GROUND-WATER MODELS AS A MANAGEMENT TOOL IN FLORIDA

By C. B. Hutchinson

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Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

GROUND-WATER MODELS AS A MANAGEMENT TOOL IN FLORIDA

By C. B. Hutchinson

ABSTRACT

Highly sophisticated computer models provide powerful tools for analyzing historic data and for simulating future water levels, water movement, and water chemistry under stressed conditions throughout the ground-water system in Florida. Models that simulate the movement of heat and the subsidence of land in response to pumping also have potential for application to hydrologic problems in the State.

Florida, with 22 ground-water modeling studies reported between 1972 and 1984, has applied computer modeling techniques to a variety of water-resources problems. Models in Florida generally have been used to provide insight to problems of water supply, contamination, and impact on the environment. The model applications range from site specific studies, such as estimating contamination by wastewater injection at St. Petersburg to a regional model of the entire State that may be used to assess broad-scale environmental impact of water-resources development. Most recently, ground-water models have been used as management tools by the State regulatory authority to permit or deny development of water resources. As modeling precision, knowledge, and confidence increase, the use of ground-water models will shift more and more toward regulation of development and enforcement of environmental laws.

INTRODUCTION

Water managers often do not fully understand the objectives and scope of modeling projects that they have funded. There is an aura of mystery in considering the modeling approach as "black-box magic" to provide solutions to ground-water problems. In reality, a model's accuracy relies heavily on the experience of the hydrologist and the magnitude of the data collected in the field. Completed models need to be improved as additional data become available. When used with caution, models can be effective tools for water-management purposes.

This report deals with the types of models applicable to ground-water hydrologic problems in Florida, with descriptions of the various types of information required for their use and the results they produce. Its purpose is to provide an understanding of the scientific aspects of ground-water modeling to nonscientists engaged in problems of planning and managing the State's water resources.

Modeling of ground-water flow is a relatively new technique that has grown with the availability and capability of computers since the mid-1960's. Since that time, rapid progress has been made in development and application of models for water-resources management. Ground-water models have been particularly suitable to Florida where about 4 billion gallons of ground water is used daily and where 8 billion gallons per day flows from more than 300 natural springs. Models have been applied to such diverse problems as ground-water depletion by pumping, contamination by waste disposal, and saltwater intrusion. As demand for ground water in the State increases, more reliance may be placed on models to help decision making.

The information presented here is general; however, it provides an elementary description of modeling procedures, including the limitations and predictive capabilities of the different model types. The report should aid the reader in understanding some basic concepts of ground-water modeling and their applicability to water-resources evaluation.

CONCEPT OF MODELING

The human mind has difficulty in considering many factors simultaneously in making decisions. Decision-making problems faced by water managers and hydrologists involve tens or hundreds of variables. The hydrologists have to know the characteristics of the aquifers, flow conditions, recharge and discharge areas, pumping effects, and many other related factors. In the past, hydrologists and water managers used an intuitive approach on the basis of their knowledge and experience. With improved technology, a disciplined technique that can determine the relevant factors and their interrelation in ground-water development has become available for use by water managers and hydrologists. This technique can implement decisions effectively and can provide the means to update, modify, and redefine the hydrologic systems and objectives as ground-water development progresses. This technique is the modeling approach.

Modeling generally is divided into scale models and mathematical models. Scale models are reproductions of real systems at a reduced scale that can be operated in a laboratory. Numerous difficulties have been encountered in scaling factors, and scale models are expensive to construct and operate. Scale models are unpopular today and are not widely used in ground-water studies.

Mathematical models are systems of mathematical equations that describe the flow behavior of ground-water systems. In ground-water reservoirs, these mathematical equations are complicated partial-differential equations. Because of the uniqueness of aquifer systems, these equations are almost impossible to solve analytically. Models were developed to solve the complex mathematical equations.

Generally, mathematical models can be classified as analog models or digital models. Analog mathematical models are constructed under the concept of duplicating the partial-differential flow equation under a set of physical laws. Thermal, membrane, conducive media, and resistance-capacitance network models are examples of analog models. The potential for updating analog models is restricted, and the construction and operation costs of these models are high. Therefore, analog models are used less today than a decade ago.

Digital models require a computer to solve the flow equations numerically. Digital models are easy to update and redefine and can be constructed and operated economically. Throughout this report, the term "model" refers to digital models.

The fundamental principle involved in digital models is to subdivide an aquifer region into a gridded network and an appropriate time period into a series of time steps. Within each grid, the aquifer properties are assumed to be uniform and represented by single values. Over the grid network, different equations are written describing the head (water level) in terms of aquifer properties and stress (pumping, injection, or recharge) and as a function of time. These equations are solved simultaneously by the aid of a computer in accordance with predescribed boundary and initial hydrologic conditions determined by the modeler.

Two digital modeling methods are frequently used by water managers and ground-water hydrologists, namely the finite-difference method and the finite-element method. The finite-difference method is based on differential calculus, whereas the finite-element method is based on integral calculus. The difference between these two methods, insofar as modeling approaches are concerned, is the concept of discretization (subdividing) of the aquifer region.

The concept of the finite-difference method involves the approximation of derivatives by finite differences. In this method, an aquifer is discretized into aquifer blocks with finite sizes. Either centers of blocks or intersects of grid lines are selected as nodes where heads are described by a set of difference equations. The derivative of head between two adjacent nodes is approximated by the head difference between the two nodes divided by the distance between them. The time-head derivative is also approximated by the head difference between the beginning and end of a time step divided by the length of the time step. A difference equation is written at each node to approximately replace the exact partial-differential flow equation. A numerical equation solving technique is implied to solve the finite-difference equations simultaneously to obtain heads at each node. If the aquifer properties are previously known, then heads resulting from the finite-difference model would closely approximate heads in the aquifer at the nodes.

The mathematical concept involved in the finite-element method is not as straightforward as that of the finite-difference method. Mathematically, in the finite-element method, the objective is to transform the partial-differential flow equation into an integral equation that includes derivatives of the first order only. The integration is then performed numerically over the discretized elements. The finite-element method involves principles of the functional approach (calculus of variation approach) or the weighted residual approach. Without knowledge in calculus, the finite-element method is more difficult to understand than the finite-difference method, which involves the fundamental concepts of derivatives only.

In addition to the mathematical differences, there are major advantages and disadvantages of the two methods. Although the finite-difference method employs simpler computer programs than the finite-element method, ease of programming may not be of interest to the user who is interested only in model output. Users seldom modify the main program of a model. To simplify computer programming, the finite-difference method usually uses a square or rectangular grid system that subdivides the modeled area by straight lines along the grids. Such approximations could create significant errors and use an excessive amount of computer core space due to rigidity of the grid system. Model boundaries seldom follow straight lines, thus the accuracy of model results may be reduced. On the contrary, the finite-element method uses a flexible grid, usually triangles, along the irregular boundaries, and the boundaries can be modeled without significant distortions. The accuracy of the model results from the finite-element method, in some cases, can be increased and may be better than those from the finite-difference method. Pumpage from several wells within a grid block in the finite-difference method must be summed up and placed at the node in the center of the grid block despite individual well locations. In the finite-element method, the grid can be designed so that individual wells coincide with single nodes.

