Groundwater resources management research

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Importance of groundwater

Groundwater is one of the earth's most widely distributed natural resources. It has been a source of water supply since the dawn of recorded history. Many great economic developments have been made possible through the use of groundwater. For many towns and villages, industries, and irrigated farms, it is the *only* source of water. In spite of its importance for mankind, it is surprising that only 1,200 km^3 of the 3,100 km^3 of water mankind uses yearly comes from groundwater reservoirs (AMBROGGI 1978). The remaining 1,900 km^3 comes from surface water stored in lakes and streams. Agriculture is the greatest consumer – 2,400 km^3 a year – followed by industry with 500 km^3, and other human activities with 200 km^3. To supply these needs it has long been the policy to construct dams, behind which the water of streams backs up to form surface water reservoirs. These reservoirs not only supply water but also serve to control floods and to produce hydro-electric power.

The future prospects for any large expansion of dam reservoirs, however, seem to be limited for the following reasons:

- few sites are suitable for dams and dam reservoirs because of their geological, geomorphological, and topographical conditions; most suitable sites already have a dam
- the residence time of the water stored in dam reservoirs rarely exceeds a year, which offers inadequate protection against rainfall deficits that last longer than a year
- the annual costs of regulating surface water by a dam reservoir now amounts to about US $ 0.10 per m^3 (op. cit.)

As against this:

- the storage capacity of many groundwater reservoirs generally far exceeds that of dam reservoirs
- the life-time of a groundwater reservoir is much longer than that of a dam reservoir
- groundwater can usually be recovered and used at the site where it is needed
- groundwater has a nearly constant temperature and chemical composition – the average price of recovering groundwater is about US $ 0.02 per m^3 (op. cit.)

Under these circumstances it is not surprising that more and more interest is nowadays being shown in groundwater. The world's groundwater resources still offer great prospects for development. An estimated 4.2 million km^3 of it is stored in the upper 800 m of the continents, which represents 97 per cent of all the readily available fresh water in the world. The quantity stored in lakes and streams is only 0.126 million km^3.

If we further consider that, unlike oil and minerals, groundwater is a renewable resource, with 12,000 km^3 of water being cycled through underground reservoirs annually and only one

Groundwater recovery along the borders of Lake Chad by means of a shadoof. The water is used to irrigate a wheat crop. The container is made of reeds.

tenth of that being recovered, it is evident that great possibilities for this natural resource lie ahead.

The management problem

During the last decades, one of the greatest advances in man's attitude towards groundwater has been the realization that groundwater is not a utility to be used with mere indifference; like every natural resource, groundwater must be wisely managed. It is now understood that the world's No. 1 raw material must be carefully protected against over-exploitation, and diligently safeguarded from contamination by pollutants or salt water. Undesirable side effects such as depletion of the groundwater reservoir, deterioration of the water quality, and subsidence of the land must be avoided.
Primarily, groundwater resources management is governed by one of three concepts:
- the safe-yield concept
- the mining concept
- the dual-purpose concept

The safe-yield concept

The safe yield of a groundwater reservoir is that yield of groundwater that can be recovered without causing long-term declines of the watertable. This concept is not new. MEINZER (1932) in the United States of America was one of the first to identify it. He wrote: 'The most urgent problems in groundwater hydrology at the present time are those relating to the rate at which rock formations will supply water to wells in specified areas – not during a day, a month, or a year, but perennially'.
The idea behind the safe-yield concept is that groundwater abstraction from a basin should be limited to the average annual rate of the basin's recharge, thus keeping the basin essentially in hydrological equilibrium. In some humid regions, like The Netherlands, where agriculture depends on both rainfall and a shallow groundwatertable, groundwater pumpage is under strict control. Added to this is the awareness that even a slight decline of the watertable due to groundwater pumpage can destroy certain valuable ecosystems.
Operating a groundwater reservoir on the basis of the safe-yield concept frequently means that large quantities of groundwater in static storage are not used. Such a policy allows these immense quantities to be held for future emergency use, for example, when the region in question suffers from a long period of drought or when, for whatever reason, surface water supplies are interrupted.
In the last decades the safe-yield concept has fallen somewhat into disuse. The reason is that it has not been possible to separate from the safe

Animal power used for recovering groundwater in the Konya Plain, Turkey.

yield the various practical aspects of groundwater recovery methods, distribution, jurisprudence, and costs. TODD (1959) therefore re-defined the safe yield of a groundwater basin as 'the amount of water that can be withdrawn annually without causing an undesirable influence in the basin'.

