GROUND-WATER MODELS FOR WATER RESOURCES PLANNING

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ABSTRACT

In the past decade hydrologists have emphasized the development of computer-based mathematical models to aid in the understanding of flow, the transport of solutes, transport of heat, and deformation in the ground-water system. These models have been used to provide information and predictions for water managers. Too frequently, ground water was neglected in water-resource planning because managers believed that it could not be adequately evaluated in terms of availability, quality, and effect of development on surface-water supplies. Now, however, with newly developed digital ground-water models effects of development can be predicted. Such models have been used to predict hydrologic and quality changes under different stresses. These models have grown in complexity over the last ten years from simple one-layer flow models to three-dimensional simulations of ground-water flow which may include solute transport, heat transport, effects of land subsidence, and encroachment of saltwater. This paper illustrates, through case histories, how predictive ground-water models have provided the information needed for the sound planning and management of water resources in the United States.

INTRODUCTION

Ground-water reservoirs in the United States include a wide range of geologic and hydrologic conditions. These reservoirs vary from those that drain and refill naturally on an annual basis, to those where the annual recharge is but a small fraction of the annual withdrawal and water is being mined from storage. United States ground-water reservoirs constitute an enormous freshwater resource. Underlying the United States are about 246 trillion cubic meters (m^3) of ground-water within a few thousand meters of the land surface. About 48 percent of the total population and 95 percent of the rural population of the United States are dependent on ground water for water supply.

Withdrawals of ground water consisted of about 3590 cubic meters per second ($m^3 s$) in 1975. This is 20 percent of the total water withdrawal use (excluding hydro-electric power generation). Withdrawal of ground water for irrigation has seen the greatest increase, from 875 m^3s in 1950 to more than 3066 m^3s per day in 1970.

During the 1980's, ground-water use for all purposes is expected to increase substantially throughout the United States, with the greatest increases in the arid southwestern areas. Large supplies will be needed for the new energy industries, for irrigation, and municipal supplies. Withdrawals of ground water to meet these needs will have varied and widespread effects. Some of the problems that may occur include:

(1) Depletion of ground-water reservoirs,

(2) Substantial reduction or elimination of streamflow,

(3) Deterioration of water quality,

(4) Land subsidence.

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These problems are causes for growing concern and water resource managers need hydrologic information and prediction analyses to help them estimate what will happen if a withdrawal plan is implemented.

A major emphasis in the past decade was the development of computer-based mathematical models to aid in the understanding of ground-water flow and the transport of solutes in the ground-water system. Such models are now widely used to provide information and prediction. Over time, the complexity of ground-water computer models has grown from simple one-layer flow simulations to three-dimensional simulations which may include solute transport, heat transport, effects of land subsidence, and encroachment of saltwater.

Electric analog and digital models have been used in the United States for the past 20 years. The U.S. Geological Survey established an analog model laboratory in Phoenix, Arizona, in 1960 and constructed more than 100 models. The digital computer model replaced the analog model in the 1970's and now plays a major role in many ground-water investigations. More than 250 digital models have been constructed for a wide variety of hydrogeologic conditions, stress conditions, and water resource problems. A description of digital models that have been used in evaluation of water resources management problems is given in a report by Bachmat and others (1978); this report also contains information on model accessibility, inadequacies of model data, and inadequacies of modeling.

The purpose of this paper is to describe ground-water modeling procedures and to give case histories of the use of ground-water models in the planning and management of water resources.

GROUND-WATER MODELING PROCEDURE

There are four basic types of ground-water models: flow, solute transport, heat transport, and deformation. Some ground-water studies need sophisticated models while others require only a single-layer flow model.

A summary of the major steps in a ground-water modeling study is shown in fig. 1. The first phase consists of the collection and interpretation of the hydrologic data to describe the hydrogeologic framework and hydrologic stress. A conceptual model of the operation of the ground-water system is then developed. The conceptual model is a description of the physical framework, and hydrologic stresses including sources of recharge and discharge and direction of ground-water flow and variation of aquifer properties.

The next step is to translate the conceptual model into a mathematical model of flow or of solute transport. The model is calibrated by trial-and-error adjustment of transmissivity, leakance, storage, recharge boundaries, and discharge (Konikow, 1978). The objective of the calibration is to determine whether the model can simulate field observations. The model parameters are adjusted to minimize differences between the observed data and computed data.

If the model does not duplicate field conditions then the physical framework should be modified, new estimates of the hydrologic system, or changes made in the conceptual model. The model feedback may indicate data deficiencies and it may be necessary to collect additional data before calibration can continue.