At least 22 ground-water models have been used in Florida between 1972 and 1984 (fig. 1). All of them used the finite-difference method. The early models were oriented north-south to aline with the State survey. In 1979, the U.S. Geological Survey instituted the Regional Aquifer Systems Analyses (RASA) study with models oriented northwest-southeast along the major axis of the Florida peninsula and encompassing all of the State (16 through 20 in fig. 1). Under this scheme, a general model of the entire State can be run to simulate broad-scale conditions in understanding the aquifer system as a whole and also to generate information, such as boundary conditions, as inputs to subregional models that provide local detailed information on the flow system in smaller areas.

Ground-water models can serve as decision-making tools to study the courses of action and their alternatives. Specific uses of modeling in Florida are the assessment of effects of wastewater injection, geothermal heating, and large-scale pumping. These applications will be described in a later section of the report.

TYPES OF GROUND-WATER MODELS USED IN FLORIDA

Ground-water models that have been or can be applied in Florida are:

1. Flow model;
2. Solute-transport model;
3. Saltwater-freshwater sharp-interface model;
4. Heat-transport model; and
5. Land-deformation model.

Eight available models that have a high potential for application in Florida are shown in table 1.

Information on aquifer characteristics, such as thickness of the aquifer units and their capability for storing and transmitting water, geological and hydrological boundary conditions, and stresses (pumping, injection, or natural recharge), is needed to calibrate a ground-water model and to understand the ground-water system. The calibrated model may then be used to assess hydrologic impact of climatological extremes, such as drought or flooding. The model may also be applied to analyze the effects of development, such as large well fields, wastewater injection, and recharge-well networks.

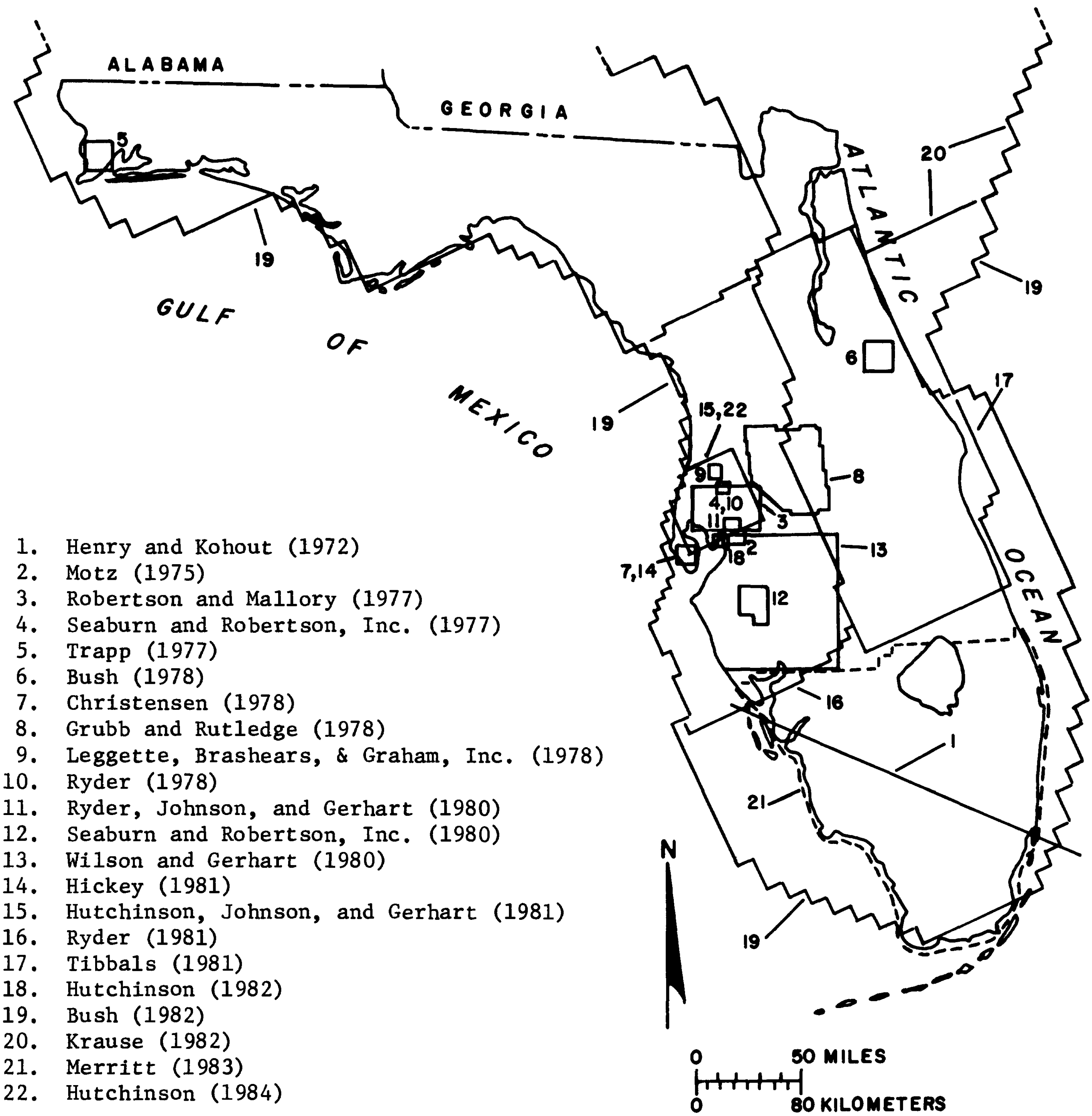


Figure 1.--Ground-water modeling studies in Florida, 1972 through 1984.

Table 1.--Selected ground-water models applicable to hydrologic situations in Florida

Category	Purpose of model	Special features	Author(s) (year)
Flow	Simulation of hydraulic head and flow in a single aquifer.	Two-dimensional, finite-difference method, saturated flow.	Prickett and Lonnquist (1971)
Flow	Simulation of hydraulic head and flow in multiple aquifers.	Three-dimensional or quasi-three-dimensional, finite-difference method, saturated flow, storativity of confining bed.	Trescott (1975) Trescott and Larson (1976 supplement)
Flow	Simulation of hydraulic head and flow in a single aquifer.	Two-dimensional, finite-difference method, saturated flow, evapotranspiration, storativity of confining bed.	Trescott, Pinder, and Larson (1976)
Flow	Simulation of hydraulic head and flow in multiple aquifers.	Quasi-three-dimensional, finite-element method, saturated flow, flexibility of grid system.	Mallory (1979)
Sharp interface	Simulation of hydraulic head and/or position of interface between freshwater and saltwater in a single aquifer.	Two-dimensional, finite-difference method, immiscible fluids.	Mercer, Larson, and Faust (1980)
Flow and Solute transport	Simulation of hydraulic head, flow, and chemical concentration of one nonreactive constituent in a single aquifer.	Two-dimensional, single-phase, finite-difference method and method of characteristics.	Konikow and Bredehoeft (1978)
Flow, Solute transport, and Heat transport	Simulation of pressure contaminant concentration and temperature in multiple aquifers.	Three-dimensional multiphase, miscible fluids, many parameters, difficult to follow documentation.	INTERA (1978)
Flow	Simulation of hydraulic head and flow in multiple aquifers.	Three-dimensional, finite-difference method, saturated flow, input specified in independent files.	McDonald and Harbaugh (1984)

Solute-transport models simulate the movement and concentration of a single chemical constituent dissolved in water. In principle, the solute-transport model contains a flow model that computes the average flow velocities. The solute-transport model may contain dispersion phenomenon caused by irregularity of flow paths as well as molecular diffusion if the concentration of the chemical constituent is high. Some solute-transport models can also handle ion exchange (adsorption and desorption) if such information is available. Most solute-transport models do not consider chemical reactions among constituents or between the water and rocks comprising the aquifer. The U.S. Geological Survey has two documented chemical reaction models, namely WATEQF--a computer program for calculating chemical equilibrium of natural waters (Plummer and others, 1978)--and PHREEQE--a computer program for geochemical calculations (Parkhurst and others, 1982).