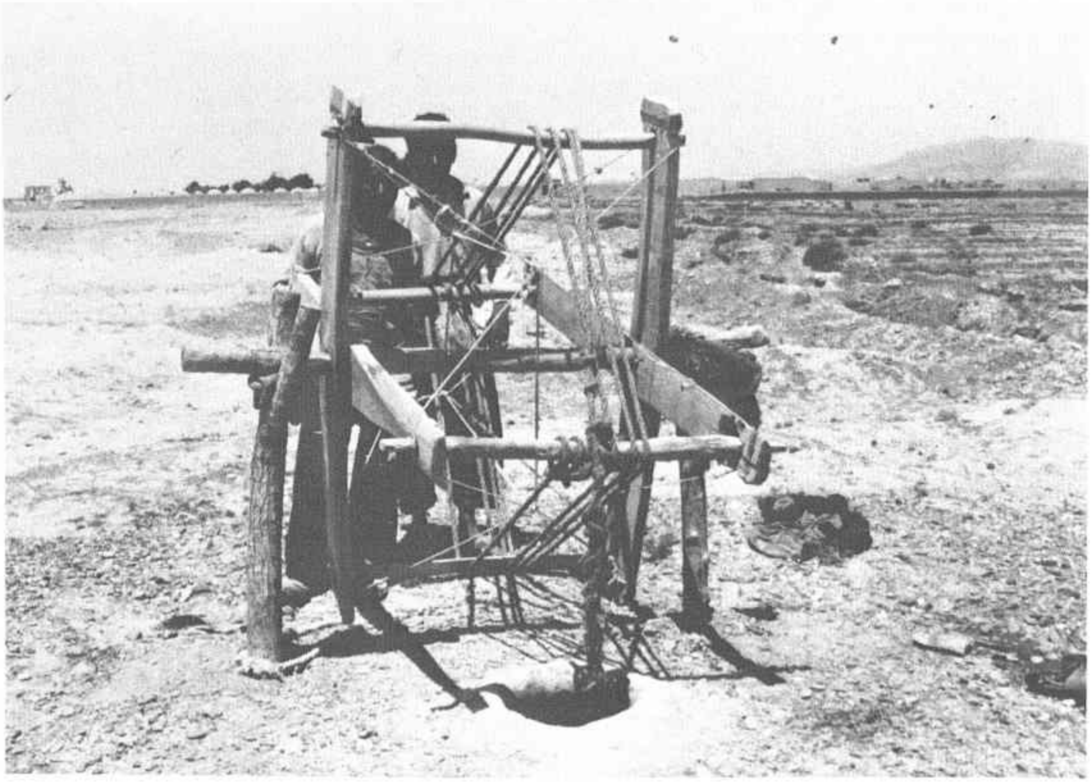
The mining concept

If the safe-yield concept were to be applied in arid and semi-arid regions where the natural recharge of groundwater basins is meagre, hardly any groundwater could be recovered. In such regions, therefore, groundwater is sometimes deliberately mined. The quantities of groundwater that can be mined are known as the secular reserves and are located between the undisturbed watertable and the maximum economic pumping lift.

The idea behind the mining of groundwater is that once a prosperous economy is established, more expensive schemes such as water importation, desalinization, or the re-use of waste water can then be introduced. Here, we can speak of an economic safe yield, which is the yield that can be withdrawn without the danger of the wells drying up before an adequate tax base for the more expensive water supplies has been established. In the United States of America, regions that have developed economically using groundwater for initial water supplies are the Los Angeles Coastal Plain, the Texas High Plains,

Artesian well in the Konya Plain, Turkey.

