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Project Summary

A New Approach and Methodologies for Characterizing the Hydrogeologic Properties of Aquifers

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In the authors' opinion, the ability of hydrologists to perform field measurements of aquifer hydraulic properties must be enhanced if we are to improve significantly our capacity to solve ground water contamination problems at Superfund and other sites. Therefore, the primary purpose of this report is to provide motivation and new methodology for measuring K(z), the distribution of horizontal hydraulic conductivity in the vertical direction in the vicinity of a test well. Measurements in nearby wells can then be used to build up three-dimensional distributions. For completeness, and to enhance the usefulness of this report as a field manual, existing methodology for the measurement of effective porosity, vertical hydraulic conductivity, storativity and hydraulic head, are presented also. It is argued that dispersion-dominated models, particularly two-dimensional, vertically. averaged (areal) models, have been pushed about as far as they can go, and that two-dimensional vertical profile or fully three-dimensional advection-dominated transport models are necessary if we are to increase significantly our ability to understand and predict contaminant transport, reaction, and degradation in the field. Such models require the measurement of hydraulic conductivity distributions, K(z), rather than vertically averaged values in the form of transmissivities.

Three devices for measuring K(z) distributions (the impeller flowmeter, the heat.pulse flowmeter, and a multi-level slug test apparatus) are described in detail, along with application and data reduction procedures. Results of the various methods are compared with each other and with the results of tracer studies performed previously. The flowmeter approach emerged as the best candidate for routine K(z) measurements. Impeller meters are now available commercially, and the more sensitive flowmeters (heat pulse and electromagnetic devices) are expected to be available in the near future.

Three-dimensional transport models tend to be advection-dominated rather than dispersion-dominated, and most of the standard finite-difference and finite-element algorithms produce excessive amounts of numerical dispersion when applied to advection-dominated models. Therefore this report closes by providing an introductory review of some newer numerical methods that produce a minimum of numerical dispersion by tracking the flow.

This Project Summary was developed by EPA's Robert S. Kerr

Environmental Research Laboratory, Ada, OK, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The present writers are of the opinion that field measurement capability must increase if we are to improve significantly our ability to handle ground water contamination problems associated with Superfund and other sites. To this end, the single most important parameter concerning contaminant migration is the hydraulic conductivity distribution. If one can't predict where the water goes, how can one expect to predict the movement of a contaminant that is carried by the water? Most conventional flow analyses are based on fully-penetrating pumping tests to get a transmissivity field and large longitudinal dispersion coefficients to account for contaminant spreading in the direction of flow. We call such models dispersion-dominated. In the authors' opinion, the time has arrived to develop and apply aquifer tests for determining the horizontal hydraulic conductivity as a function of vertical position (K(z)) within a well or borehole. When this is done at a number of locations in the horizontal plane, the resulting data can serve as a basis for developing two-dimensional vertical cross-section, quasi three-dimensional or fully three-dimensional flow and transport models that do not require large, scale-dependent, dispersion coefficients.

Shown in Figure 1 are dimensionless K(z) distributions obtained at four different scales of measurement in a single well using an impeller meter (Molz et al., 1989a). It is apparent that as the measurement interval varies from 10 ft (3.05 m) to 1 ft (0.305 m), the apparent variability of the hydraulic conductivity increases. This is the type of information that is lost when fully-penetrating pumping tests are used to obtain vertically-averaged hydraulic conductivities.

There are several techniques for making vertically-distributed measurements, including tracer tests, flowmeter tests, dilution tests and multi-level slug tests, that are described in this report. Such measurements should serve as the basis for an improved understanding and conceptualization of subsurface transport pathways, and may also allow the application of a new generation of contaminant transport models that are advection-dominated and largely free of the problems associated with large, scale.dependent, dispersion coefficients. All of this taken together constitutes what the authors are advocating as the new approach to characterizing the hydrogeologic properties of aquifers.