Saltwater-freshwater sharp-interface models consider ground-water flow systems containing two fluids of different density with a sharp interface without consideration of diffusion and dispersion. These models have potential applications to areas along coastal Florida where the fresh ground-water system may extend from the Gulf of Mexico to the Atlantic Ocean and float on a denser saltwater base. Sharp-interface models generally can be used to analyze regional ground-water flow problems where the transition zone between freshwater and saltwater is narrow and can be considered as a sharp interface between freshwater and saltwater. Successful applications of sharp-interface models in Florida have not been documented; however, the potential for their use is high.

Heat-transport models couple the flow of heat with water or steam in the analysis of geothermal problems in aquifers. Heat-transport models are conceptually similar to solute-transport models in that a flow model is coupled with a heat-flow model. Movement of heat is related to movement of the water and the thermal conductance of the rocks that comprise the aquifer. In Florida, a heat-transport model was applied to assess thermal convection of seawater in the deep Floridan aquifer (Henry and Kohout, 1972). The majority of heat-transport models have been applied to studies associated with hot springs and geothermal reservoirs of the western states. In Florida, possible use of heat-transport models may be in assessment of the impact of disposal or temporary storage of hot water, such as from air-conditioning systems, introduced into aquifers containing cooler water, such as the Boulder zone of south Florida.

Land-deformation models have been used in evaluating land subsidence that results from slow compaction of aquifers and confining beds when ground water is withdrawn. Land-deformation models have not been used in Florida where land subsidence caused by dewatering typically occurs as sudden, localized collapse of sinkholes rather than compaction of formations. Potential, however, exists for use of land-deformation models in south Florida where compaction of thick clay confining beds might be possible as a result of ground-water withdrawals from the underlying Floridan aquifer or from the aquifers that consist of alternating layers of sand, limestone, and thick clayey formations.

DEVELOPMENT OF MODELS

Models are useful only to knowledgable water managers and ground-water hydrologists. Digital models normally are built on the basis of available information. If used with caution, ground-water models can be used in Florida to analyze the aquifer systems in relation to the following questions:

1. What would be the impact on an aquifer system if dams were built along a canal?

2. How would dredging of ship channels in a saltwater bay affect the inland freshwater aquifers?

3. How would pumping from a large well field impact on heads, streamflow, springflow, evapotranspiration, and lake stages in adjacent areas?

4. What would be the combined drawdown in an area caused by simultaneous pumping of several large well fields?

5. What would be the optimum pattern of pumping that would minimize the hydrologic impact?

6. How would the freshwater-saltwater sharp interface move in response to seasonal and long-term pumping along the coast?

7. What would be the impact of droughts on ground-water levels and saltwater movement?

8. How would wastewater impact the hydrologic system after it is injected?

9. How long after pumping begins would it take for the aquifer system to reach a new equilibrium?

10. How would geothermal effects impact on ground-water circulation in thick aquifers?

Although just 10 questions are posed, they illustrate the types of problems in Florida that may be evaluated by use of ground-water models.

The procedures for applying a ground-water model are perhaps best illustrated by the following example.

A. PROBLEM--A 10-million-gallon-per-day supply of water is proposed to be pumped for a municipal supply in central Florida. One mile from the proposed well field is a large spring. Because of ecological and other constraints, it is desirable that the average long-term flow of the spring not be reduced by more than 10 percent.

B. APPROACH--Flow of most springs in Florida is a function of head and hydraulic characteristics of the artesian aquifer. A ground-water flow model of the artesian aquifer that simulates changes in heads due to pumping will be built to test proposed pumping patterns so that the constraint on reduction of spring discharge is met.

Procedures for modeling ground-water systems and simulating proposed stress conditions depend primarily on the hydrogeologic characteristics of the aquifer and the nature of the problem. Model analysis is most productive when accurate hydrogeologic information is collected with specific objectives in mind. Application of modeling results may require knowledge of economic, legal, political, and other constraints.

Modeling procedures normally follow the sequence discussed below.

1. Stating the problem in a logical way;
2. Conceptualizing the flow system;
3. Selecting the correct type of model;

4. Discretizing the aquifer system;
5. Analyzing and selecting correct boundary conditions;
6. Collecting and analyzing input data;
7. Calibrating and testing the model against available information; and
8. Simulating impacts on the basis of the proposed stress conditions.

This sequence may not always follow the same chronological order, but it should comprise the modeling procedures. For example, a model could be used early in a study to determine data needs and to improve knowledge of the flow system. As applied to the above illustrated example, modeling procedures follow the sequence outlined above, but during model calibration, hydraulic characteristics of the aquifer, such as transmissivity, storage coefficient, and vertical leakage, are adjusted until an acceptable calibration is reached. A chart of the modeling procedures that contain these loops is illustrated in figure 2. In the following sections, the above procedures are used to illustrate solution of the example problem that assesses the impact of well-field development on flow of a nearby spring.

Stating the Problem

The hydrologic problem must be defined precisely for effective data collection and modeling. In the example, the problem statement is defined as: "Can a well field be located and operated without reducing the flow of a nearby spring by less than 10 percent? If it can, then what is the configuration of that well field?"

Conceptualization of the Flow System

The second step in a ground-water modeling investigation is to evaluate available information on hydrologic and geologic conditions of the flow system. The conceptualization process clarifies the understanding of the flow system and provides initial estimates of hydrologic parameters for trial runs of the model.

The conceptualization of the illustrated example would be centered on the spring and its relation to existing or prospective well-field sites (fig. 3). Hydrogeologic information to be assessed includes hydraulic properties of the aquifers, areas where water enters (recharge) and leaves (discharge) the aquifers, leakage between the unconfined surficial aquifer and the underlying confined Floridan aquifer, relation between aquifer head and flow of the spring, and boundary conditions. Estimates of pumpage, recharge rate, locations of lakes and streams, evapotranspiration, and amount of and time of springflow are also important to the model construction.