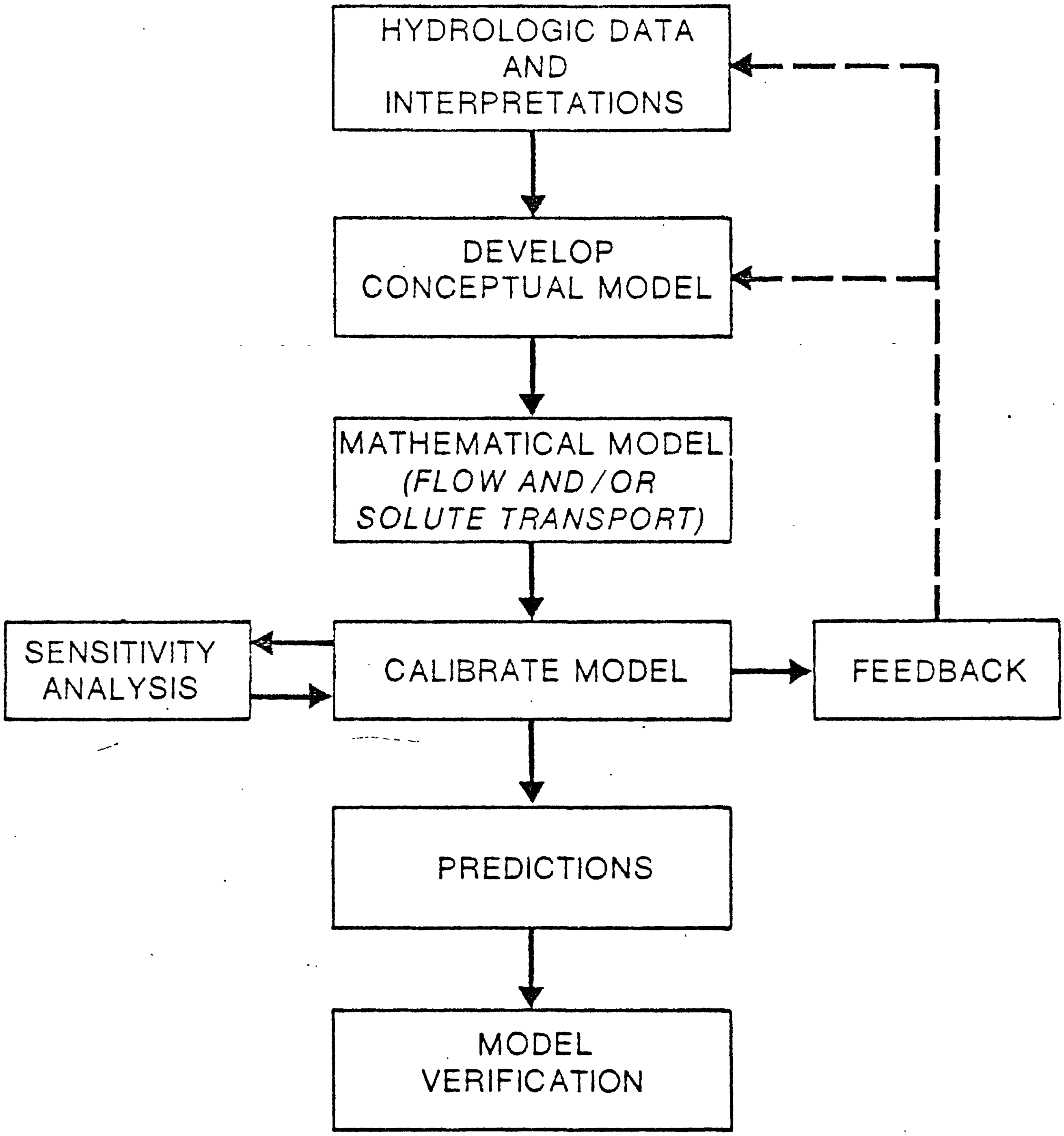

Figure 1 - Ground-Water modeling steps

The hydrogeologic experience of the modeler is a most important factor in the calibration. The modeler must be familiar with the data accuracy, and the uncertainties in estimating the aquifer framework or hydrologic stress. Sensitivity tests are made by varying aquifer parameters and observing the ensuing effects. The sensitivity tests assist in defining data requirements and model reliability.

When the hydrologist is satisfied that the model accurately simulates the real system, the model may be used to evaluate water resource management problems or predict changes. If the model predictions accurately match the predicted changes, the model is considered verified. A model that has been calibrated only to reproduce historical data should not be considered a verified model (Konikow, 1978).

EXAMPLES OF USE OF GROUND-WATER MODELS

Models have been used to simulate ground-water hydrology in a wide variety of geologic environments. To illustrate this variety, the following sections describe the use of models in four hydrologically complex areas: the Arkansas River Valley (Colorado), the Rocky Mountain arsenal (Colorado), the San Luis Valley (Colorado), and southwest Florida.