Selected Methodology

After studying a number of methodologies for measuring K(z) distributions, two techniques, the flowmeter method and the multi-level slug test, emerged as the most practical methodologies for obtaining K(z) information, and were, therefore, studied in detail. Of the two, the flowmeter was more responsive, less sensitive to near-well disturbances due to drilling, and easier to apply. As illustrated in Figure 2, a flowmeter test may be viewed as a natural generalization of a standard fully penetrating pumping test. In the latter application, only the steady pumping rate, QP, is measured, whereas the flow rate distribution along the borehole or well screen, Q(z), as well as QP is recorded during a flowmeter test.

Various types of flowmeters based on heat pulse or impeller technology have been devised for measuring Q(z), and a few groundwater applications have been described in the literature (Hess, 1986; Morin et al., 1988a; Molz et al., 1989a,b). The most low-flow-sensitive types of meters are based on heat.pulse, electromagnetic, or tracer-release technology (Hess, 1986), but to the authors' knowledge such instruments are not presently available commercially, although several are nearing commercial availability. Impeller meters (commonly called spinners) have been used for several decades in the petroleum industry, and a few such instruments suitable for groundwater applications are now available for purchase (Further information available upon request). A meter of this type was applied at the Mobile site to produce the kind of hydraulic conductivity data shown in Figure 1.

Impeller Meter Tests

Once the necessary equipment is obtained, impeller meter tests can be a relatively quick and convenient method for obtaining information about the vertical variation of horizontal hydraulic conductivity in an aquifer. The idea and methodology behind the impeller meter test are illustrated in Figure 2. One first runs a caliper log to ascertain that the screen diameter is known and constant. If it is not constant, the variations must be taken into account when calculating
discharge. A small pump is placed ir
well and operated at a constant flow ra
QP. After pseudo steady-state behavior
obtained, the flowmeter, which wh
calibrated measures vertical flow witl
the screen, is lowered to near the bott
of the well, and a measurement
discharge rate is obtained in terms
impeller-generated electrical pulses o
a selected period of time. The meter
then raised a few feet, another readi
taken, raised another few feet--and so
As illustrated in the lower portion
Figure 2, the result is a series of d
points giving vertical discharge, Q, witl
the well screen as a function of verti
position z. Just above the top of t
screen the meter reading should be eq
to QP, the steady pumping rate that
measured independently on the surfa
with a water meter. The procedure m
be repeated several times to ascert
that readings are stable.

While Figure 2 applies explicitly to
confined aquifer, which was the type
aquifer studied at the Mobile si
application to an unconfined aquifer
similar. Most impeller meters are capal
of measuring upward or downward flc
so if the selected pumping rate, C
causes excessive drawdown, one c
employ an injection procedure as
alternative. In either case, there will
unavoidable errors near the water tal
due to the deviation from horizontal flc
It is desirable in unconfined aquifers
keep QP as small as possible consist
with the stall velocity of the meter. Th
more sensitive meters will have
advantage.

The basic analysis procedure
flowmeter data is quite straightforwa
One assumes that the aquifer
composed of a series of n horizon
layers and takes the difference betwe
two successive meter readings, whi
yields the net flow, ΔQ, entering t
screen segment between the elevatio
where the readings were taken, which
assumed to bound layer i,(i = 1,2, ...,
One then employs the Cooper.Jac
(1946) formula for horizontal flow to a w
or an alternative procedure to obtain K
values.

Heat-Pulse Flowmeter Tests

Application of impeller met
technology will be limited at many si
due to the presence of low permeabi
materials that will preclude the pumpi
of test wells at a rate sufficient to oper
an impeller meter. Another type
flowmeter that is in the prototype sta
the heat.pulse flowmeter, can be used
an alternative to an impeller meter