The model will simulate head in the artesian aquifer while holding flow of the spring at a constant rate. It will be used to predict drawdown under various distributions or patterns of pumping. Flow of the spring is considered to be in direct proportion to head in the aquifer. That is, the smaller the difference between the head in the artesian aquifer and the stage of the spring pool, the smaller the flow of the spring. When head in the aquifer falls to

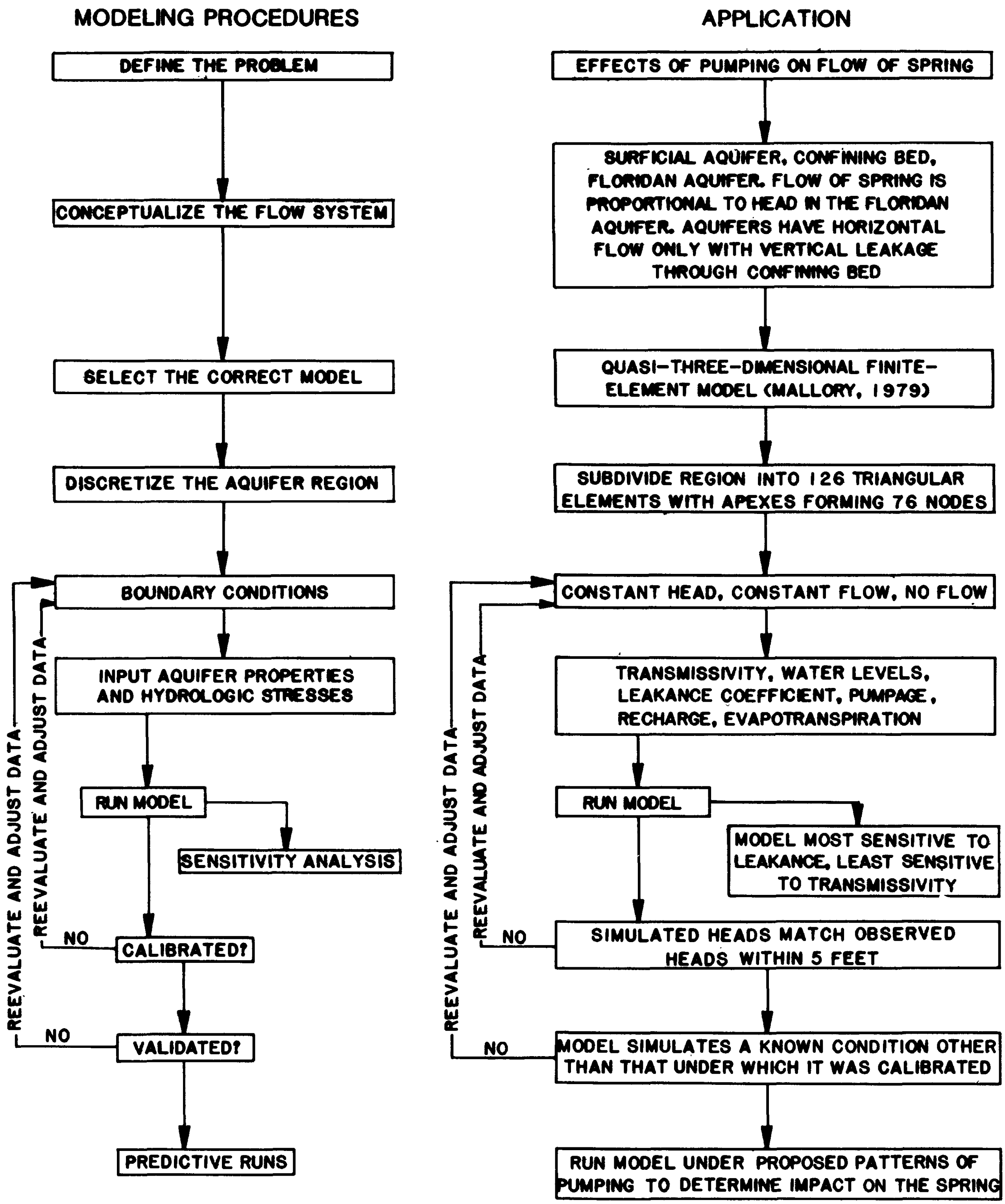


Figure 2.--Modeling procedures and their application to an example where effects of ground-water pumping on flow of a spring are to be determined.

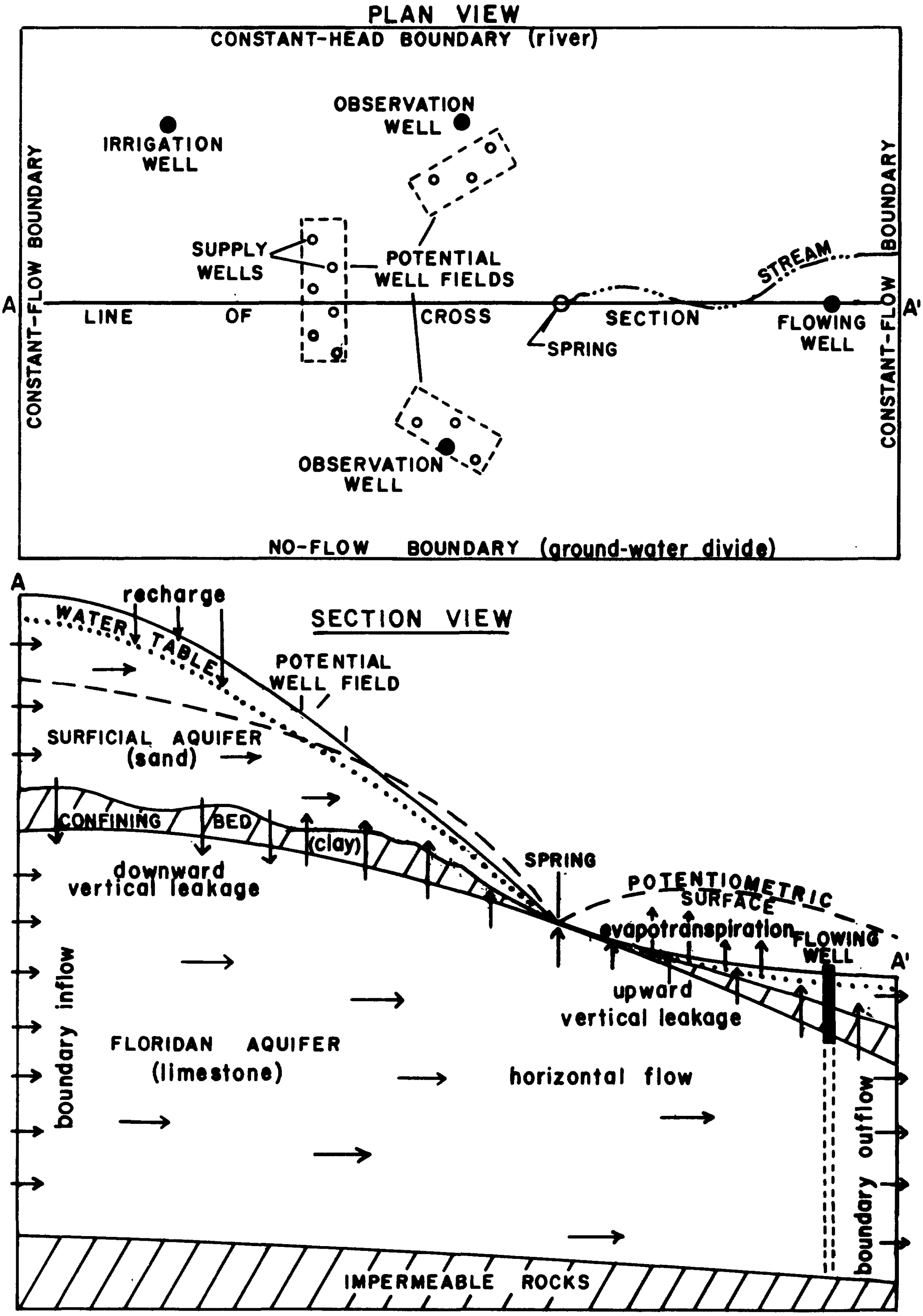


Figure 3.--Conceptualization of the ground-water system for an example where effects of ground-water pumping on flow of a spring are to be determined.

the level of the spring pool, flow of the spring will cease. The model-simulated drawdown at the spring can be superimposed on the spring's stage-flow relation to estimate the reduction in flow that should result from the proposed pumping.