Traditional way of qanat building in Iran.



and the Central Arizona Plain (HALL and DRACUP 1970).
For the economic development of arid regions AMBROGGI (1978) advocated the mining of groundwater. He refers to thirty years of experience in northern Africa where a single year of unusually heavy rainfall, which can be expected at least once in 15 years, can replenish aquifers that have been mined in previous years, even those in which the watertable drawdown is as much as 10 to 20 m. In some regions it seems possible to deplete a groundwater reservoir for as long as 40 years and still have it refilled by natural processes.

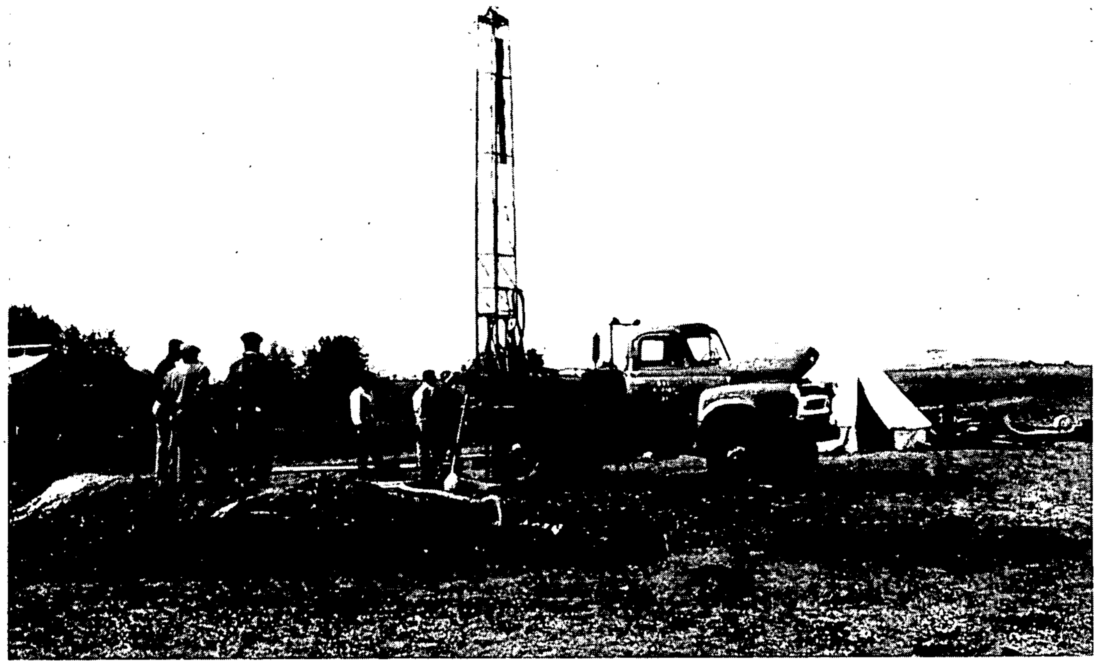
The dual-purpose concept

Mining of groundwater in some places serves a dual purpose: (1) to lower the watertable and thus prevent soil salinization, and (2) to make more water available for irrigation. Examples of this technique are well known from the United States of America where the introduction of irrigation with surface water led to steadily rising watertables. Vast areas became waterlogged and had to be drained artificially. When several of these conventional drainage systems did not function properly because the drain pipes silted up, large numbers of wells were drilled and pumped to lower the watertable. With the extra water thus obtained the area of irrigated land could be substantially enlarged. At present about one third of all irrigation water used in the United States is groundwater.
Other examples of groundwater mining for a dual purpose are known from the Soviet Union (Uzbekistan en Kazakstan) and Pakistan where in the Indus Plain thousands of tubewells have been drilled.
In general this concept of groundwater resources management is only possible when the groundwater is of good to fair quality or, if this is not so, when the groundwater can be mixed with good quality surface water. It goes without saying that this technique requires an efficient irrigation service capable of properly operating and maintaining the well system.