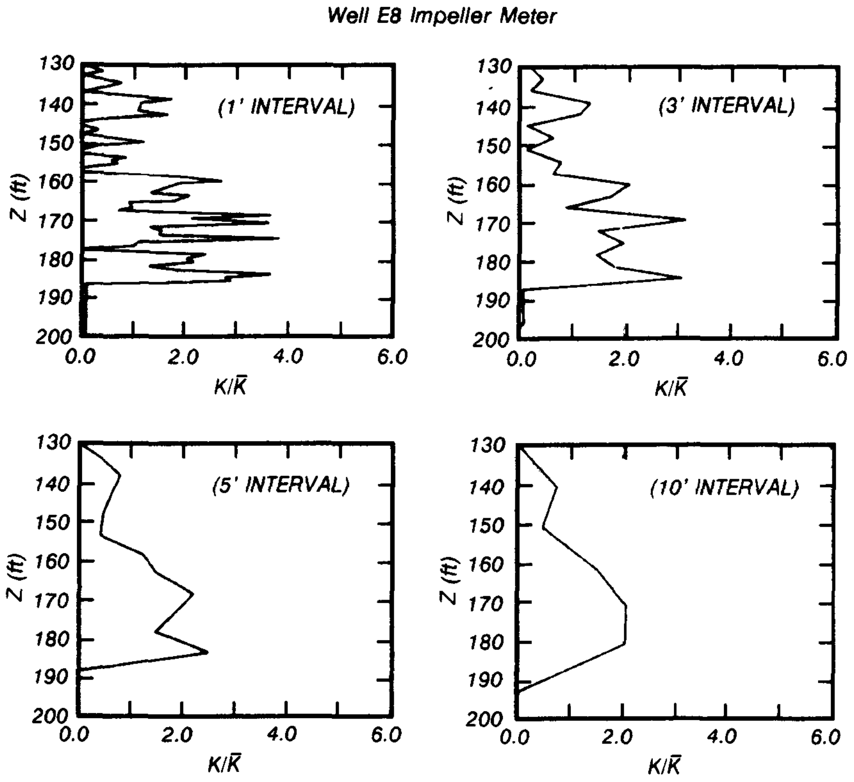

Figure 1. *Dimensionless horizontal hydraulic conductivity distributions based on impeller meter readings taken at the various measurement intervals indicated on the figure.*

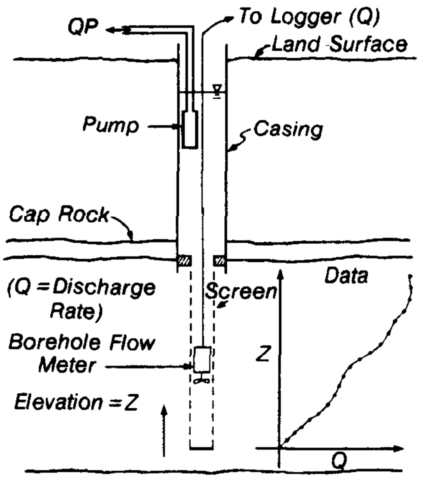

Figure 2. *Apparatus and geometry associated with a borehole flowmeter test.*

virtually any application, and it has the advantage of greater sensitivity. Spinner flowmeters measure a minimum velocity ranging from about 3 to 10 ft/min (1 to 3 m/min), which limits their usefulness in many boreholes having slower water movement. Flow volumes of as much as 4 gal/min (15 L/min) may go undetected in a 4-in (10 cm) diameter borehole when flow is measured with a spinner flowmeter, and much larger volumes may go undetected in larger diameter holes. Heat-pulse flowmeters are particularly useful for application to fractured rock aquifers where flows are often small and contaminant transport pathways difficult to visualize. Such meters may be used to locate productive fracture zones and to characterize apparent hydraulic conductivity distributions.

The urgent need for a reliable, slow.velocity flowmeter prompted the U.S. Geological Survey (USGS) to develop a small-diameter, sensitive, thermal flowmeter. This meter has interchangeable flow-sensors, 1.63 and 2.5 in. (4.1 and 6.4 cm) in diameters, and has flow sensitivity from 0.1 to 20 ft/min (0.03 to 6.1 m/min) in boreholes with diameters that range from 2 to 5 in. (5 to 12.5 cm). Vertical discharge in a borehole is measured with the thermal flowmeter by noting the time-of-travel of the heat pulse and determining water volume flow from calibration charts developed in the laboratory using a tube with a diameter similar to that of the borehole under investigation (Hess, 1986).