Conceptualization may also aid in siting the prospective well fields. For example, sites located within the area from which the spring derives its water should be avoided. The favorable site would probably be where the confining bed is thin, thus inducing a high rate of downward leakage from the surficial aquifer. In turn, this may minimize drawdown in the pumped aquifer, thereby minimizing the decrease in flow of the spring if the spring discharges from the pumped aquifer.

Selecting the Correct Type of Model

Selecting the correct type of model and putting data into it are difficult tasks. Model selection usually depends upon the expertise of a hydrologist. For the illustrated example, a model representing steady-state flow should suffice because long-term average conditions are to be simulated. If short-term trends or seasonal fluctuations in heads were to be simulated, then a transient-flow model would be appropriate.

The conceptualized flow system indicates that horizontal flow occurs in two aquifer layers representing the surficial aquifer and the Floridan aquifer. The areal extent of the aquifer system is large compared to its thickness (miles compared to feet), and horizontal flow is generally considered to be much more important than vertical flow. The two aquifer layers are coupled by vertical leakage through a confining bed that separates them. Leakage is downward where the water table in the surficial aquifer is above the potentiometric surface of the Floridan aquifer. In the vicinity of the spring, these head relations are reversed, and leakage is upward. A quasi-three-dimensional flow model will represent the flow system. This flow model eliminates a layer representing the confining bed where the horizontal flow is very, very, small as compared with vertical leakage. Quasi-three-dimensional flow models seem particularly applicable to ground-water problems in Florida.

The most widely applied ground-water flow models in Florida (and elsewhere) probably are the two-dimensional models of Trescott and others (1976) and Prickett and Lonnquist (1971) and the three-dimensional model of Trescott (1975), supplemented by Trescott and Larson (1976). Because of their extensive use, computer programs for these models are thoroughly established and documented. In the example problem, the change in discharge is computed manually using the superpositioning technique. In Florida, the three-dimensional model of Trescott was modified to compute spring discharge (Ryder, 1981); however, the modifications are not documented, and the model code is not readily available.

Discretization of the Aquifer System

The continuous aquifer is discretized by a grid system into a series of cells (grid blocks or elements). The grid system is used to input estimated values of heads, hydraulic characteristics of the aquifer, and water chemistry.

These parameters are usually measured at individual points through wells or test holes, then extrapolated between points. This extrapolated value is entered at a respective cell or node in the grid system as model input data. The sizes of individual cells are determined by the hydrologist based on the nature of the problem and availability of data. For example, a coarse grid with each cell occupying several square miles would be practical for a regional model of extensive size where there are few points of known information. A fine grid, consisting of cells with 1,000 feet or less per side, would be proper for a local model to simulate municipal well fields if sufficient hydrologic information is available.

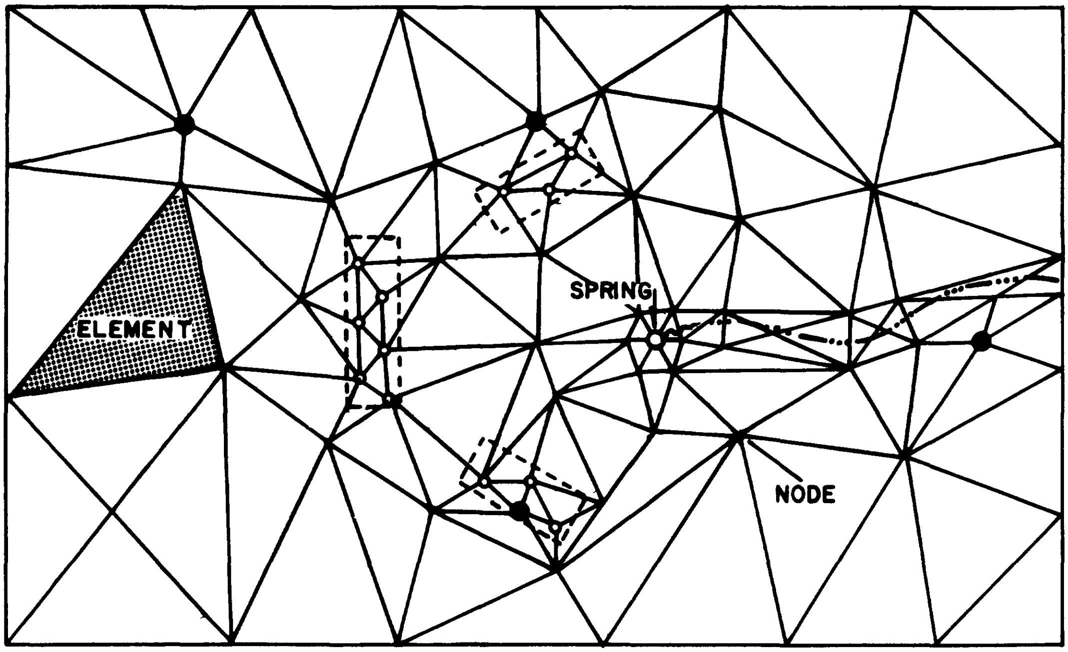
The discretization process may or may not affect the model accuracy. In practice, hydrogeologic information is not known accurately; therefore, the definition of hydrologic and geologic boundaries and pumping histories are frequently difficult to define precisely. All factors should be carefully analyzed before selecting a model. Advantages of one method might be disadvantages of the other. An in-depth discussion of technical advantages and disadvantages of the finite-difference and finite-element methods is given by Faust and Mercer (1980a).

In the example problem, the aquifer can either be discretized into a series of elements or a series of blocks as shown in figure 4. The finite-element grid contains an array of triangular elements within which the hydraulic properties are assumed to be constant and are represented by average values. Because the elements contain nodes at their verticies where water level and flow are approximated, the grid system is node centered. The finite-difference grid contains an array of rectangular or square blocks within which the hydraulic properties of each block are assumed to be constant. Water level and flow are approximated at nodes located at centers of the blocks, thus the grid system is block centered. For the illustrated example, the finite-element method was selected because of the flexibility of its grid. The arrangement of nodes can be designed to coincide with the spring, its outlet channel, proposed well-field sites, and observation wells.