Groundwater quality

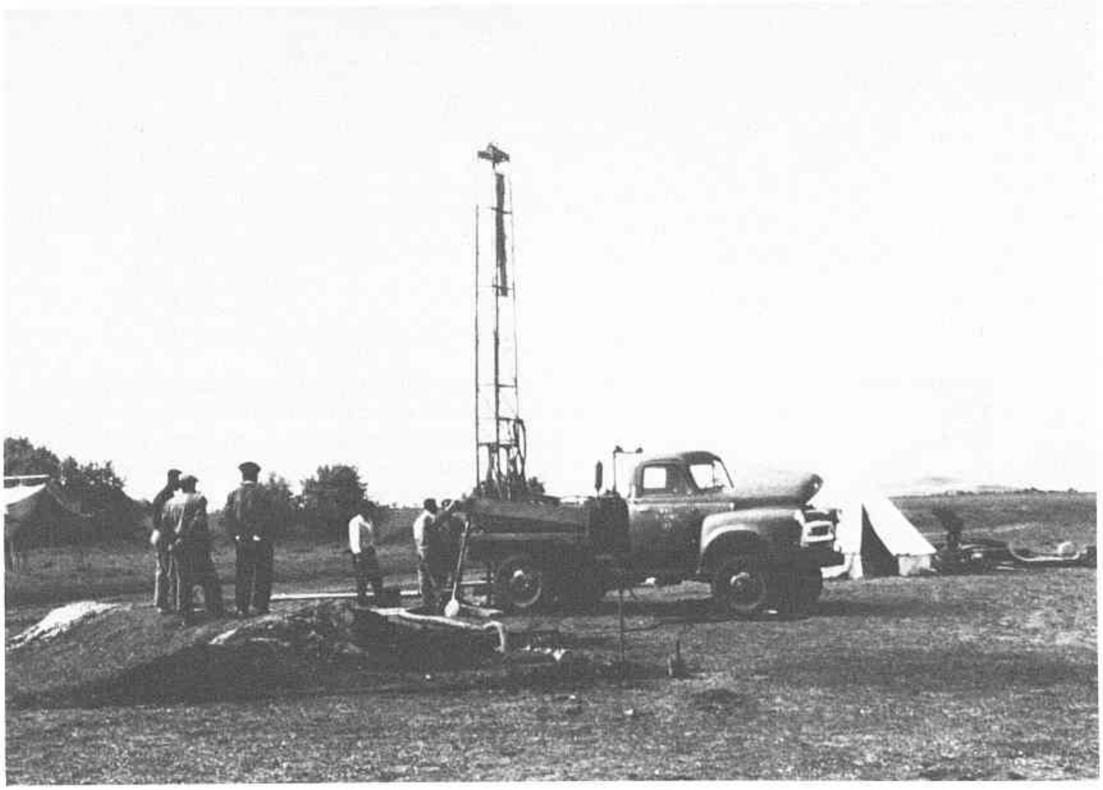
The vast expansion in population, industry, and irrigation (approximately 200 million ha were under irrigation in 1978), has led to a vastly increased waste disposal. Until recently large surface water bodies but also groundwater reservoirs have served as virtually infinite waste disposal sinks. Since the residence time of groundwater in underground reservoirs is long, there is growing concern about the groundwater resources becoming irreversibly polluted by the underground disposal and transport of contaminants.
The problem of contaminant transport in groundwater systems can perhaps best be illustrated by

Modern way of waterwell drilling.



