United States
Environmental Protection
Agency

Research and Development

Robert S. Kerr Environmental
Research Laboratory
Ada OK 74820

EPA/600/S2-89/028 Sept. 1989

Project Summary

Groundwater Modeling: An Overview and Status Report

Paul K.M. van der Heijde, Aly I. El-Kadi, and Stan A.Williams

This report focuses on groundwater models and their application in the management of water resource systems. It reviews the kinds of models that have been developed and their specific and general role in water resource management.

The report begins with the introduction of system concepts applicable to subsurface hydrology and presents groundwater modeling terminology, followed by a discussion of the role of modeling in groundwater management with special attention to the importance of spatial and temporal scales. The model development process is discussed together with related issues such as model validation. A separate section provides information on model application procedures and issues. In addition to a review of the model application process, this chapter contains discussion of model selection and model calibration and provides information on specific aspects of pollution modeling. The report also contains an extensive overview of current model status. Here, the availability of the models, their specific characteristics, and the information, data, and technical expertise needed for their operation and use are discussed. Also discussed are quality assurance in groundwater modeling and management issues and concerns. The report concludes with a review of current limitations in modeling and offers recommendations for improvements in models and modeling procedures.

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).

Background

In the mid-1970s, by request of the Scientific Committee on Problems of the Environment (SCOPE), part of the International Council of Scientific Unions (ICSU), the Holcomb Research Institute (HRI) at Butler University, Indianapolis, Indiana, carried out a groundwater modeling assessment. This international study, funded in large part by the U.S. Environmental Protection Agency (EPA) through its R.S. Kerr Environmental Research Laboratory in Oklahoma, resulted in a report published by the American Geophysical Union (AGU) in its series, *Water Resources Monographs*. In 1985 a second edition of this monograph was published, based on information collected at HRI through its International Ground Water Modeling Center (IGWMC) from its inception in 1978 until December 1983. The Center is an international clearinghouse for groundwater models and a technology transfer center in groundwater modeling. Since 1983 the Center has been linked to the TNO Institute of Applied Geosciences, Delft, The Netherlands, which operates the European office of the IGWMC. Supported largely by the EPA and in part by HRI, the Center organizes and conducts short courses and seminars, and carries out a research program to advance the quality of modeling in groundwater management, in support of the Center's technology transfer functions.

The report summarized herein presents results of research and information processing activities performed by the

IGWMC under a research and technology transfer cooperative agreement initiated in 1985. The report serves three functions: (1) it provides an introduction to groundwater modeling and related issues for use as instruction material in short courses and for self study; (2) it provides an overview of the status of major types of groundwater models; and (3) it presents a discussion of problems related to the development and use of groundwater models.

Introduction

Groundwater modeling is a methodology for the analysis of mechanisms and controls of groundwater systems and for the evaluation of policies, actions, and designs that may affect such systems.

Models are useful tools for understanding the mechanisms of groundwater systems and the processes that influence their composition. Modeling serves as a means to ensure orderly interpretation of the data describing a groundwater system, and to ensure that this interpretation is a consistent representation of the system. Modeling can also provide a quantitative indicator for resource evaluation where financial resources for additional field data collection are limited. Finally, models can be used in what is often called the predictive mode by analyzing the response a system is expected to show when existing stresses vary and new ones are introduced. They can assist in screening alternative policies, in optimizing engineering designs, and in assessing operative actions in order to determine their impacts on the groundwater system and ultimately on the risks of these actions to human health and the environment.

In managing water resources to meet long-term human and environmental needs, groundwater models have become important tools.

The field of groundwater modeling is expanding and evolving as a result of:

- Widespread detection of contaminated groundwater systems
- Enhanced scientific capability in modeling groundwater contamination in terms of the physical, biological, and chemical processes involved
- Rapid advancement of computer software and hardware, and the marked reduction in the cost associated with this technology.

The rapid growth in the use of groundwater models has led to unforeseen problems in project management. Some of the projects in which these sophisticated tools have been used have even led to adversary legal procedures in which the model application or even the model's theoretical framework and coding have been contested. Often, the key issue is the validity of model-based predictions. Other issues of concern include code availability and reliability, model selection and acceptance criteria, project review and procurement, data requirements, information exchange, and training.

The Groundwater System

Groundwater is a subsurface element of the hydrosphere, which is generally understood to encompass all the waters beneath, on, and above the earth's surface. Many solar-powered processes occur in the hydrosphere, resulting in a continuous movement of water. This dynamic system is referred to as the hydrologic cycle. Its major elements are atmospheric water, surface water, water in the subsoil (shallow and deep vadose zone), groundwater, streams, lakes and ocean basins, and the water in the lithosphere. (Figure 1).