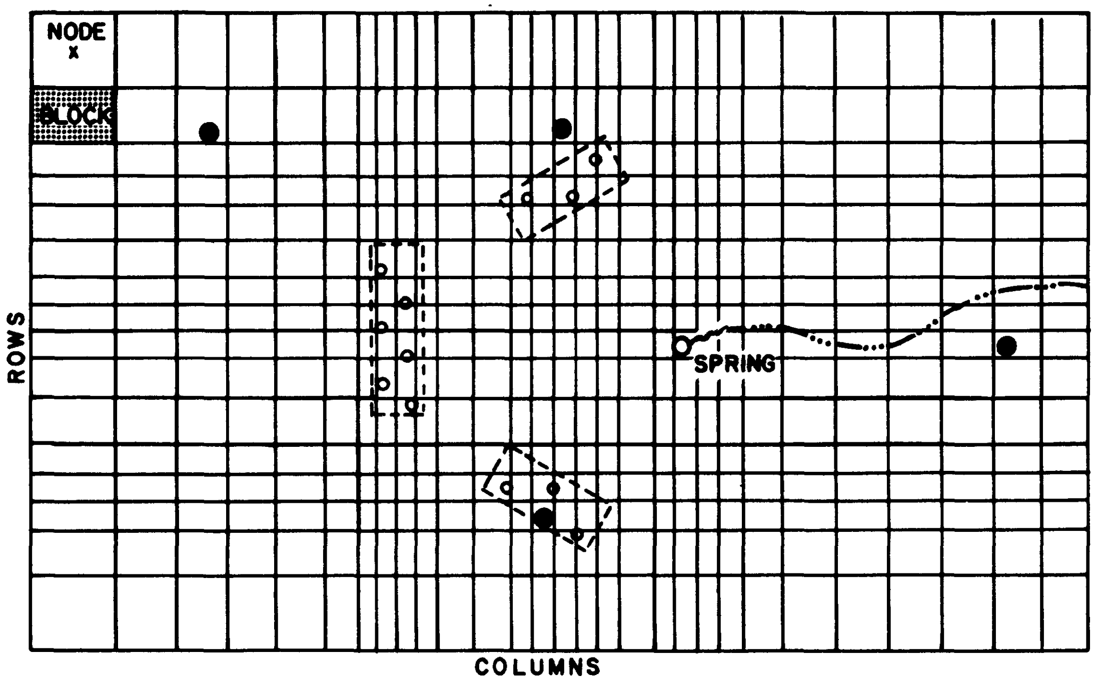
Evaluation of Boundary Conditions

The ground-water system usually extends beyond the area to be modeled. Nevertheless, the physical boundaries of the aquifer, such as faults and valley walls, should be input to the model. If aquifers encompass thousands of square miles and extend far beyond the area of interest, then hypothetical model boundaries are required. If hypothetical boundaries are used, they should be placed in areas that will not be affected by stresses from within or beyond the model area so that model results would not be affected. Boundaries usually are classified as constant-head or constant-flux.

Constant-head boundaries represent boundaries where water levels have negligible change with time. In Florida, such boundaries may represent the coastline, large surface-water bodies that fluctuate only slightly, or areas that are far beyond the influence of pumping stresses. Errors can result if a cone of depression created by pumping in the model area spreads to the constant-head boundary. Flow into or out of the boundary would be proportional to the slope of the water surface (hydraulic gradient) in the vicinity of the boundary as induced by the cone of depression. By definition, head at the constant-head boundary will not change in the model; therefore, boundary-flow error would result from the artificially steep hydraulic gradient. Model results will be affected by the inaccurate flow at the boundary.



FINITE-ELEMENT GRID
126 elements 76 nodes
node centered



FINITE-DIFFERENCE GRID
16 rows 29 columns 464 nodes
block centered

Figure 4.--Comparison of finite-element and finite-difference grid systems.

Constant-flux (also termed constant-flow) boundaries represent boundaries where flow rates into or out of the model along its boundaries are known and kept constant. Models generally simulate this type of boundary condition by specifying flow rates as recharge or discharge at the boundary. In a special case, the no-flow boundary, flow is simulated by assigning a transmissivity of zero to a grid just outside the boundary. This prohibits flow into or out of the modeled area. When cones of depression spread to a constant-flux boundary, water levels at the boundary will change, but flow rates will remain constant. In this case, some errors probably occur in the model results because, as the hydraulic gradient changes, so does the boundary flow.

Another boundary that has the combined features of the constant-head and constant-flux boundaries is termed the head-controlled flux (HCF) boundary. For simulations where an increase of the model area is undesirable, the HCF boundary may be used to allow changes in water levels and flow at the boundary. The flux in or out of the boundary is calculated on the basis of Darcy's law using the head gradient between the model boundary and an assumed constant-head point at a specified distance beyond the boundary. This concept can be viewed as a leaky river (beyond the model boundary) being turned on its side so the river bottom lies perpendicular to the plane of the model. Flow from the unlimited source of the river moves laterally through the bottom, which is hydrologically connected with the aquifer. The HCF boundary is useful in situations where cones of depression spread to the model boundary. Under this condition, the model will simulate head and flow at the boundary somewhere between the extremes simulated under constant-flow or constant-head boundary conditions.

There is no clear-cut method for determining the type of boundary that should be used. Frequently, model sensitivity to boundary conditions is tested by assigning different types or combinations of boundaries. If model results are not affected by the different boundaries, then the model is insensitive to boundary conditions, and boundaries are not important. Otherwise, boundaries should be considered carefully, or the model grid should be expanded to insure that boundary effects are negligible.

Data Collection

Procedures for collecting data in the field should be designed to answer questions under investigation. After conceptualization of the aquifer system or evaluation of initial model runs, data may be needed to refine or redefine the conceptual model and to increase the accuracy of the model results. Information that is generally required for a ground-water model is shown in table 2.

Collecting representative data is an important modeling procedure. Different combinations of aquifer properties may give computed solutions that fit observed conditions equally well. The more accurate the model input data are, the more reliable the model results should be. The accuracy of the model results cannot exceed the accuracy of the input data. Similarly, values for the input data must be realistic. For example, rates of recharge and leakage should not exceed the difference between rainfall and outflows, such as evapotranspiration and runoff.

Table 2.--Principal data requirements for ground-water models

[Modified from U.S. Water Resources Council, 1980]

Aquifer characteristics	Hydrogeologic maps showing extent and boundaries of all aquifers and confining beds. Topographic map showing surface-water bodies and land forms. Water-level (hydraulic head), bedrock-configuration, and saturated-thickness maps. Transmissivity maps showing aquifers and boundaries. Map showing variations in storage coefficient. Saturated thickness. Hydraulic connection of streams to aquifers.
Hydrologic stresses	Type and extent of recharge areas (irrigated areas, recharge basins, recharge wells, natural recharge areas). Type, extent, and location of discharge areas (discharge to springs, streams, lakes, swamps, offshore). Surface-water diversions. Ground-water pumpage (distribution in time and space). Precipitation and its relation to recharge. Areal distribution of water quality in aquifer. Streamflow quality (distribution in time and space). Geochemical and hydraulic relations of rocks, natural water, and artificially introduced water or waste liquids.
Model calibration	Water-level change maps and hydrographs. Streamflow, including gain and loss measurements. Springflow, including seasonal and long-term changes. History of pumping rates and distribution of pumpage.
Prediction and optimization analysis	Economic information on water supply and demand. Legal and administrative rules. Environmental factors. Other social considerations.

