situ determination of K(h) tremendously. *Yeh and Harvey* (1990) showed that the treatment of a heterogeneous soil as an equivalent homogeneous medium results in an effective K(h) function, which can be approximated as the geometric mean of the K-values of the individual layers.

General Remarks.

A few remarks need to be made regarding the determination of soil hydraulic properties in general. Although it has long been known that factors such as the Ph of the soil, and the electrolyte concentration and sodium adsorption ratio of the percolating solution, affect soils containing the clay mineral smectite, it has now been shown that soils with low activity clays can also be affected (*Chiang et al.,* 1987). Care should therefore be taken to prevent changes in pore structure, and, thereby, in hydraulic properties during their determination, especially under laboratory conditions. Soils high in Al- and/or Fe-polymers are less likely to undergo changes in pore structure during the determination of their hydraulic properties (*Keren and Singer,* 1989; *Shainberg et al.,* 1987). If water flow occurs in more than one direction, it is necessary to check for anisotropy. *Dabney and Selim* (1987) found Ksat-values of a Bt-horizon to be three times greater in the vertical than in the horizontal direction. Although hydraulic properties are known to be affected by temperature, very little attention has been given to this fact. Hydraulic properties are often determined at one temperature and then freely applied to situations in which other, often varying, temperatures exist. *Jaynes* (1990), e.g., observed infiltration rates in the field that varied by 30% of the mean rate over a 24-h period. The changes were related to the temperature at the soil surface. The determination of Ksat with cores in the laboratory should be scrutinized for possible wall effects, especially for soils with low Ksat-values, which can be easily overestimated (*Tokunaga,* 1988).

PHYSICAL MEASUREMENTS IN THE SATURATED ZONE

Physical property measurements in the saturated zone are important for a number of reasons. Portions of this zone (aquifers) are sources for water supply, and contaminants associated with spills or waste disposal generally move off site only after the saturated zone has been penetrated. When contaminants are discovered and a rehabilitation program is instituted, much of the effort is commonly devoted to saturated-zone clean-up. A review of the 1987-90 literature has revealed that important contributions to physical-measurement problems have been made in many sub-topical areas.

Geophysics-Based Measurements

Methods having their origin in borehole geophysics are continuing to be applied in the groundwater area. Such applications are of particular interest because they usually result in properties being measured as a function of vertical position. This is a step above traditional pumping and related tests which commonly result in vertically-averaged property values. As noted by *Anderson* (1987), vertically-distributed information is needed to support the development and application of analyses based on 3-dimensional models.

A number of studies applied borehole flowmeters to the measurement of flow path and/or hydraulic conductivity distributions in both fractured and granular rocks (*Paillet et al.,* 1987; *Morin et al.,* 1988a; *Molz et al.,* 1989b; *Rehfeldt,* 1989; *Hess,* 1989). The procedure may be viewed as a generalization of a standard pumping test and shows great promise as a means for obtaining detailed permeability information in both fractured and granular media. *Molz et al.* (1990) presented results of a study in a granular fluvial aquifer. The sensitivity limitation (stall velocity) associated with impeller meters is being reduced significantly by the more recently developed heat pulse (*Hess and Paillet*, 1989) and electromagnetic (*Young and Waldrop,* 1989) technologies. Hopefully, commercial versions of the existing prototype instruments will become available in the near future.

Taylor et al. (1990) reviewed various methodologies for determining the vertical distribution of hydraulic conductivity and concluded that the most effective techniques require some type of monitoring of fluid movement into or out of the formation. Also, a new test for determining hydraulic conductivity and porosity logs, based on electrical conductivity measurements in injected electrolyte, was described (*Taylor and Molz,* 1990; *Taylor et al.*, 1989).