The basic measurement principle of the USGS meter is to create a thin horizontal disc of heated water within the well screen at a known time and a known distance from two thermocouple heat sensors, one above and one below the heating element. One then assumes that the heat moves with the upward or downward water flow and records the time required for the temperature peak to arrive at one of the heat sensors. The apparent velocity is then given by the known travel distance divided by the recorded travel time. Thermal buoyancy effects are eliminated by raising the water temperature by only a small fraction of a centigrade degree. The geometry associated with the flowmeter is shown in Figure 3.

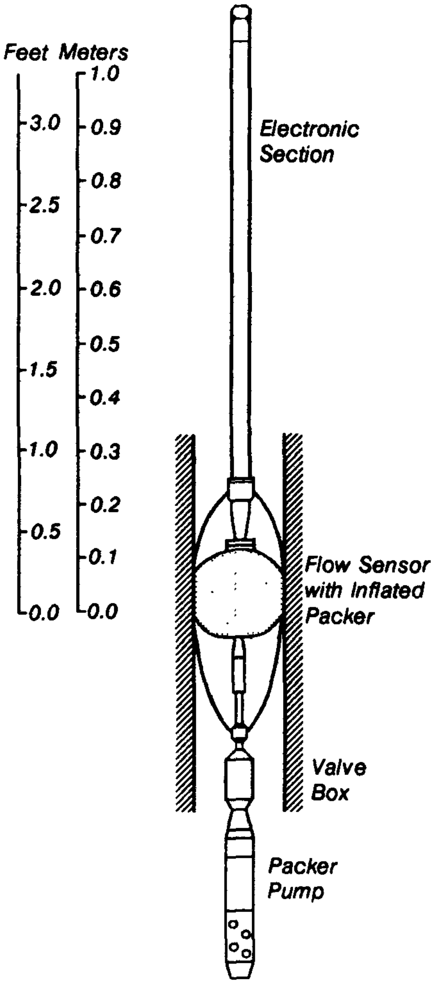

Figure 3. *The U.S. Geological Survey's thermal flowmeter with inflated flow-concentrating packer (modified from Hess, 1988).*

The USGS heat-pulse meter has been applied to the granular aquifer at the Mobile site and to several fracture flow systems. In the present report the authors describe applications to fractured dolomite in northeastern Illinois, fractured gneiss in southeastern New York, and a granitic fracture zone on the Canadian shield in Manitoba. In these applications, supplemental information was obtained from acoustic-televiewer logs, temperature logs, and caliper logs. Information similar to that shown in Figure 4 was obtained. The case studies illustrate potential application of the thermal flowmeter in the interpretation of slow flow in fractured aquifers. The relative ease and simplicity of thermal-flowmeter measurements permits reconnaissance of naturally occurring flows priors to hydraulic testing, and identification of transient pumping effects, which may occur during logging. In making thermal flowmeter measurements, one needs to take advantage of those flows that occur under natural hydraulic-head conditions as well as the flows that are induced by pumping or injection. However, thermal-flowmeter measurements interfere with attempts to control borehole conditions during testing, because the flowmeter and wireline prevent isolation of individual zones with packers. In spite of this limitation, the simplicity and rapidity of thermal-flowmeter measurements constitute a valuable means by which to eliminate many possible fracture interconnections and identify contaminant plume pathways during planning for much more time consuming packer and solute studies. The thermal flowmeter is especially useful at sites similar to the site in northeastern Illinois, where boreholes are intersected by permeable horizontal fractures or bedding planes. Under these conditions, naturally occurring hydraulic-head differences between individual fracture zones are decreased greatly by the presence of open boreholes at the study site. These hydraulic-head differences could only have been studied by the expensive and time consuming process of closing off all connections between fracture zones in all of the boreholes with packers. The simple and direct measurements of vertical flows being caused by these hydraulic-head differences obtained with the thermal flowmeter provided information pertaining to the relative size and vertical extent of naturally occurring hydraulic-head differences in a few hours of measurements. Additional improvement of the thermal-flowmeter/packer system and refinement of techniques for flowmeter interpretation may decrease greatly the time and effort required to characterize fractured-rock aquifers by means of conventional hydraulic testing.