Arkansas River Valley (Colorado)

An analog model, a digital flow model, and a digital solute transport model were used in the Arkansas River Valley of Colorado to define the operation of the stream-aquifer system and to predict the effects of the proposed changes in water management (Moore and Wood, 1967). The area of study extends from Pueblo, Colorado, to the Kansas line, a distance of 240 kilometers (fig. 2). The Arkansas Valley is underlain by an unconsolidated sand-and-gravel aquifer (fig. 3). Development of ground-water for irrigation in the early 1960's reduced the flow of the Arkansas River and caused legal disputes between ground-water and surface-water users.

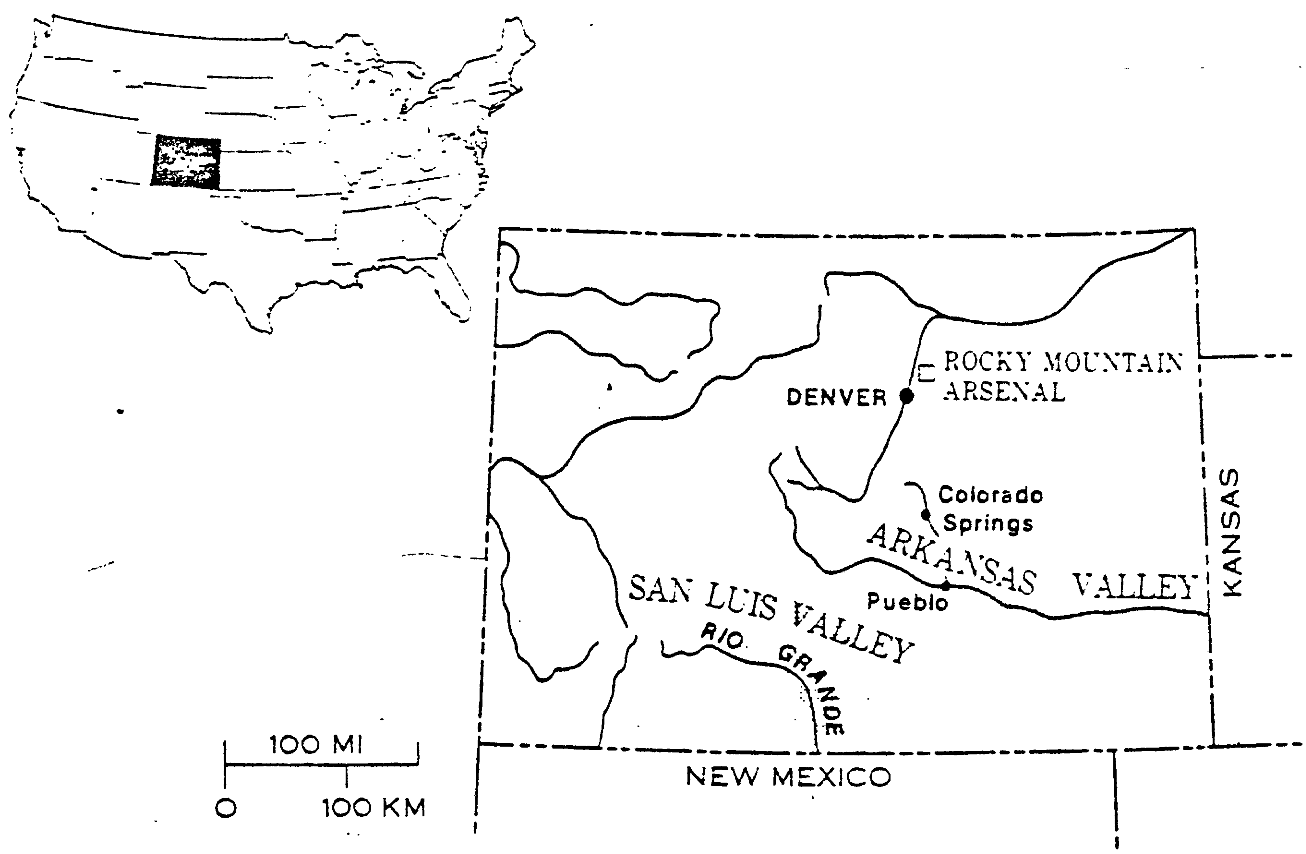

Figure 2 - Colorado model studies

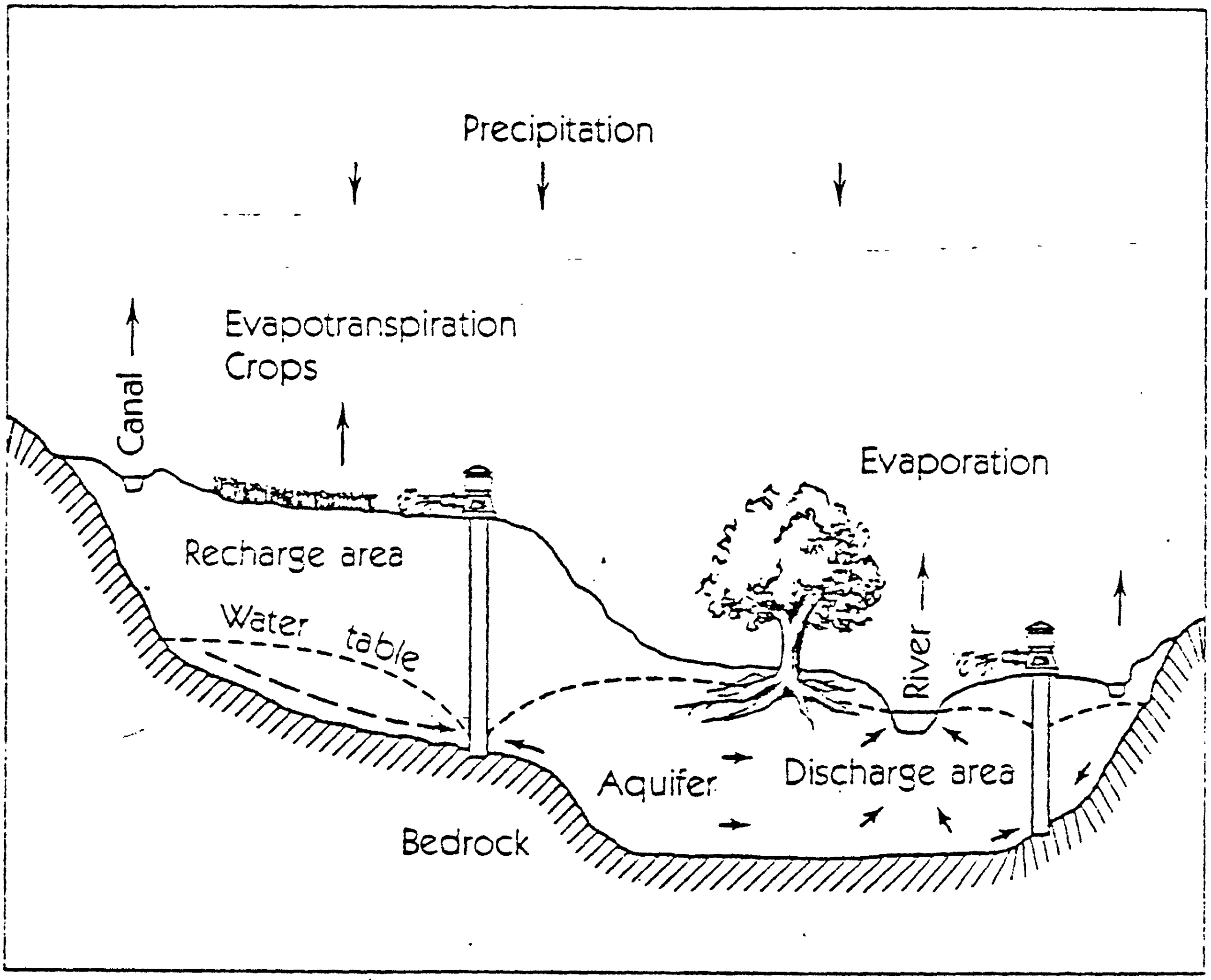

Figure 3 - Arkansas Valley hydrogeologic section

An electrical analog model was constructed in 1966 to simulate the stream and aquifer. The model incorporated aquifer transmissivity, specific yield, and hydrologic boundaries. It was calibrated using streamflow records, well hydrographs, and water-level-change maps. It was one of the first attempts to define, on a large scale, stream-aquifer relations and to evaluate evapotranspiration loss from a water table. The analog model provided the basis for later constructing a digital model of the valley. The digital model was used to predict changes in ground-water storage and the availability of surface-water at successive downstream diversion points on a month-by-month schedule under various management plans (Taylor and Luckey, 1974).