the present search for a geologic disposal site for radio-active waste.
The slow movement of groundwater is a factor in its favour when the contaminants are biodegradable or are bacteria and viruses that decompose or die with time. During the long residence time underground the water may be freed of these undesired substances. After groundwater has moved a sufficient distance from the source of pollution, the concentration of contaminants may be so reduced by dispersion and other attenuation factors that the groundwater eventually becomes pollution-free. How far the groundwater must move depends on the type of aquifer material, the flow velocity, the type of contaminant, etc. A sandy aquifer, for example, is a much better purifier than an aquifer of cavernous limestone or laterite through which the water may flow so fast that no natural purification takes place. For situations where the water quality change can be measured by the amount of total dissolved solids, GROVE (1976) has presented methods of quantifying chemical reactions for rate and equilibrium controlled ion-exchange reactions and radioactive decay.
In the last decades salt-water intrusion into coastal aquifers has become a serious issue in groundwater resources management (TODD 1953). If coastal aquifers are pumped beyond the safe-yield, watertables will decline and sea water will flow inland (Figure 1). For every metre of watertable drop, the salt water will rise 40 m. Coastal aquifers must therefore be carefully managed to preserve the depth of the interface between fresh water and salt water.
A common method of protecting fresh groundwater in coastal areas is to recharge the groundwater artificially to create a fresh water ridge along the coast and thus form a barrier against intruding sea water. Solutions to the problem have been presented by HENRY (1959), BEAR (1960), BEAR and DAGAN (1962,1964), and GLOVER (1964). For predicting the movement of salt water fronts in coastal aquifers, PINDER and COOPER (1970) presented a numerical model. KASHEF (1976) reviewed the advances made in the theory of salt water intrusion.
The intrusion of salt water into fresh water aquifers is not confined to coastal regions. It may also occur in groundwater basins far inland where fresh water overlies salt water or where a local body of fresh water occurs amidst salt water (Figure 2). When a well in the fresh-water zone is pumped the interface between fresh and saline water will rise. If the upconing salt water reaches the bottom of the well, brackish or salty water will be pumped. BEAR and DAGAN (1968) presented a formula for the rise of the cone below the centre of the well.
The high crop yields obtained by modern agriculture require an intensive use of fertilizers and pest-

Modern way of waterwell drilling.



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conditions defined. Hence we may speak of *mathematical models and call this approach to* groundwater flow problems the analytical method. Many of the analytical solutions were developed between 1950 and 1960. The books of POLUBARINOVA-KOCHINA (1962), BEAR (1972), VERRUIJT (1972), HUISMAN (1972), and others are good references that present the available analytical formulas, their solutions, and applications.

Viscous fluid models

The analogy between the differential equations for steady two-dimensional flow of groundwater and those for two-dimensional flow of a viscous fluid between closely spaced parallel plates has led to the use of viscous fluid models (Hele-Shaw models). Variations in an aquifer's hydraulic conductivity or transmissivity are accounted for by varying the interspace of the parallel plates. Fluid is supplied or withdrawn from the model interspace at rates proportional to the groundwater flow. The fluid levels between the plates represent the hydraulic heads of the aquifer. This type of model is used in either a vertical or a horizontal position. In vertical position the model can be used to study the seepage under a dam, sea water intrusion into coastal aquifers, drainage towards ditches, etc. In horizontal position the model is used for the study of the regional effects of pumping, recharge, and flow in multi-layered aquifers (SANTING 1958; COLLINS *et al.* 1972).

An advantage of models of this kind is that they are capable of simulating a free surface and the interface between fresh and salt water for both steady and unsteady flow conditions.

Electric models

The analogy between the flow of groundwater and the flow of electricity has led to the use of electric analog models. Models have been developed on the basis of two systems:

- the continuous system
- the discrete system

In the first, a conductive medium (electrolytes or conductive paper) is used to model the aquifer properties. In the second the aquifer properties are modelled by an assemblage of discrete electric elements comprising a network. These elements represent certain portions of the aquifer which are interconnected through nodes. The system consists of an array of electric resistors or an array of electric resistors and capacitors (PRICKET 1975).

The continuous systems were developed in the 1950s and were used mainly for steady-state flow problems in homogeneous aquifers with irregular boundaries. The discrete systems, which were developed between 1950 and 1965, had a much wider field of application. They were used to analyse non-homogeneous and anisotropic aquifers under either steady or unsteady state situations. They thus allowed the study of problems of variable pumping, recharge, evapotranspiration, surface-water/groundwater relationships, and non-linear effects of unsaturated flow.