While the case studies described in the present report did not all involve contaminated groundwater, the potential application to plume migration problems and sampling well screen locating is obvious. The relationship of flowmeter measurements to more standard tests such as caliper and televiewer logs indicated also. Hopefully, therm flowmeters and other sensitive devic such as the electromagnetic flowmet being developed by the Tennesse Valley Authority (Young and Waldro 1989) will be available commercially the near future.

Multilevel Slug Tests

The flowmeter testing procedure generally superior to the multilevel sl test approach, because the latt procedure depends on one's ability isolate hydraulically a portion of the te aquifer using a straddle packer. Howeve if reasonable isolation can be achieve which was the case at the Mobile te site, then the multi-level slug test is viable procedure for measuring $K(z)$. equipment needed for such testing available commercially, and the te procedure has the added advantage not requiring any water to be injected in or withdrawn from the test well if a wat displacement technique is used to caus a sudden head change.

The testing apparatus used in th applications reported herein is illustrate schematically in Figure 5 for the aquif geometry at the Mobile site (Melville al., 1989). Two inflatable packe separated by a length of perforate galvanized steel pipe comprised th straddle packer assembly. Aquifer te length as defined by the straddle pack was $L=3.63$ ft (1.1 m). A larger packe referred to as the reservoir packer, w attached to the straddle packer with (2.54 cm) Triloc PVC pipe, creating a un of fixed length of approximately 100 (30.5 m) which could be moved with th attached cable to desired positions in th well. When inflated, the straddle pack isolated the desired test region of th aquifer and the reservoir packer isolate a reservoir in the 6" (15.2 cm) casin above the multilevel slug test unit an below the potentiometric surface of th confined aquifer.

In a typical test, water was displaced i the reservoir above the packer. The hea increase then induced a flow dow through the central core of the reservo packer and down the Triloc pipe to th straddle packer assembly. In th assembly, water flowed from th perforated pipe, through the slotted we screen, and into the test region of th aquifer.

The multilevel unit described was use for slug tests by inserting the plunge displacing a volume of water in th reservoir and then recording the dept variation, $y=y(t)$, relative to the initi