In 1971-72, a solute-transport digital computer model was developed for a part of the Arkansas River Valley. This model was used to describe and predict monthly salinity changes in the aquifer and in the Arkansas River (Konikow and Bredehoeft, 1974). A finite-difference approximation was used to solve the flow equations and method of characteristics to solve the solute transport equation. The model was calibrated with measured values of streamflow, water levels, and water-quality changes. A sensitivity analysis also was made to help define the data monitoring requirements. This model greatly improved the understanding of the water-quality variations and their relation to irrigation practices.

Results of these model studies have been used as a basis for modifying the Colorado State water law, for developing ground-water supplies, for administering water distribution, and for evaluating the impact of proposed developments on interstate compacts.

Rocky Mountain Arsenal, Colorado

A digital solute-transport model was used to evaluate a chemical pollution problem at the Rocky Mountain arsenal (fig. 2) near Denver, Colorado (Konikow, 1977). The model used a finite-difference solution for the ground-water flow and the method of characteristics to solve the solute-transport equation. Liquid waste from the manufacturing of chemicals and pesticides has been discharged into unlined ponds from 1943 to 1956. The waste contained chloride concentrations of several thousand milligrams per liter. Beginning in 1956, severe crop damage occurred to fields irrigated with ground water north of the arsenal. This prompted the construction of an asphalt-lined evaporation pond and a deep waste-disposal well.