A variety of geophysical methods were used to determine hydraulic properties of fractured rocks and/or fracture locations. *Hardin et al.* (1987) studied the propagation of tube waves in crystalline rock and related this to fracture locations and transmissive properties. *Taylor and Fleming* (1988) used azimuthal resistivity surveys (Wenner array) to obtain useful information about anisotropy, directional connectivity and porosity of fracture systems. A number of papers were devoted to the analysis of temperature or electrical-conductivity logs of borehole fluids in an attempt to infer hydraulic information (*Michalski,* 1989; *Silliman and Robinson,* 1989; *Tsang et al.*, 1990; *Michalski and Klepp,* 1990). Much of this work depended on the presence of natural internal flow in the tested wells, which is rather common in fracture systems. However, when natural flow is not present, or is too small to be detected, flow can often be induced by pumping wells near the test well. Taken as a whole, the studies showed that a significant majority of fractures are usually inactive hydraulically. The data of *Tsang et al.* (1990), based on fluid electrical conductivity measurements, were validated against independent hydraulic measurements using packer tests. *Michalski and Klepp* (1990) discussed the implications of selective fracture flow on the interpretation of data from water-quality monitoring wells, while two other papers related various geophysical logs to groundwater quality determinations (*Poole et al.*, 1989; *Park and Dicky,* 1989).

Several studies were published that involved the application or analysis of surface seismic methods. *Birkelo et al.* (1987) performed a seismic reflection study during a pumping test in a phreatic aquifer and were able to map the water-table positions. *Duran* (1987) used a marine electromagnetic conductivity tool to help interpret continuous seismic reflection data in the Delaware River shipping channel. The two types of data, along with the results of a limited number of cores, enabled Duran to identify sediment types and thicknesses. *Ayers* (1989) used seismic refraction and reflection techniques to map the bedrock surface and thickness of an alluvial aquifer in Nebraska.

Electrical resistivity methods also found several applications in the groundwater area. *Frohlich and Kelly* (1988) were able to make estimates of specific yields in glacial aquifers based on surface resistivity measurements. A similar type of study was reported by *Ebraheem et al.* (1990) wherein horizontal resistivity profiling and vertical electrical sounding were used to identify locations (gob valleys) where coal refuse was buried. *Park et al.* (1990) used DC resistivity methods to delineate a groundwater flow barrier beneath the San Bernardino Valley in Southern California.

An additional paper dealt with the use of gamma-gamma and neutron-epithermal neutron logs to identify perched water tables (*Poeter,* 1988). Such logs often display a distinctive response in the presence of perched water.

Measurements Involving Tracers and Dispersion

In the previous IUGG report, *Anderson* (1987) discussed a number of ground water experiments that involved the use of tracers. Such studies have continued to be popular, especially in Canada. Several comments and notes were published concerning the Borden tracer test and related studies (*Freyberg,* 1986; *Sudicky,* 1986). *Naff et al.* (1988) discussed the manner in which moments were obtained for conservative tracers in the Borden study (*Freyberg,* 1986) and suggested an alternative approach that more explicitly represents the three-dimensional nature of the flow field. In the final analysis, however, *Naff et al.* (1988) found it puzzling that their 3-D model did not result in an improved fit to the field moments, given that, in their opinion, the data were 3-D in nature.

White (1988) commented on the paper by *Sudicky* (1986) dealing with the spatial variability of hydraulic conductivity at the Borden site. He questioned whether the K-values obtained by *Sudicky* (1986) in the laboratory on repacked 50-mm long cores were representative of in-situ values. In his reply, *Sudicky* (1988a) agreed that White's concerns were well taken in general, but he maintained that in the case of the Borden aquifer, the error variance due to remixing was small compared to the natural ln(K) variance between samples. *Molz and Güven* (1988) also commented on the work by *Sudicky* (1986). Based on the published data, they suggested that there was no solid basis for assuming that the Borden hydraulic conductivity field was statistically homogeneous (stationary). Given a lack of stationarity, they questioned the uniqueness of the asymptotic macro-dispersivity calculated by *Sudicky* (1986). In an extensive reply, which presented new data, *Sudicky* (1988b) made a credible defense of his analysis and concluded for a second time that "there is reason to believe that field-scale dispersivity is a measurable quantity that can be obtained by procedures other than arbitrary curve fitting."