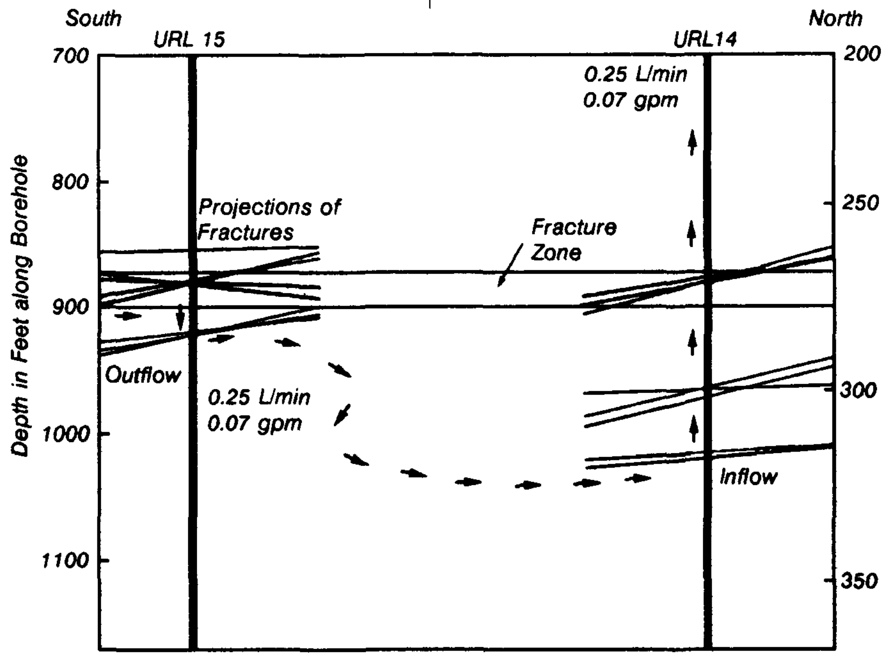

Figure 4. *Distribution of vertical flow measured with the heat-pulse flowmeter in boreholes URL14 and URL15 in southeastern Manitoba superimposed on the projection of fracture planes identified using the acoustic televiewer.*

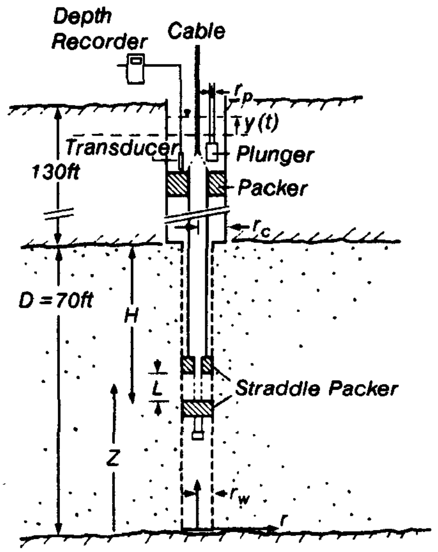

Figure 5. *Schematic diagram of the apparatus for performing a multilevel slug test.*

potentiometric surface (falling head test). Plunger withdrawal was used to generate a rising head test. Head measurements were made with a manually operated digital recorder (Level Head model LH10, with a 10 psig pressure transducer, In Situ, Inc.).

Three methods of analysis have been pplied to the collected slug test data. In the first and second methods, it is assumed that the flow from the test section is horizontal and radially symmetric about the axis of the well. In the first method the quasi-steady state assumption is made. In the second, a transient analysis is applied. In the third analysis, also quasi-steady state, the possibility of vertical flow and anisotropy are considered using curves generated by a finite element model.

Typical results of a series of tests at different elevations are shown for well E6 in Figure 6. The data shown are from plunger insertion tests where a sudden reservoir depth increase to approximately y° = 3ft. was imposed. The depth variation, y = y(t), which is nearly an exponential decay, is a result of flow into the aquifer test section adjacent to the straddle packer. The different slopes of the straight line approximations (least squares fits) are due to the variability of the hydraulic conductivity in the aquifer at the different test section elevations. Tests repeated at a given elevation were generally reproducible, with the maximum difference in slopes of the straight line fits to the data being less than 11%. From this data it is easy to calculate hydraulic conductivity distributions as described in the report.

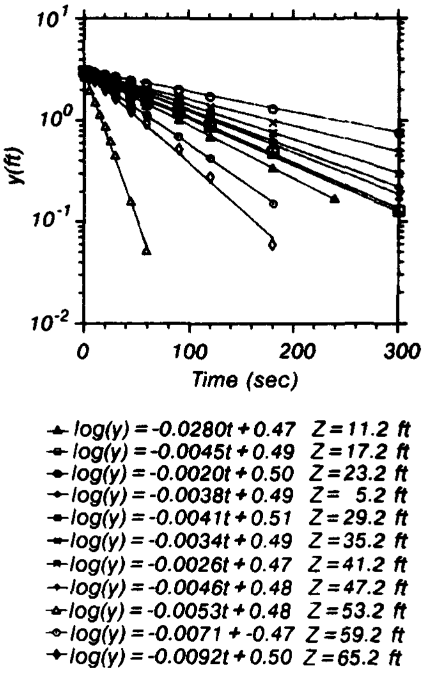

Figure 6. *Multilevel slug test data from well E6, $B = Log(^{y_1}/_{y_2})/(t_2\text{-}t_1)$ = magnitude of the slope of the log y(t) response.*

Modeling of Advection-Dominated Flows

There are a variety of ways in which vertically-distributed hydraulic conductivity distributions can be used to understand and assess problems involving contaminated ground water. A significant amount of insight will be obtained simply by observing and discussing the implications of such information on patterns of contaminant migration. However, use of the vertically-distributed data in three-dimensional mathematical models will be a common procedure for developing quantitative assessments of a variety of possible activities such as evaluation of site remediation plans. Thus it is worthwhile to devote part of this report to a discussion of the relationship between vertically-distributed hydraulic conductivity data and mathematical modeling (Güven et al., 1989).