The records of about 200 observation wells were used to determine the hydrogeologic characteristics, including saturated thickness and transmissivity of the alluvial aquifer. The transmissivity of the alluvial aquifer ranged from 0 to 1800 m^2/day per second and its saturated thickness was generally less than 18 meters. No data were available to define effective porosity and dispersivity; hence these characteristics were estimated by trial and error with the model. The model represented an area of 88 square kilometers which included the entire zone where chloride concentrations, in ground water, were more than 200 mg/L.

Four separate time periods were studied to approximate the hydrologic history of the aquifer. A comparison of observed and computed patterns of chloride concentration indicated that an effective porosity of 30 percent and a longitudinal and transverse dispersivity of 30 meters provided the best fit. The contamination problem was simulated for a 30-year period (1943 - 1972) and comparisons were made of chloride distribution changes (fig.4).

Model analysis indicated that the geologic framework of the area markedly restricted the transport and dispersion of dissolved chemicals in the aquifer. Dilution by seepage from unlined canals was important in reducing the level of chloride concentration downgradient from the arsenal. The model was used to evaluate proposals to reclaim the contaminated ground water of (Konikow, 1977).

San Luis Valley, Colorado

Analog and digital models of unconfined and confined aquifers in the San Luis Valley (fig. 2) of south-central Colorado were developed by Emery, Patten, and Moore (1965). Ground-water withdrawal for irrigation had reduced the flow of the Rio Grande and this affected downstream flow to New Mexico and Texas. The upper or unconfined aquifer (fig. 5) was modeled.

This model was used to predict the effects of pumping a network of wells to salvage water lost by evaporation of nonbeneficial vegetation in the