Movement of water occurs both within each element of the hydrologic cycle and as exchanges between the elements, and results in the dynamic character of this relatively closed system. The exchange processes between the surface subsystem and the atmosphere include evaporation, precipitation (rainfall and snowfall), and plant transpiration. Infiltration, seepage, groundwater recharge from streams, and subsurface discharge into lakes and streams (both interflow and baseflow) are interelement processes between the earth's surface and subsurface. Surface runoff forms the link between the earth's surface and the network of streams. In addition, interactions take place between the subsurface hydrosphere and elements of the earth's biological environment (e.g., consumptive use of water by plants).

A groundwater system is an aggregate of rock in which water enters and moves, and which is bounded by rock that does not allow any water movement, and by zones of interaction with the earth's surface and with surface water systems. In such a system, the water may transport solutes and biota; interactions of both water and dissolved constituents with the solid phase (rock) often occur.

Water enters the groundwater system in recharge zones and leaves the system in discharge areas. In a humid climate, the major source of aquifer recharge is the infiltration of water and its subsequent percolation through the soil into the groundwater subsystem. This type of recharge occurs in all in-stream areas except along streams and their adjoi floodplains, which are generally charge areas. In arid parts of the w recharge is often restricted to mour ranges, to alluvial fans bordering th mountain ranges, and along the chan of major streams underlain by thick permeable alluvial deposits.

In addition to these natural rech processes, artificial or man-made charge can be significant. This type o charge includes injection wells, indu infiltration from surface water bodies, irrigation.

Outflows from groundwater syst are normally the result of a combina of inflows from various recharge sour Groundwater loss appears as interflo streams (rapid near-surface runoff); groundwater discharge into streams sulting in stream baseflow); as spri and small seeps in hillsides and va bottoms; as wetlands such as lakes marshes fed by groundwater; as capil rise near the water table into a zone fr which evaporation and transpiration occur; and as transpiration by phre phytes (plants whose roots can live in saturated zone or can survive fluctuati of the water table). Other outflows are tificial or human-induced, as agricult drainage (tile-drains, furrows, ditch and wells for water supply or dewater (e.g., excavations and mining).

The unsaturated zone has a signific smoothing influence on the tempo characteristics of the recharge of grou water systems. High variable (hou precipitation and diurnal evapotranspi tion effects are dampened and seaso and long-term variations in flow ra become more prominent further from soil surface. In this dampening t higher-frequency fluctuations are tered, a process that continues in t groundwater zone. Its ultimate effect c be observed in stream base flow, whi is characterized by seasonal and lor term components.

Model Development

In groundwater modeling, a distincti is often made between two major ca gories of activities: model developme and model use in management. Mod development consists of researching t quantitative description of the groun water system, a software developme component, and model testing. Mod development is closely related to the s entific process of increasing knowledg observing nature, posing hypotheses the observed information, verifying t proposed relationships, and thus esta lishing a credible theoretical framewo and improving our understanding of nature. Model development is often driven by the short-term and less frequently by the long-term needs of natural resources management. The resulting, often-generic computer codes are used in model application as part of a larger set of activities which included data collection and interpretation, technical design, economical evaluation, and so forth.

The final report presents a complete, detailed discussion of the model development process, scenarios and databases as well as model applications and management issues including quality assurance.

Groundwater Modeling and Management

Groundwater management is concerned with the efficient utilization of groundwater resources in response to current and future demands, while protecting the integrity of the resources to sustain general environmental needs. Groundwater modeling has become an important methodology in support of the planning and decision-making processes involved in groundwater management.

Groundwater modeling provides an analytical framework for understanding groundwater flow systems and the processes and controls that influence their quality, particularly those processes influenced by human intervention in the hydrogeologic system. Models can provide water resource managers with necessary support for planning and screening of alternative policies, making management decisions, and reviewing technical designs for groundwater remediation based on a risk analysis of benefits and costs. Such support is particularly advantageous when applied to development of groundwater supply, groundwater protection, and aquifer restoration.