As pointed out previously, once one moves from the use of vertically-averaged aquifer properties in two-dimensional mathematical models to the use of vertically-distributed aquifer properties in three-dimensional models, the nature of the physical process represented by the model changes dramatically. In many situations, the model changes from one being largely dominated by dispersion (low Peclet number flows) to one largely dominated by advection (high Peclet number flows). Unfortunately, most of the standard finite-difference and finite-element algorithms for solving mathematical models do not work well when applied to advection-dominated flows, especially those that involve chemical or microbial reactions. The necessary evolution from dispersion-dominated to advection-dominated numerical algorithms for solving the flow and transport equations is far from trivial, so it is important to call attention to some of the newer numerical methods, particularly those that produce a minimum of numerical dispersion when used to solve the transport equation.

A complete numerical analysis of contaminant migration in the subsurface usually involves solution of the ground water flow equation and the transport (advection/dispersion) equation. The latter equation is the more complicated due primarily to the existence of the advective transport term which gives the transport equation a hyperbolic character and makes its solution subject to numerical dispersion. In general, the techniques for solving such an equation can be grouped into three classes; namely, Eulerian, Lagrangian, and Eulerian-Lagrangian methods. Eulerian methods are more suited to dispersion-dominated systems while Lagrangian methods are most suited to advection-dominated systems. Eulerian-Lagrangian methods have been introduced to deal efficiently and accurately with situations in which both advection and dispersion are important.

The Eulerian methods are based on the discretization of the transport equation on a numerical solution grid that is fixed in space, and all of the terms of the equation, including the advective transport term, are discretized together and the resulting algebraic equations are solved simultaneously in one solution step. As discussed by Cady and Neuman (1987), while Eulerian methods are fairly straightforward and generally perform well when dispersion dominates the problem and the concentration distribution is relatively smooth, they are usually constrained to small local grid Peclet numbers.

Methods which are based on solutions of the transport equation on a moving grid, or grids, defined by the advection field, or methods which do not rely on a direct solution of the Eulerian transport equation but which are based on an analysis of the transport, deformation and transformation of identified material volumes, surfaces, lines or particles by tracking their motion in the flow field are generally called Lagrangian methods (Cady and Neuman, 1987). In the present report, we reserve this term only for methods which are based on tracking alone and will consider the moving-grid methods which have been called Lagrangian before by some authors simply as special cases of the Eulerian-Lagranglan methods.

Reviews of Eulerian-Lagrangian methods (ELM) have also been presented recently by Cady and Neuman (1987). These methods combine the advantageous aspects of the Lagrangian and the Eulerian methods by treating the advective transport using a Lagrangian approach and the dispersive transport and chemical reactions using an Eulerian approach. According to how the advective transport is taken into account, these methods can be generally grouped into three classes; one class makes use of particle tracking and relates the concentration at a grid node to the solute mass associated with each particle and the particle density around that node, while the second class treats concentration directly as a primary variable throughout the calculations without resorting to the use of a particles, and the third class consists models in which the first and seco approaches are used together in adaptive manner depending on t steepness of the concentration gradient

It may be useful to point out th Eulerian-Lagrangian methods have be developed extensively for the numeri modeling of complex three-dimensio industrial and environmental flows and the solution of various fluid mechani problems particularly over the la decade (Oran and Boris, 1987). The methods are now becoming popular al in the area of subsurface contamina *migration modeling.*