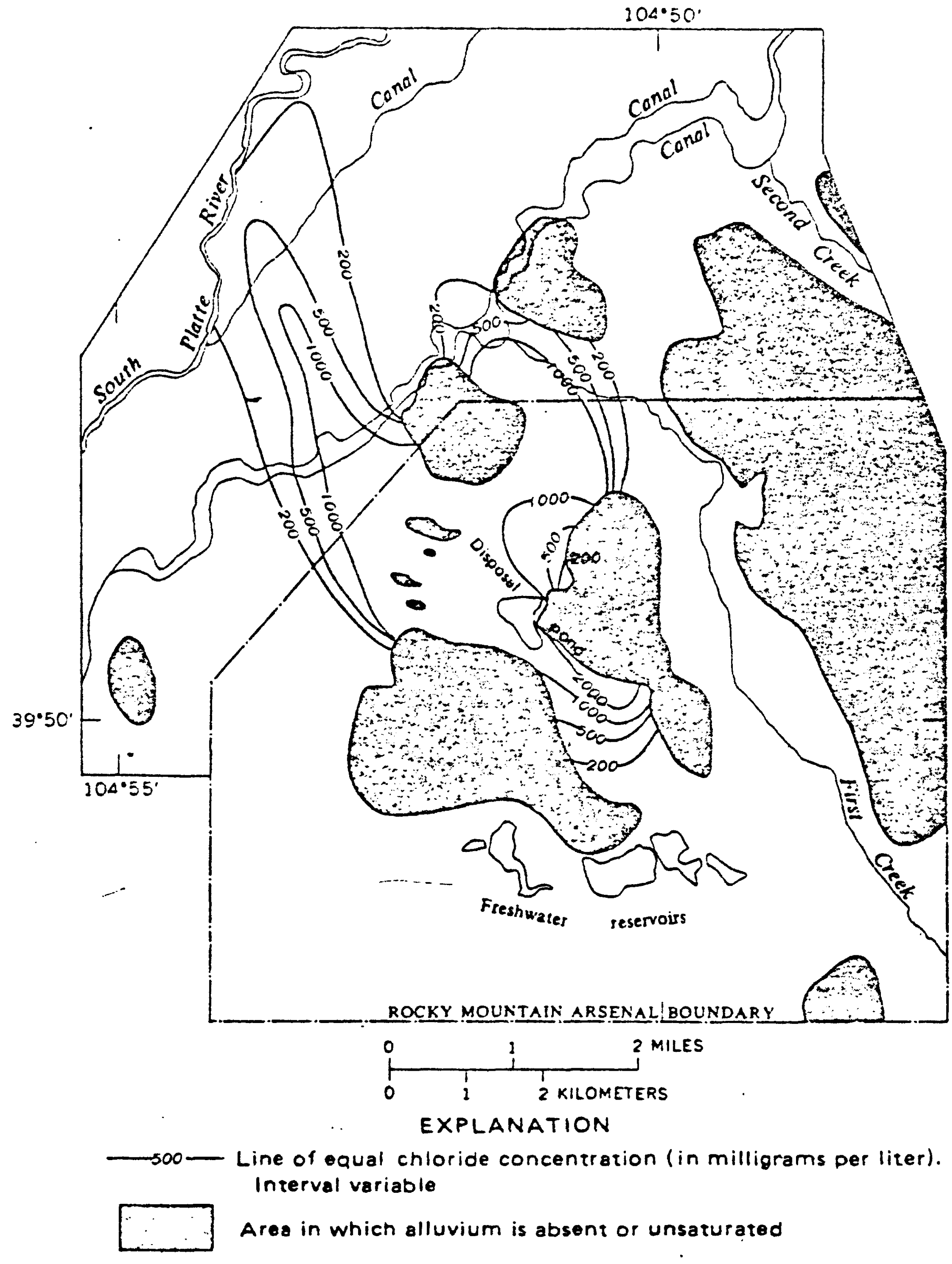

Figure 4 - Rocky Mountain arsenal chloride concentration, computer start of 1961 (Konikow, 1977)

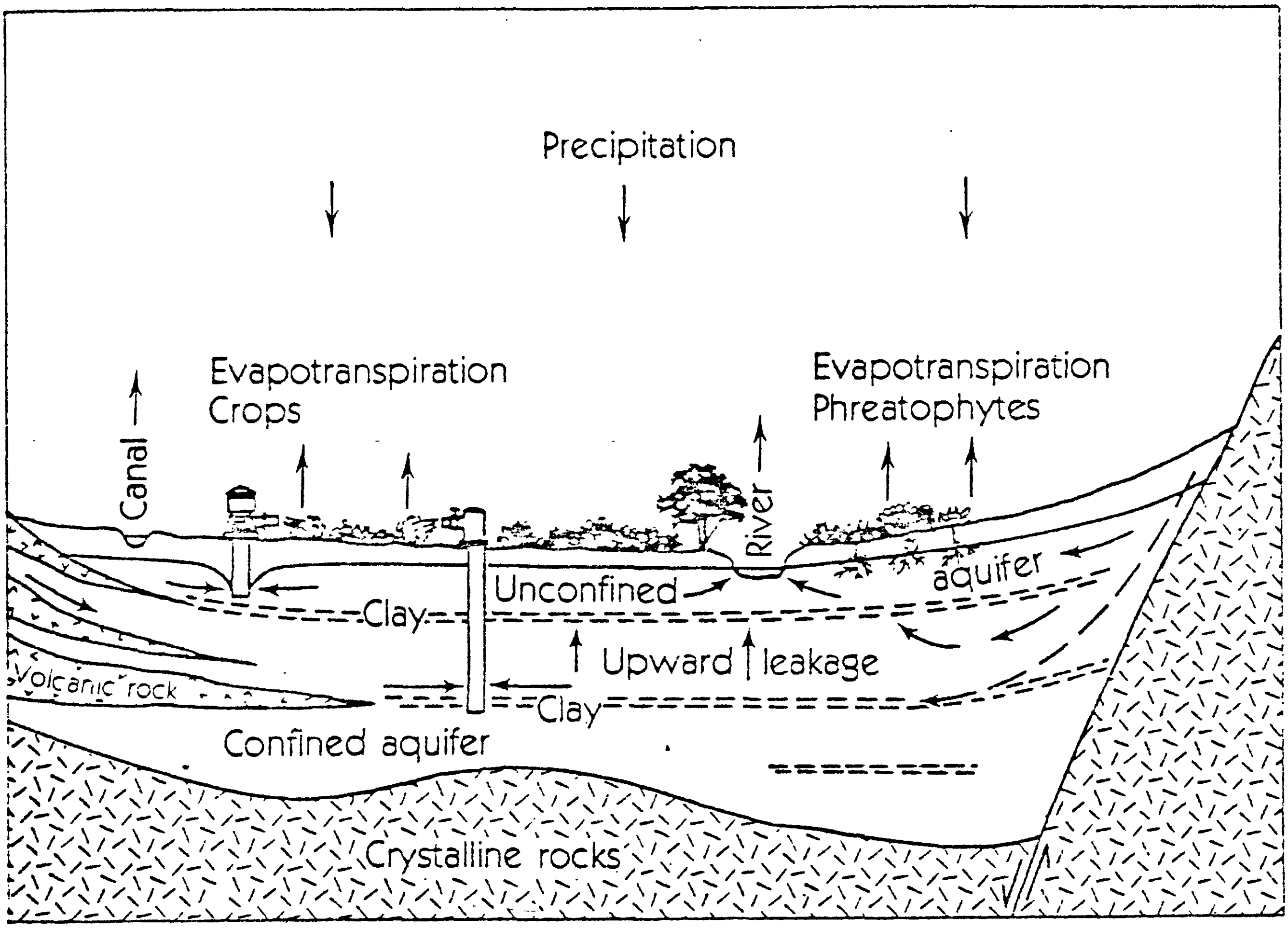

Figure 5 - San Luis hydrogeologic section (Emery and others, 1975)