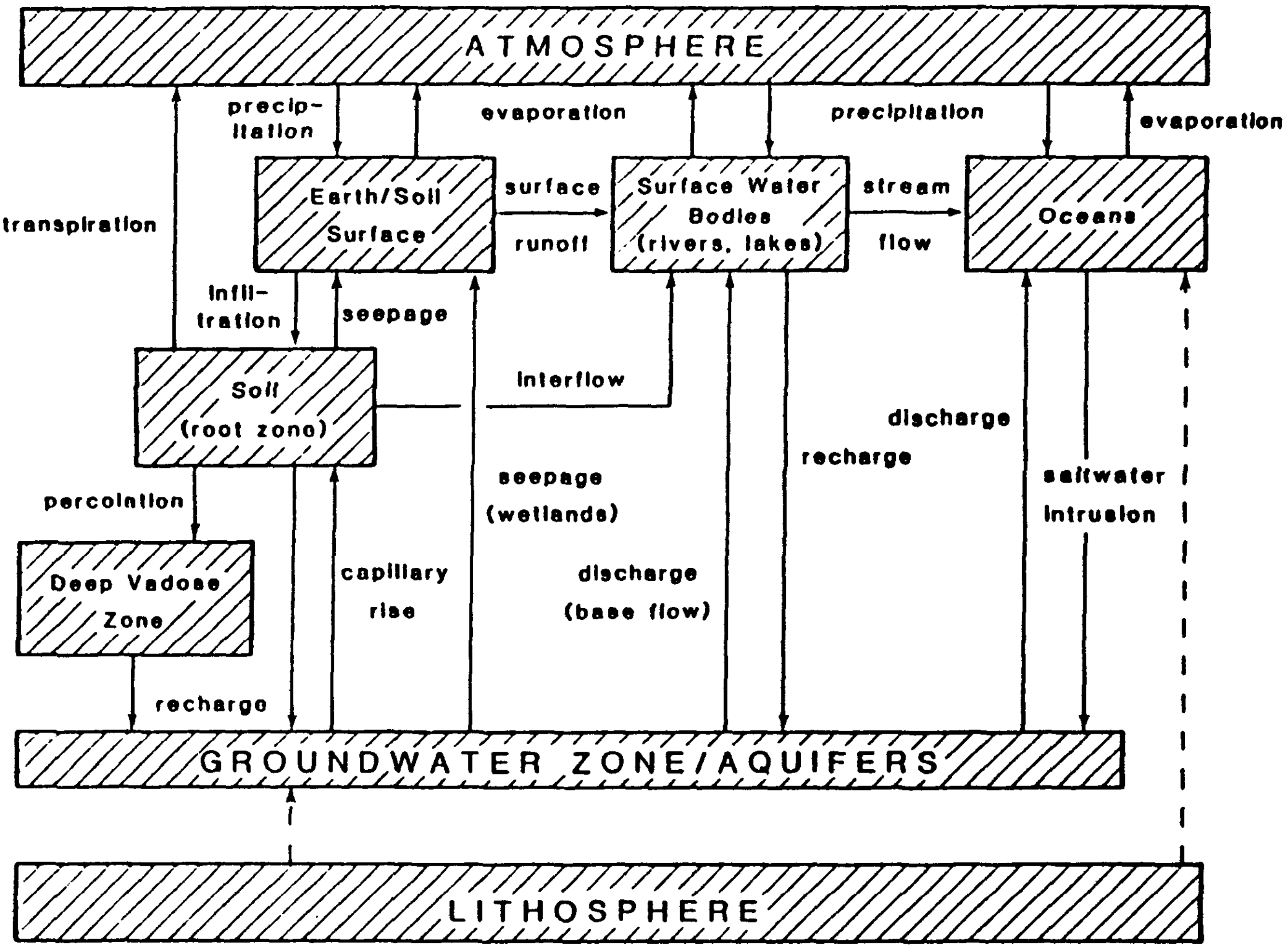

Figure 1. Elements of the hydrologic cycle and their interactions.

Successful utilization of modeling is possible only if the methodology is properly integrated with data collection, data processing, and other techniques and approaches for evaluation of hydrogeologic system characteristics. Furthermore, frequent communication between managers and technical experts is essential to assure that management issues are adequately formulated and that the technical analysis using models is well targeted.

Where precise aquifer and contaminant characteristics have been reasonably well established, groundwater models may provide a viable, if not the only, method to predict contaminant transport and fate, locate areas of potential environmental risk, identify pollution sources, and assess possible remedial actions. Some examples in which mathematical models have assisted in the management of groundwater protection programs are:

- Determining or evaluating the need for regulation of specific waste disposal, agricultural, and industrial practices
- Analyzing policy impacts, as in evaluating the consequences of setting regulatory standards and rules
- Assessing exposure, hazard, damage, and health risks
- Evaluating reliability, technical feasibility and effectiveness, cost, operation and maintenance, and other aspects of waste disposal facility designs and of alternative remedial actions
- Providing guidance in siting new facilities and in permit issuance and petitioning
- Developing aquifer or well head protection zones
- Assessing liabilities such as post-closure liability for waste disposal sites

Models generally applied to groundwater pollution problems can be divided into two broad categories: (1) flow models describing hydraulic behavior of single or multiple fluids or fluid phases in porous soils, or porous or fractured rock, and (2) contaminant transport and fate models for analysis of movement, transformation, and degradation of chemicals present in the subsurface. In the context of groundwater protection programs, a distinction is often made between site-specific and generic modeling.