Availability of Computer Code

Several well documented comput codes for three-dimensional flow a solute transport modeling as well parameter identification and uncertain analysis are available in the publ domain. These codes have be developed by universities, vario government agencies and governme supported laboratories. There are al several proprietary codes developed private consulting firms and resear organizations such as the Electric Pow Research Institute. Many of these cod have been listed in the rece monographs by Javandel et al. (198 and van der Heijde et al. (1985). In th regard, the International Ground Wat Modeling Center (IGWMC) serves as information, education, and resear center for groundwater modeling wi offices in Indianapolis, Indiana (IGWM Holcomb Research Institute, Butl University, 4600 Sunset Avenu Indianapolis, Indiana 46208) and Del the Netherlands. IGWMC operates as clearinghouse for groundwater modeli codes and organizes an annual series short courses on the use of vario codes. Similar specialized short cours are also organized by various universiti as well as professional organizatio such as the National Water We Association (NWWA, 6375 Riverside D Dublin, Ohio 43017). NWWA al maintains the Ground Water On Li computer data base for publications the ground water area. Th aforementioned references ar organizations may be consulted for t availability of various modeling codes.

Supplemental Information

This report is devoted mainly to presentation of the information a experience gained from six years of fie experimental and theoretical studies

Auburn University that was funded by the U.S. Environmental Protection Agency through the Robert S. Kerr Laboratory. In one way or another, most of this work dealt with the understanding and measurement of hydraulic conductivity distributions in the field, with all measurements made in the saturated zone. However, the title of the present report, "A New Approach and Methodologies for Characterizing the Hydrogeologic Properties of Aquifers," implies more than the measurement of horizontal hydraulic conductivity as a function of vertical position in a granular aquifer. The additional information, including methodology for measuring specific storage, porosity, hydraulic head, and hydraulic conductivity in the vertical direction, was kindly supplied by a Colleague at the Lawrence Berkeley Laboratory and is included in the report in two separate chapters.

Most individuals attempting to deal with subsurface contamination problems in the field are well aware that more information is needed than that resulting from the measurement of hydrogeologic properties as they are defined herein. Measurement of chemical and biochemical subsurface properties, input from geologists, geophysicists, biologists and other scientists, measurement of subsurface geometry, and information concerning the interplay of field measurements and regulation are all important, but beyond the scope of this report. In order to compensate for this shortcoming, a national conference entitled "New Field Techniques for Quantifying the Physical and Chemical Properties of Heterogeneous Aquifers" was convened in Dallas, Texas on March 20-23, 1989. Similar to this report, the conference was motivated by the need to enhance field measurement capabilities if, as a Nation, we are to solve the many site-specific problems being addressed by the Superfund and other programs. The meeting provided a much needed forum for professionals from government regulatory agencies, universities, and private industry to discuss, describe or display the best and most applicable techniques or equipment for measuring aquifer properties that have an important influence on contaminant migration. The conference featured a broad spectrum of invited and submitted papers and displays dealing with the most important topics facing ground water scientists, engineers and consultants in this field of inquiry. Approximately 50 papers were presented and the 883 page proceedings is available from the Water Resources Research Institute, 202 Hargis Hall, Auburn University, AL 36849 at a moderate cost. The proceedings is intended to serve as a broad-based supplement to this report.

Given the current level of understanding concerning contaminant migration in porous media, it was necessary for the authors of this report, and also for the participants in the aforementioned conference, to attempt to identify practical and useful measurement techniques and equipment while recognizing the fact that we are working within a framework of basic understanding that is far from perfect. This is a classical example of a situation that requires innovative engineering solutions. Within this context, it is hoped that the work described in the present report will serve as part of the basis for the "next step" in field measurements that must be taken if we are to improve significantly our ability to characterize, evaluate and reclaim contaminated aquifers.

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The complete report, entitled "A New Approach and Methodologies for Characterizing the Hydrogeologic Properties of Aquifers," (Order No. PB 90-187 063 ; Cost: $31.00 subject to change) will be available only from:

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