central part of the valley, (Emery, 1970). The salvage plan provides for the construction of 129 wells to pump 103 x $10^3 m^3$ of water annually for 50 years. The models show that the water level decline would range from 0.3 to 30 meters and that declines exceeding 3 meters would be confined mainly to the vicinity of the salvage wells. This reassured the local irrigators that the salvage project would have little or no effect on water levels in the principal irrigated areas. The analog model was later expanded to include both the unconfined and confined aquifer systems, (Emery, Patten, and Moore 1975). The expanded model was used to administer the permitting of ground water by the Colorado State Engineer and for making management decisions on the development of ground water.

Southwest Florida

A finite difference ground-water model was used in southwest Florida to simulate potentiometric head changes for the period 1976-2000 (Wilson, 1978) that would result from proposed ground-water withdrawal. The study covered an area of about 15,500 square kilometers, (fig. 6) including all or parts of six counties near Tampa, Florida. Ground water use for irrigation and municipal supplies in this area is expected to increase and there also will be a shift in the centers of pumping for phosphate mining. The model was constructed to evaluate the operation of the hydrologic system and to assess the impacts of future development. A particular concern in the evaluation was the impact of development on the potentiometric head and movement of the freshwater-saltwater front. In addition, the public was particularly concerned over a proposed expansion of phosphate mining. Annual withdrawals for irrigation, the principal use of ground water, are projected to increase by about 4.4 m^3 /s from 1976 to 2000.

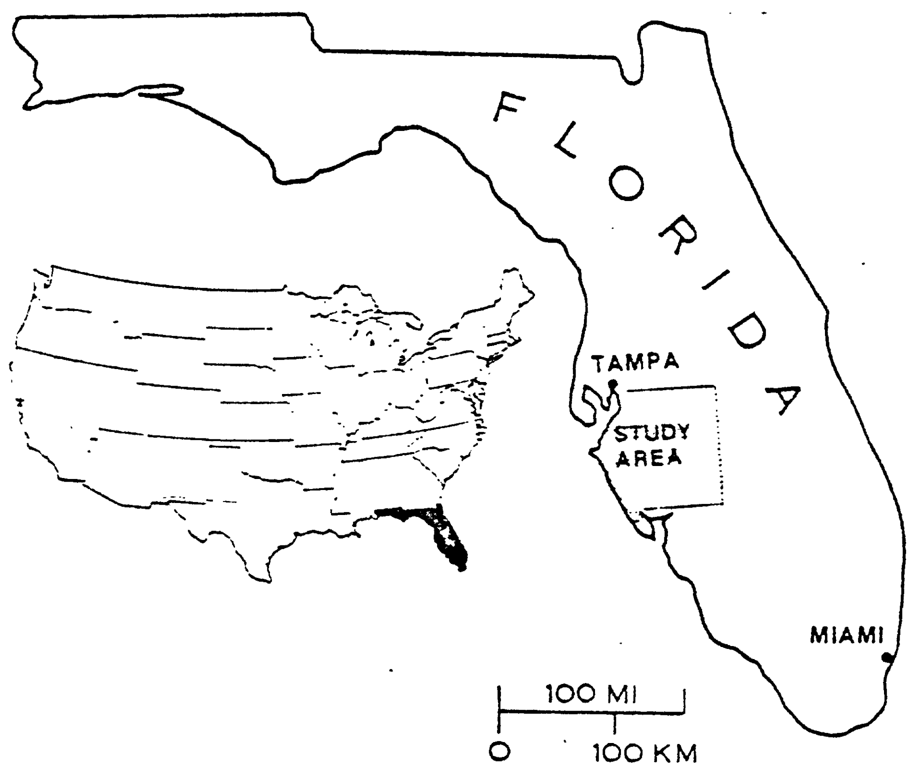

Figure 6 - Southwest Florida model study

A three-fold increase in pumping for municipal supplies is also anticipated. Detailed maps were made of the potentiometric surface of the Floridan limestone aquifer. The model was calibrated using these potentiometric surface maps under both steady state and transient conditions. The principal assumptions in the model analysis were: ground-water flow is essentially horizontal although water also moves vertically into and out of the Floridan aquifer across a confining bed (fig.7).