Güven and Molz (1988) commented on several aspects of the Twin Lake tracer test as presented by *Taylor and Howard* (1987). In the resulting discussion (*Taylor and Howard,* 1988), three different scales of dispersion were identified: the local scale, the field scale and the full-aquifer scale. It was agreed that some confusion between the scales exists, and that the dispersion lengths carefully measured in the Twin Lake experiment were very small, with the local values scale independent (*Killey and Moltyaner,* 1988; *Moltyaner and Killey,* 1988; *Moltyaner,* 1989).

Information has been published concerning on-going or recently completed tracer tests in the United States. *Molz et al.* (1988) described forced gradient tracer tests performed at a site near Mobile, Alabama. Based on their data, the authors concluded that reliable predictions of solute transport in natural aquifers requires detailed knowledge of the major non-stationary features of the hydraulic conductivity distribution in an aquifer. A description of a tracer experiment completed recently in a sand and gravel aquifer by the U.S. Geological Survey in Cape Cod, Massachusetts, is due to be published in the near future (*LeBlanc et al.*, 1991; *Garabedian et al.*, 1991). Preliminary results of a second large tracer experiment being performed at a site near Columbus, MS, may be found in and *Young and Boggs* (1990).

A number of papers dealt with various aspects of parameter estimation based on tracer tests. *Rainwater et al.* (1987) analyzed multiple-well tracer studies involving both conservative and chemically reactive species to obtain information on hydraulic and chemical parameters. The procedure was tested in the laboratory and a field test is planned. *Duffy and Al-Hassan* (1988) presented both a time and frequency response analysis of tracer data from an intermediate-scale experiment. They concluded that the frequency domain method, based on the Fourier transform of tracer breakthrough curves, is less sensitive to random variations in the data than the time domain method (method of moments), which is the more popular approach. *Leap and Kaplan* (1988) studied single-well tracer tests as a means for estimating regional advective velocities. The procedure, which was tested in the laboratory, involves injecting a slug of tracer, allowing it to drift with the flow for a selected period of time, and then pumping it back to the well at a constant rate.

At least two papers were published that dealt with the use of tracers introduced in part by natural processes. *Larson et al.* (1987) measured the depth of penetration of H-bomb-derived tritium into the saturated zone of a glaciofluvial aquifer, which allowed them to calculate an average recharge rate of 34-41 cm per year. Their values agreed with estimates based on water budget analyses, and the authors suggested that their approach can be applied at many sites. In a study with similar objectives, *Dettinger* (1989) used natural-occurring chloride to estimate average annual recharge rates for 16 watersheds in the Basin and Range Province of the U.S. Results were reasonable and may be applied to many semiarid and arid basins in the Western U.S.

Pumping, Slug and Related Testing

As pointed out by *Butler* (1990), more or less standard pumping tests are still the primary means of estimating the large-scale storage and transmissive properties of aquifers. *Butler* (1990) presented a persuasive argument that information resulting from such tests can be improved significantly by better understanding and more careful application of the conventional procedures. Several other authors published the results of careful applications of traditional techniques that provided insight for understanding the methods themselves and their inter-relations (*Franke*, 1987; *Urban and Gburek*, 1988; *Sen*, 1988; *Motz*, 1990).

Several papers dealt with refinements to the performance and analysis of slug tests. *Loman et al.* (1987) provided information for analyzing rate of rise tests in auger holes and pits of arbitrary geometries. *Bouwer* (1989) provided new information on the well known slug testing procedure that he and Rice developed in 1976. Included is information on use of the method in confined aquifers, effect of draining gravel packs on the rise of the water level, effect of hole diameter, and computer processing of field data. *Peres et al.* (1989) presented a new analysis procedure for slug tests in confined aquifers that considers well bore storage and skin effects, while *Chapuis* (1989) discussed various shape factors for use in the analysis of slug and related tests. Based on a numerical analysis of 2-D radially symmetric flow during a slug test, *Widdowson et al.* (1990) presented a method for analyzing slug tests of arbitrary cylindrical geometry in confined and unconfined aquifers.