By the mid 1960s the electric analog was fully developed and was being used routinely by many groundwater hydrologists. Its great advantage was and still is that it is capable of solving large and complex problems involving tens of thousands of nodes, as in three-dimensional flow problems. Disadvantages are that the problem of the common watertable case, in which the aquifer's transmissivity is a function of the depth of flow, has not been satisfactorily solved and that some of the equipment needed for the model is rather costly.

An electric analog model can solve a set of simultaneous equations almost instantaneously after source, sink, and boundary values are impressed on the model. But the process of measuring node voltages, making mass balances, and preparing watertable contour maps takes a great deal of time. Digital computers are fast in processing data but slow in solving large numbers of simultaneous equations, particularly when the equations are non-linear. For this reason the 'hybrid system', which combines a small digital computer and an electric analog model, was developed.

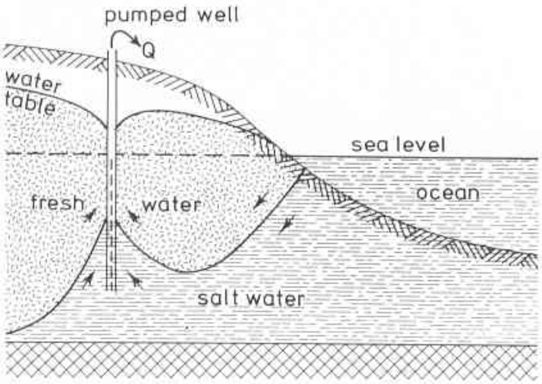

Figure 1.
Fresh and salt groundwater near a coast. Effect of overpumping: salt groundwater enters the well.

icides. Some of these chemicals may move downward with deep percolation water and contaminate the groundwater. In arid zones, deep percolation water from irrigated land, in addition to transporting salts from the consumed water, also leaches soluble minerals from the soils and underlying rocks as it moves to and through the groundwater reservoir. The leaching also picks up soluble solids that are constantly being produced by chemical weathering. Moisture and carbon dioxide, originating from decaying vegetation, greatly accelerates chemical weathering in irrigated areas. As most irrigation systems produce significant quantities of deep percolation water, it is obvious that unless natural drainage is maintained or a portion of the salty water evacuated in some other way, the underlying groundwater will deteriorate and eventually salinize completely.

Land subsidence

Movements in the earth's surface can be one of the undersirable consequences of heavy groundwater pumping. Subsidence of as much as 10 m and horizontal movements of several metres have been recorded in some regions. Subsidence is largest where water level declines are greatest

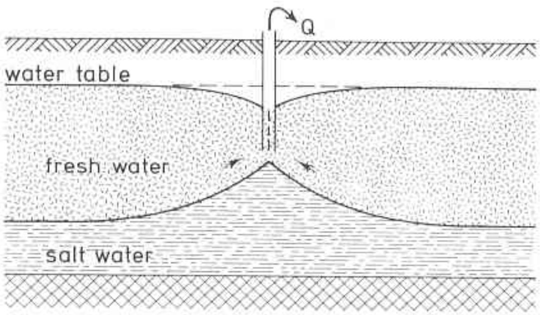

Figure 2.
Fresh groundwater overlying salt groundwater in an unconfined inland aquifer. Upconing of salt water beneath a pumped well.

and aquifers and aquitards (layers of low permeability) are thickest and most compressible. Horizontal movements produce cracks and fissures in the earth which may damage buildings, roads, bridges, and pipelines. BOUWER (1978) refers to examples in the United States of America where groundwater pumping for irrigation in the San Joaquin Valley, California, has caused a total subsidence of 8.5 m and subsidence rates of as much as 0.55 m a year; a subsidence of 40 to 60 cm per 10 m watertable drop was measured at some places. Parts of Mexico City have subsided about 8 m since heavy groundwater pumping began in 1938.

Groundwater models

In the complex business of managing groundwater resources, major advances have been made in the last 25 years. These advances became possible through the development of models of some sort, the most important of which will now be reviewed (PRICKET 1976).