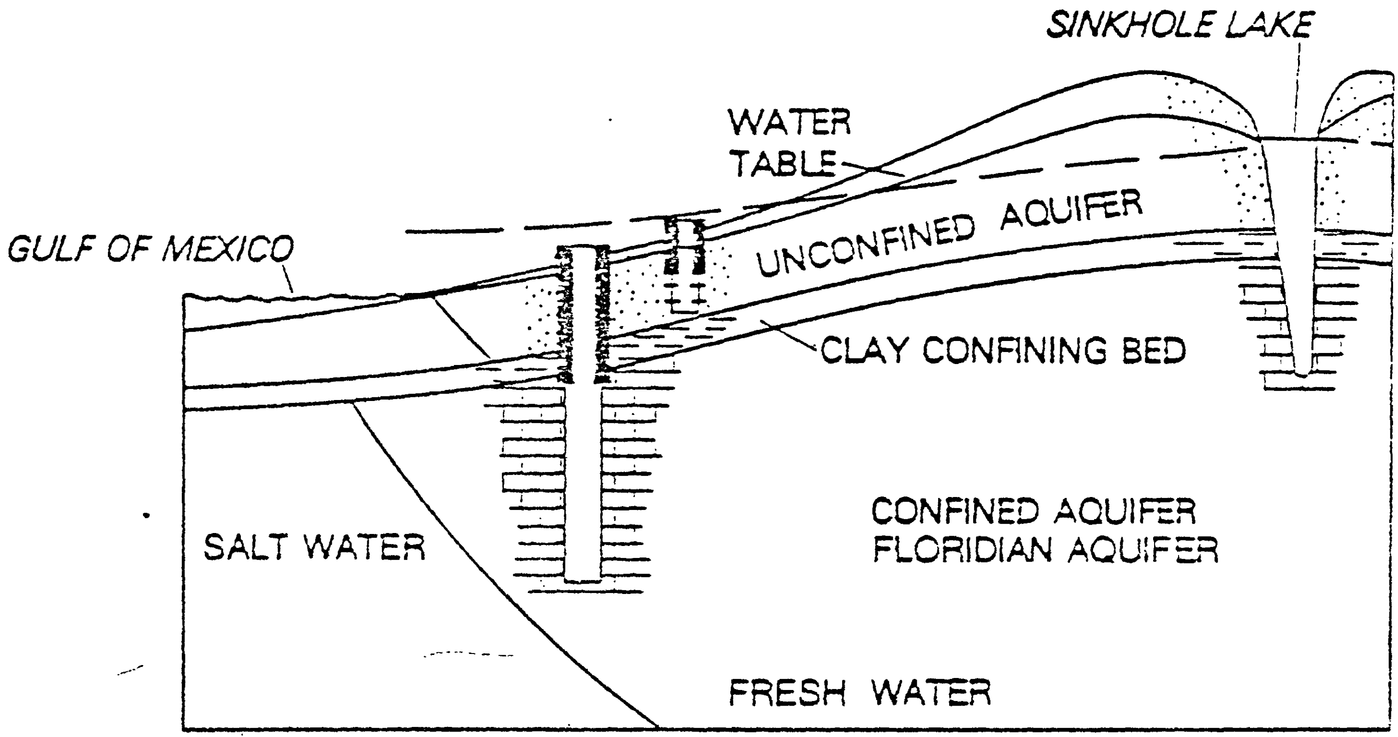

Figure 7 - Southwest Florida hydrogeologic section

CONCLUSIONS

1. Ground-water models are constructed for both scientific and management purposes. Scientific models are built to understand the nature of ground-water systems, how they function, and how they respond to hydraulic or chemical stresses, and to identify additional data required to understand them better. In this application, therefore, they are largely a learning tool to improve hydrologic understanding.

2. Management models may be of similar construction but commonly are built around a larger set of consideration of which the hydrology may be only one. They are intended to aid decisionmaking for planning and management functions. Alternative schemes can be tested in the search for optimal ones for a given set of conditions. Many models are now employed as management aids in industry, agriculture, government, and municipalities.

3. Ground-water investigation can be greatly aided by the use of ground-water models to understand the flow systems to help design data collection programs, and to make predictions for water resource management.

4. The accuracy of ground-water models can be improved by additional values of aquifer properties such as: transmissivity, storage coefficient, and leakance. A major problem in model calibration has been the inaccuracy of ground-water withdrawal data. More effort is needed to improve the field determination of groundwater use.

5. The models used in many studies are too complex. A modeler should start with a simple model. Then as confidence is gained in the understanding of the hydrologic system, the model can be made more complex. Many of the existing complex models have inadequate field data to describe the hydrologic or water quality parameters. Complex models are frequently used too early in an investigation. For example, for a waste disposal problem, one should not start with a solute transport model. The first step would be to calibrate a ground-water flow model.

6. Models should be first used to synthesize data and to check the hydrologic assumptions on the the operation of the hydrogeologic system. A model is no more reliable than the data used for calibration.

7. The hydrogeologic understanding and experience of the modeler is essential in calibrating the model. The modeler must be familiar with the field condition and accuracy of the data.

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