Two papers were found that dealt with the use of pumping tests in non-uniform aquifers. *Butler* (1988) developed a method for analyzing pumping tests in non-uniform but radially symmetric aquifers. The solution reveals that drawdown during a pumping test can be considered to consist of two components that are dependent and independent of near-well properties, respectively. In a later paper (*Butler and McElwee*, 1990), the analysis was extended to variable-rate pumping tests in non-uniform, radially symmetric aquifers.

Thrailkill (1988) developed a technique called drawdown interval analysis for analyzing pumping tests in shallow conduit flow carbonate aquifers. In such aquifers, the diffusion equation is not applicable because a flow continuum does not exist. In place of hydraulic conductivity, the drawdown-interval method allows one to calculate the flow exponent and the flow coefficient. The technique was applied to field data sets. *Neuman and Gardner* (1989) developed and applied a deconvolution method for the estimation of aquitard/aquiclude vertical hydraulic diffusivities on the basis of water-level measurements in piezometers completed in both the confining layers and in neighboring aquifers. The procedure can be applied to situations involving arbitrary water-level fluctuations. If the specific storage of the confining layers can be determined independently, such as with a laboratory consolidation test, then the hydraulic diffusivities can be converted to vertical hydraulic conductivities.

Several authors elaborated on methods for determining aquifer properties that involved observation wells but no pumping. *Reynolds* (1987) applied the floodwave-response technique to a glacial-outwash valley aquifer. Reasonable values were obtained for the hydraulic diffusivity and, after additional analysis, the storage coefficient. The floodwave response method is relatively inexpensive.

The water level in an open well completed in a confined aquifer responds to the pressure head disturbance caused by Earth tide dilatation of the aquifer. *Hsieh and Bredehoeft* (1987) applied an Earth tide analysis to water level fluctuations in a well and calculated a reasonable value for the transmissivity. In a later paper, *Hsieh et al.* (1988) elaborated further on their method in response to criticism by several colleagues. They concluded that their analysis, based on the previous work by *Bredehoeft* (1967) is correct in all essential respects. *Rojstaczer* (1988) analyzed the response of a partially confined aquifer to changes in atmospheric pressure. Through the analysis, which utilized five dimensionless parameters, he was able to make estimates of, or place bounds on, the vertical pneumatic diffusivity of the unsaturated zone, the lateral permeability of the main aquifer, and the composite vertical hydraulic diffusivity of the overlying saturated materials.

Two papers were located that used relatively large-scale geologic concepts in an effort to quantify certain hydrologic properties of aquifers. This is important because it is often the larger-scale trends that control contaminant movement. *Phillips and Wilson* (1989) used geological characteristics as a means for estimating spatial correlation scales for hydraulic conductivity. The authors pointed out that the large number of field measurements required to apply traditional geostatistical methods are seldom available. They suggest a method that involves geologic mapping and threshold crossing theory. Somewhat in the same spirit, *Anderson* (1989) proposed the use of hydrogeologic facies models to delineate large-scale spatial trends in glacial and glaciofluvial sediments. These models form a framework for identifying the locations and types of field data necessary to delineate heterogeneity. According to *Anderson* (1989), the methodology for glacial sediments can be extended to other sediment types.

