WRC RESEARCH REPORT NO. 7

FURTHER STUDY OF AQUIFER PERFORMANCE

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FINAL REPORT

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Introduction

This termination report refers to Project 65-02G as sponsored by the U.S. Department of Interior, Office of Water Resources Research, and by the Water Resources Center, University of Illinois, as authorized under the Water Resources Research Act of 1964, Public Law 88-379. The project title was "Further Study of Aquifer Performance," and had the objective of developing a generalized treatment of reservoir engineering principles as underlie, describe and control the performance of aquifers used for sources, storage and conduits of water (cf. page 21 of the University of Illinois' "Request for an initial allotment of funds authorized by the Water Resources Research Act of 1964," under date December 1, 1964).

Special Identifications

(1) Project personnel: -- Professor Walter Rose, Project Director, and Research Assistant Professor H. O. Pfannkuch, Project Consultant; also Messrs. H. D. Fara, John Fried, George Miel and Balbir Singh, Graduate Student project workers.

(2) Period and level of active support: -- The above named graduate students worked as a team during the summer months in 1965. Except for nominal computer costs and the purchase of a special analytical balance, essentially all project funds were spent as summer salaries for these students, and in the support of the project director who spent several weeks in the organization of this work. Subsequently three graduate theses programs have developed out of this project, as described below. Continuations in these theses programs have subsequently been supported by other agencies,

notably the American Petroleum Institute under Grant-in-Aid 177 during 1965-66.

(3) Budget summary: -- Altogether approximately $6,500 has been charged against Project 65-02G (US INT WATER RESOURC), for which approximately 0.7 man-years work has been performed, and out of which inventoried equipment valued at $900 has been obtained.

Summary of Work Performed

Work undertaken during the above identified period of active support already has been summarized in the FY 65 Annual Report of the University of Illinois Water Resources Center. This work, and the related subsequent work that has been continued, can be logically classified into three categories, as follows:

(1) Work dealing with new approaches based on modern concepts of continuum mechanics and nonequilibrium thermodynamics, by which fluid transport, diffusion, dispersion and heat transfer in aquifer systems can be analyzed without first assuming the validity of Darcy's famous empirical law. This work is summarized in two publications (in press), namely in: "Reservoir Engineering Reformulated," presented at the 25th Annual Pennsylvania State University Conference on Reservoir Engineering, by Walter Rose (October 1966, cf. Proceedings, in press); and in "Transport Through Interstitial Paths of Porous Solids," Chapter 5 in Flow Through Porous Media, edited by R. J. M. DeWiest (Academic Press, 1967, in press), also by W. Rose.

(2) Work dealing with the characterization of the microscopic details of pore geometry of aquifer systems, by exhibiting pore

connectivity between selected sample points and by specifying the morphology of the interstitial surfaces around small neighborhoods of these selected sample points. This work which is mathematical in nature (based on certain topological graph theorems and differential geometry) is summarized in the Ph.D. thesis of H. D. Fara titled "On the Geometry of Porous Media" (February 1967, University of Illinois, W. Rose, Advisor).

(3) Work dealing with the development of finite difference algorithms to model in three-dimensional space the unsteady-states of motion of water that is in part or in whole bounded by so-called free surface boundaries, as relating to problems such as the shape of falling rain drops, wave motion, action of water in hydraulic structures and open channels, as well as to soil infiltration problems, aquifer performance, and individual well problems. The Ph.D. thesis of Balbir Singh nearing completion (scheduled for publication in spring 1967 under the title "Numerical Study of Time-dependent Free Surface Flows") will provide the detailed summary statement of this work.

The integrating factor which makes each of the above described separate activities simply an aspect of one general problem is easily seen. In the first place, the transport problems, of interest in connection with aquifer performance, clearly have to be formulated before they can be solved. And as shown above, such formulations often lead to high-order, nonlinear partial differential equations, the logical specification of which has constituted one category of project activity. To solve these equations, however, boundary conditions also have to be specified, resulting in the project work dealing with the delineation of pore geometry as the second category reported here. Finally, the third category of the project work then has been directed to the development of special numerical methods useful for generating solutions to the equations of transport, and for obtaining integrals representative of particular problem situations.

Summary of Findings

With respect to the three categories of work performed as described above, the following specific findings can be identified:

(1) It has been shown that Darcy's law of linearity between flux and mechanical energy gradient driving force is only descriptive of groundwater flow under the limiting conditions of the steady-states of motion of incompressible fluid occupying the entire pore space of homogeneous porous media. Unsteady-states of the motion of compressible fluids only partially filling the pore space of anisotropic media require a more general description. This is provided by making reference to certain basic postulates of nonequilibrium thermodynamics, and thereby a general approach has been developed which holds not only for the description of fluid flow of homogeneous fluids, but also for the important coupled processes where diffusion and heat transfer simultaneously are occurring. The basic work of Bachmut and Bear ("A unified treatment of transport phenomena in porous media," TECHNION, Research

Project CV-54, Report 3, July 1965, Haifa) may be taken as the primary reference for this work.

(2) It has been shown that porous solids can be suitably modeled with respect to the detailed geometric characteristics of the pore space, which information then can be used as the needed boundary condition for a synthesis of a description of transport processes by the theory described above, and by the mathematical methods identified below. The early work of Griffiths ("Grain-size distribution and reservoir-rock characteristics" Bull. AAPG, v. 36, p. 205, 1952) represents that basic reference suggesting these possibilities.

(3) It has been shown that water motion with free-surface boundary conditions, as governed by the Navier-Stokes equations in the microscopic sense and by the Fourier diffusivity equation in the macroscopic sense, can be suitably modeled by finite difference computing schemes. Representative problems require about one hour of computing time (IBM 7094 system) as responding to an input listing of in excess of 1000 instructions, but in the continuing work these heavy requirements likely will be lessened. In any case, the project workers have verified the importance of making use of a true balance of normal and tangential stresses across the free surface boundary, instead of the approximate representations as described in the basic reference on this subject, namely Welsh _et al_. ("The MAC Method. A computing technique for solving viscous, incompressible, transient fluid-flow problems involving free surfaces," Low Alamos Scientific Laboratory Report LA-3425, dated March 21, 1966).

Recommendations for Continuing Work

The work of this project has exposed the need for certain continuing research dealing with the following questions:

(1) How exactly are the transport coefficients as obtained from the general nonequilibrium thermodynamics theory of flow, diffusion and heat transfer, to be obtained by experimental methods?

(2) How can the abstract modeling of porous media geometry be applied in particular cases of real systems?

(3) How can the computing techniques be simplified so that the generalized equations of transport phenomena can be studied with a minimized usage of computer time and labor?

These questions currently are being considered in the continuing work at Illinois.

Key Words

COUPLED TRANSPORT PROCESS IN POROUS SOLID SYSTEMS; POROUS MEDIA INTERSTITIAL GEOMETRY; NUMERICAL ANALYSIS OF FREE SURFACE FLOWS.