Calibrating and Testing the Model

After initial estimates of hydrologic properties of the aquifer and head distribution are assigned to each cell and node, the calibration process of matching model results to field data follows. Commonly two processes are used in calibrating a model, namely parameter estimation and trial and error method. The former uses statistics to adjust hydrologic properties of the aquifer to minimize the difference between simulated and observed water levels. The latter minimizes the difference between simulated and observed water levels by manually adjusting the hydrologic properties through trial-and-error processes during different model runs. The trial-and-error calibration is easy to perform; therefore, it prevails in model calibration.

For the illustrated example, the trial-and-error calibration would adjust the aquifer properties within realistic ranges until the simulated water levels match the observed long-term average levels. Calibration is complete when the difference between simulated and observed water levels reaches a preselected value. This value usually equals the expected accuracy of the field data. For example, if observed water levels were input to the model from a water-level map with a 10-foot contour interval, the calibration criteria might be half that interval, or 5 feet.

Once the model is calibrated, its validity may be tested using another set of observed data. If the model does not simulate the second data set, additional calibration may be required. Recalibration can also be undertaken as additional data become available.

Sensitivity analysis is a technique that tests the model's response to changes in hydrologic properties of the modeled aquifer. The method usually involves varying individual parameter values over the feasible range that might exist in the real system and observing changes in simulated water levels. Parameters are varied one at a time with other parameters held constant. If model results change in proportion to the variation of parameter, the model is sensitive to that parameter. When sensitivity is tested early in the calibration, results show which parameters should be adjusted during the calibration. When sensitivity is tested after the calibration is completed, results may be used to assess the degree of reliability of each hydrologic parameter. The hydrologist or water manager should then examine each parameter to see whether there is enough confidence in the observed data or if additional data are needed. In the illustrated example, sensitivity tests indicate that simulated water levels rise several feet for a 25-percent increase in recharge rate, thereby indicating that the model is sensitive to recharge. On the other hand, when transmissivity is changed by 50 percent, simulated levels change only a few inches, indicating that the model is not sensitive to transmissivity. The model calibration would be most affected by adjusting recharge. In the calibrated model, transmissivity could vary widely from that of the actual aquifer, therein limiting confidence in the model-derived transmissivity.

Simulating Future Impacts

Models are used to understand ground-water flow systems and to evaluate the potential impacts by development. In the illustrated example, the question of interest was to evaluate whether or not flow of the spring will be decreased by more than 10 percent due to additional pumping. To answer this question, it is necessary to know the extent of the cone of depression caused by pumping. Some ground water discharging to the spring would be intercepted by the cones, which contributes water to the pumping wells, thereby reducing discharge of the spring. The model can aid in locating well sites or in determining the pattern of pumping from the proposed well field to minimize springflow reduction.

Figure 5 illustrates the concept of how the model is used to solve the example problem. Comparisons are made between average simulated drawdowns resulting from two options: (1) pumping from one large well field at 10 million gallons per day (Mgal/d) or (2) pumping from two small well fields at 5 Mgal/d each (total of 10 Mgal/d). The graph shown in figure 5 indicates that the large

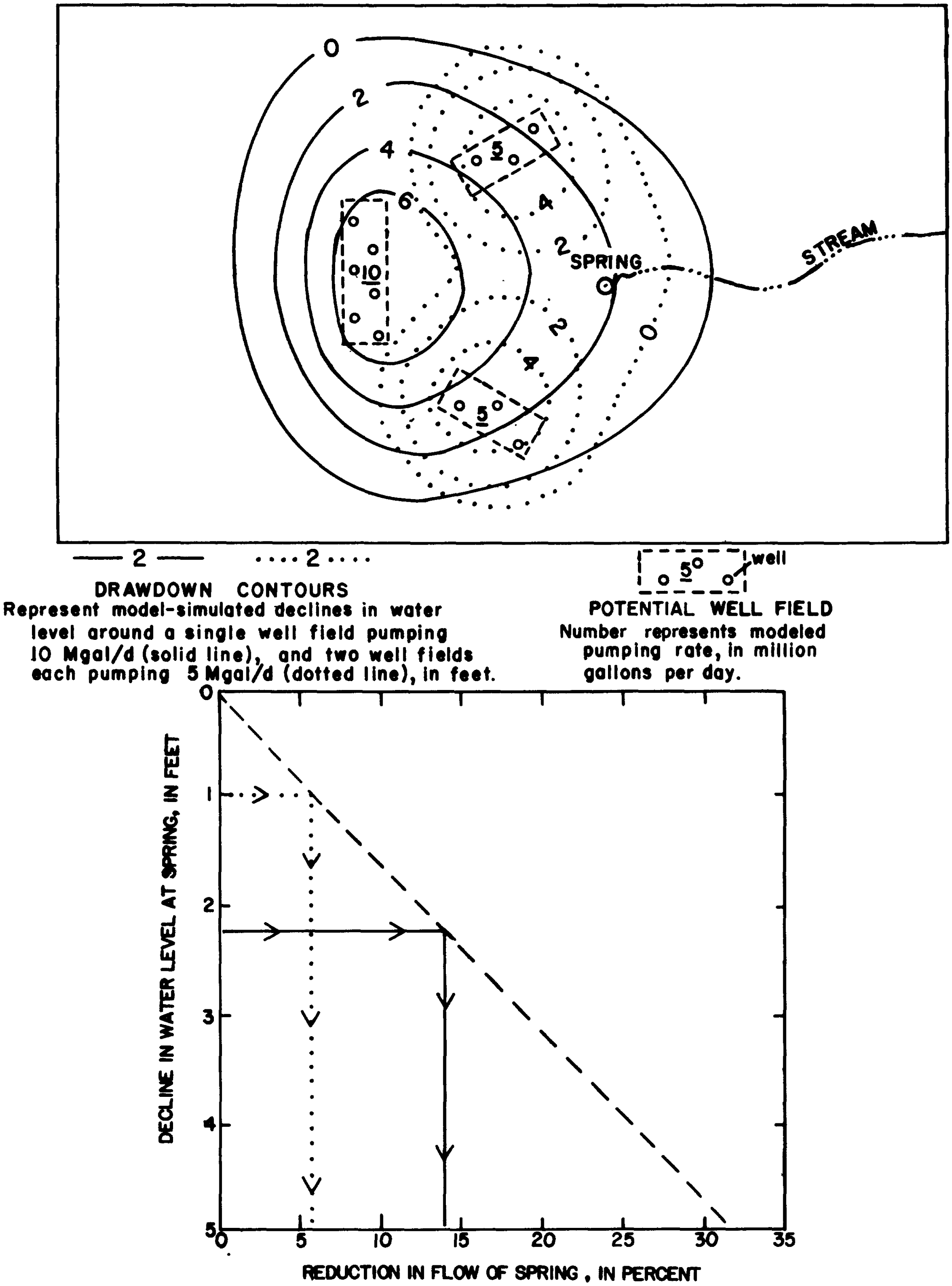


Figure 5.--Hypothetical comparison of model-simulated decline in water level and flow of a spring under different pumping arrangements for water-resources management.

well field probably would reduce flow of the spring by 14 percent, and the two small well fields probably would reduce flow by 6 percent. Without consideration of other factors, option 2 would satisfy the constraint that long-term average flow of the spring not be reduced by more than 10 percent. These solutions are not unique; the spring-flow reduction constraint probably could also be achieved by other well-field configurations. Nevertheless, this example indicates the potential of using a model for decisionmaking.