Design and Analysis of Measurement Schemes

In addition to the problem of making a measurement, one is often faced with the problem of deciding the best way to perform the measurement. A number of contributions were made in this area. *Knopman and Voss* (1987) performed a rigorous sensitivity analysis of the 1-D advection-dispersion equation and explained the implications of their results for parameter estimation and sampling design. *Lu and Schmittroth* (1988) developed a two-dimensional parameter estimation code that is based upon a sequential least-squares algorithm that incorporates a finite element groundwater flow code. The approach emphasizes the sequential nature of the problem that allows knowledge of site hydrology to be systematically improved as information from additional wells becomes available. *Meyer and Brill* (1988) attacked the problem of locating wells in a groundwater monitoring network under conditions of uncertainty. A Monte Carlo technique was combined with a simulation model to identify a well network that maximizes the probability of contaminant detection. *Hsu and Yeh* (1989) designed a relatively complicated program for deriving optimum locations and pumping rates for an array of pumping and observation wells for the purposes of parameter identification. An example application shows that the methodology can be used to solve complicated experimental design problems in confined groundwater systems. *Nishikawa and Yeh* (1989) continued along the same line of work by using a different statistical criterion for optimizing pumping test design.

Well Construction Methodology

The great majority of information about the subsurface is obtained through the use of wells. In the authors' opinion, however, insufficient effort has been devoted to understanding how well installation and development techniques in various types of rock influence the measurements that are ultimately made. It is likely that the field of subsurface hydrology would benefit significantly from a sustained research effort in this area.

Keely and Boateng (1987a,b) examined the commonly employed methodology for the installation, purging and sampling of monitoring wells. Many problems associated with augering wells were identified, and there is a discussion of the advantages and disadvantages of cable tool drilling. Rotary air drilling is discussed, and several case histories involving different drilling techniques were presented. *Hackett* (1987a,b) provided additional information about drilling and monitoring well installation using hollow stem augers. He pointed out that, while hollow stem augers are commonly used for well construction, drilling and well installation procedures are neither standardized nor thoroughly documented in the published literature. *Strauss et al.* (1989) provided similar useful information about a type of drilling called dual-wall reverse circulation. *Morin et al.* (1988) performed a statistical analysis of geophysical logs obtained from wells in the same aquifer, but constructed using three different drilling methods: mud-rotary, augering, and surface driven, flush-joint, steel casing. The analysis showed that in their sand and gravel aquifer, augering was the most and driven casing the least disruptive to the material surrounding the well.

CONCLUDING REMARKS

In a previous IUGG report (*Abriola*, 1987; *Anderson*, 1987; *van Genuchten and Jury*, 1987) the point was made repeatedly that new methods and technologies of measurement are needed to keep pace with our ability to simulate increasingly complex laboratory and field systems. While the papers reviewed in this report indicate that significant progress was made during the past four years, it is the authors' opinion that three-dimensional heterogeneities and the related measurement problems will command the attention of subsurface hydrologists for many decades to come. More than a decade ago *Molz et al.* (1979) wondered if increasingly sophisticated measurements and measurement devices would enable us to gradually apply existing conceptual models in a truly predictive manner, or if the resulting measurements would be so ambiguous that they ultimately force the development of a radically different theory. With 12 years of hindsight, the authors are leaning a little more toward the technology-based solution.

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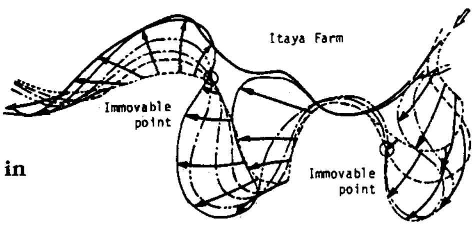

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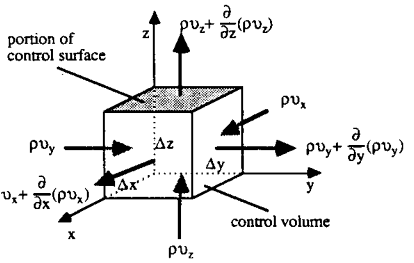

portion of control surface
z
$\rho v_z + \frac{\partial}{\partial z}(\rho v_z)$
ρv_x
ρv_y
Δz
Δy
$\rho v_y + \frac{\partial}{\partial y}(\rho v_y)$
$\rho v_x + \frac{\partial}{\partial x}(\rho v_x)$
Δx
y
x
control volume
ρv_z