However, generic modeling approaches are being increasingly contested through public comment on draft regulations or in courtroom legal procedures. An example is the recent court decision that EPA's VHS model (Vertical Horizontal Spread model) cannot be used to grant or deny a delisting petition under the RCRA permitting program.

Site-Specific Modeling

Whether for permit issuance, investigation of potential problems, or remediation of proven contamination, site-specific modeling is required as a necessary instrument for compliance under a number of major environmental statutes. The National Environmental Policy Act of 1970 (NEPA) stipulates a need to show the impact of major site-specific construction activities in Environmental Impact Statements; although not required by the regulations, potential impacts are often projected successfully by mathematical models.

Some of the most challenging site-specific problems involve hazardous waste sites falling under the purviews of RCRA (Resource Conservation and Recovery Act of 1976) and CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act of 1980-Superfund), both administered by the U.S. Environmental Protection Agency. Associated with most of these sites is an intricate array of chemical wastes and the presence of, or potential for, groundwater contamination. Furthermore, the hydrogeologic settings of such sites are usually complex. Under such conditions, groundwater models are useful instruments for analyzing compliance with RCRA and CERCLA legislation.

Generic Modeling

Where the results of environmental analysis must be applied to many sites, data availability is limited or other constraints are present. In such cases, site-specific modeling is not feasible. As a result, many decisions are made by applying models to generic management issues and hydrogeologic conditions. Models used for this type of analysis are more often analytical than numerical in their mathematical solutions, in contrast to models used for detailed analysis of site-specific conditions. Because of their limited data requirements, analytical models can be applied efficiently to a larger number of simple datasets or to statistical analyses representing a wide variety of field conditions. The cost of such exercises would often be prohibitive when using numerical models.

Conclusions

An EPA Study Group has identified a variety of new models and modeling approaches as important to groundwater protection:

- Simulation of flow and transpo multimedia (e.g., coupled model surface water/groundwater ir action)
- Representation of stochastic p esses in predictive modeling, improving the applicability of ge tistical models
- Improved modeling of hydrochem speciation
- Simulation of flow and transpo fractured and dual-porosity me including diffusion in dead- pores
- Simulation of flow and transpo soils containing macropores
- Determination of effects of con tration-dependent density groundwater flow and pollu transport
- Determination of effects of altera of geologic media on hydrolog and chemical characteristics (dehydration of clay when attac by solvents, change in sorptive ca city of material when heated)
- Representation of the three-dim sional effects of partially penetra wells on water table aquifers
- Development of models for mana ment of groundwater contamina plumes
- Development of expert systems (ficial intelligence) for such tasks selecting appropriate submodels subroutines for specific problems
- Application of parameter identifi tion models to be used with studies
- Further development of pre- post-simulation data processors
- Continued development of risk sessment and management mode
- Modeling of volatilization, multipha flow, and immiscible flow
- Incorporation of economic factors improve estimation of cleanup cos
- Development of generic and si specific parameter databases.

Fundamental research support groundwater modeling is consider necessary in such areas as:

- Transient behavior of process rameters (e.g., retardation, hydrau conductivity)
- Desorption for nonhydropho chemicals
- Multicomponent transport and che ical interaction
- Enhanced transport mechanis (e.g., piggy-backing on more m bile chemicals)
- Transport of silt with sorbed che icals in aquifers

- Improved numerical accuracy, stability, and efficiency.

Modeling the transport and fate of chemicals in groundwater is a major subject of several EPA and DOE research programs. These programs focus on immiscible flow associated with organic and oil-like liquids. Other topics currently being studied include simulation of flow and transport in fractured and dual-porosity media, representation of stochastic processes in predictive modeling, multimedia risk assessment, incorporation of volatilization in multiphase transport models, and simulation of density-dependent flow.

Paul K.M. van der Heijde, Aly I. El-Kadi, and Stan A. Williams are with International Ground Water Modeling Center, Butler University, Indianapolis, Indiana 46208.

Joe R. Williams *is the EPA Project Officer (see below).*

The complete report, entitled "Groundwater Modeling: An Overview and Status Report," (Order No. PB 89-224 497/AS; Cost: $28.95, subject to change) will be available only from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650

The EPA Project Officer can be contacted at:

Robert S. Kerr Environmental Research Laboratory
U.S. Environmental Protection Agency
Ada, OK 74820

United States
Environmental Protection
Agency

Center for Environmental Research
Information
Cincinnati OH 45268

BULK RATE
POSTAGE & FEES PAI
EPA
PERMIT No. G-35

Official Business
Penalty for Private Use $300

EPA/600/S2-89/028