In Florida, model predictions are just starting to be checked after development has taken place. Motz (1975) developed a model to predict the effects on ground water that might be caused by digging and damming a canal to divert flood waters around the city of Tampa. The U.S. Geological Survey currently is investigating the validity of those model predictions (R. L. Knutilla, U.S. Geological Survey, oral commun., 1983).

Limitations of Model Application

Models normally are used to understand a flow system in a broad sense due to constraints of grid sizes and availability of data. It is impractical to expect models to yield very precise results for aquifers with nonuniform hydrologic properties. If water managers and hydrologists are aware of the sources of errors, models are powerful and useful tools in ground-water management.

All models should be updated as additional information becomes available; therefore, ground-water models are dynamic instead of static. Information on aquifers and water chemistry usually becomes available in developed areas where many wells have been drilled. In undeveloped areas, data may be sparse and hydrologists must estimate the hydrologic properties. The accuracy of model results is no better than the accuracy of the available data. Model precision can be improved as data coverage and accuracy are improved. These limitations should be kept in mind when models are used.

In addition to the limitations of data measurement, there are unavoidable limitations involved in numerical modeling. All hydrologic properties of a discretized aquifer element or grid block are averaged and are represented in the model by single values. The magnitude of the error increases with coarseness of the grid system and length of time step. A finely gridded system with small time steps will reduce errors. In practice, however, information on aquifer properties required for each element or grid block are lacking spatially and temporally. Designing a finer grid and using small time steps cannot overcome errors that result from extrapolation of the data. Truncation errors are due to approximation of the partial-differential flow equation by the finite-difference method or the finite-element method. The model uses an iterative technique to converge on a solution to the equation until meeting some error criterion that measures goodness of fit. The magnitude of the errors depends on the grid or element size and the length of time step. Round-off errors are computational errors due to rounding of numbers by the computer. These errors usually are very small compared with other errors and have little effect on model results. Errors also result from totaling pumpage from several wells near a node and inputting it as pumpage from one well at the node. This approximation tends to concentrate pumpage rather than distribute it and could distort the cone of depression if the grid system is too coarse. Errors also result from wells partially penetrating an aquifer. Corrections for partially-penetrating wells generally are not simulated in ground-water models.

Even with the above limitations in ground-water models, the modeling approach is a reliable tool for management of ground-water reservoirs. Internal modeling errors are small compared with the uncertainties in estimating values of hydrologic properties and pumping history of an aquifer. Models have great possibilities for synthesizing aquifer systems as well as testing decision alternatives.

ROLE OF MODELS IN MANAGEMENT

Florida's water-management problems continue to grow in complexity and significance as population, agriculture, and industrial development expand and compete for available resources. Ground-water models have an important role in water planning and management, especially as related to supplies, contamination, and environmental problems.

Water Supplies

Problems of water supply arise from the need to provide water users with a safe and adequate amount of water. Approximately half the water used in Florida is ground water, and about 85 percent of the water used for public supply is ground water. Many cities and regions rely exclusively on ground water as a source of supply. The Biscayne aquifer in south Florida, for example, has been designated by the U.S. Environmental Protection Agency (EPA) as a sole or principal source of public supply. Federally funded projects that might affect the aquifer are subject to regulatory measures of the EPA in order to protect the quality of the water. The sole-source aquifer regulation is described in Public Law 93-523, section 1224(e), and is administered by the U.S. Environmental Protection Agency. Models might provide information needed in regulating this important aquifer.

A major source of ground-water supply in Florida is the Floridan aquifer, an extensive limestone layer that in places may be as much as 1,500 feet thick. In west-central Florida, prolonged pumping from the aquifer resulted in drawdowns of about 40 feet between May 1969 and May 1975. A ground-water flow model of this area, using projected demands, indicates an additional 5 to 30 feet of drawdown may occur by the year 2000 (Wilson and Gerhart, 1980). In south Florida, where the aquifer contains saltwater, a digital model was used to examine the feasibility for subsurface injection and recovery of freshwater for public supply (Merritt, 1984).

Models may be used by State and local agencies for planning, development, and management of the ground-water resources, thus minimizing potentially large drawdowns. Models also can aid water managers in regulating pumping, evaluating consumptive water use, preventing interference with surface-water resources, assessing the potential of saltwater intrusion, and other associated activities.

Contamination

Models can help water managers assess potential contamination and aid them in making decisions concerning regulation of pollution and remedial actions to help clean up contaminated aquifers. In Florida, waste-disposal activities include landfills, septic tanks, wastewater retention ponds, land-surface dumping and spills, and deep-well waste injection. Contamination also results from ground-water recharge of urban and agricultural runoffs. Contaminants may include toxic chemicals, brines, nutrients, pesticides, hydrocarbons, trace metals, and radioactive substances.

Pumping of ground water in Florida can result in problems of saltwater intrusion in coastal aquifers and upward movement of saltwater from deep aquifer zones. The effects of saltwater intrusion may include contamination of individual wells or degradation of entire agricultural and municipal water supplies in coastal areas.

Models, as applied to contamination problems in Florida, include a wastewater injection study at the city of St. Petersburg (Hickey, 1981) and a regional evaluation of potential for saltwater intrusion (Wilson, 1982) along the Gulf Coast (fig. 1). These model studies pointed out the need for water-quality monitoring networks for tracking ground-water contamination. Future potential applications of models for water management related to contamination may include regulation of freshwater-withdrawal and waste-injection rates.

Environmental Problems

Hydrologic information gained through model simulations may be used in assessing environmental problems related to ground water. Pumping may reduce the flow of streams and springs, thereby changing the stream's ecological and chemical characteristics. Soil dewatering that results from development may dry wetlands.

Models have been used by State water managers in Florida for regulating environmental impact. The Southwest Florida Water Management District, for example, has utilized ground-water models for permitting well-field withdrawal rates. The bases for the permit are projected drawdowns in the pumped aquifer adjacent to the well field and lowering of lake levels. In the future, models may also be used to evaluate pumping impacts on evapotranspiration and flow of springs and streams.

CONCLUSIONS

Water managers and planners need an understanding of ground-water models, especially in Florida where ground water is an important source of water supply and hydrologic problems are diverse. Ground-water models have been utilized since 1972 by Florida's water managers for making decisions concerning safe and adequate water supplies, preventing aquifer contamination, and protecting the environment. Regional models now aid our understanding of the ground-water flow system throughout the State. They may be used to assess regional and long-term effects of pumping on a broad scale or to provide boundary conditions for local models. Other models that have potential for application in Florida couple flow models with specialized models for simulating movement of the interface separating freshwater and saltwater, transport of contaminants introduced into an aquifer, or subsidence of land caused by ground-water development.

At least 22 model applications have been made in Florida between 1972 and 1984. The State regulatory authority has recently used models as management tools for permitting or denying development. As yet, models have not been used for enforcing environmental laws. The principal use of models in water-resources management generally has been toward increasing understanding of the flow system so that better evaluation of management and planning alternatives can be made. As modeling precision, knowledge, and confidence increase, the use of ground-water models may shift more and more toward regulation of development and enforcement of environmental laws.

This report provides a background for more effective use of ground-water models. It will aid the decisionmaker in assessing modeling procedures and results and in recognizing the limitations and predictive capabilities of the various modeling processes.

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