Analytical models

Groundwater flow problems can be described by differential equations that are obtained by combining Darcy's equation and the continuity equation. These partial differential equations, which relate the flow, hydraulic head, and aquifer parameters, are in a sense models of the particular

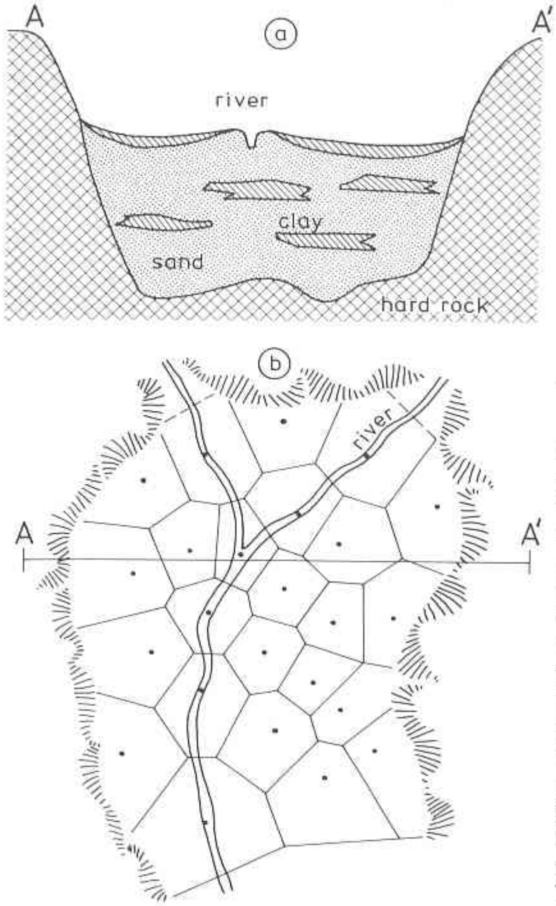

Figure 3.
Example of an asymmetrical finite difference network over a river valley: (a) cross section (b) plan. The valley walls of massive hard rock are impervious (zero flow boundary). The river is a head-controlled boundary.

Numerical Models

Partial differential equations that describe the flow of groundwater are not easy to solve when the boundary conditions are complex. In the last decade two powerful techniques, developed many years earlier in other branches of science, were put to use in finding approximate solutions to complex groundwater flow problems. These techniques are:

- the finite differences method, and
- the finite element method

The *finite differences method* was developed by RICHARDSON (1910). For more than simple conditions, however, his method was time-consuming and was therefore little used. In a later stage SHAW and SOUTHWELL (1941) again drew attention to this method. But it was not until the appearance of the digital computer, which could handle the tedious arithmetic, that the method became popular. FAYERS and SHELDON (1962) and TYSON and WEBER (1964) were among the first to develop a finite difference code that allowed a computer study of the spatial distribution of hydraulic heads in aquifers.
The method requires that the flow domain be discretized by placing a network of squares or polygons over it (Figure 3). The Darcy equation is then used to develop finite-difference expressions for the flow in each square or polygon. The difference between the inflow and outflow of each square or polygon equals the change in storage over the considered time step. An additional term is included in the equation to account for external inputs or outputs of groundwater (recharge from rainfall, irrigation water, seepage from streams or canals, or discharge by pumpage from wells, drainage towards streams, evaporation, etc. (Figure 4). There is one equation for each node with the head as an unknown. Usually an implicit (backward-difference) method is used to calculate these unknowns.
Just how powerful this technique is can be understood from the work of FREEZE (1972) who developed a digital model that can handle up to 10,000 nodes in variable grids and is capable of solving two or three-dimensional, steady or unsteady, and saturated or unsaturated flow in heterogeneous or anisotropic aquifers of varying shapes and with a wide variety of time-variant boundary conditions. In areas where accurate solutions are desired, the spacing between the nodes can be made smaller than where less accurate solutions will suffice. The accuracy or reliability of the solutions depends less on the method than on the input data, which can be very uncertain. These uncertainties cause a much greater error in the results than the method itself.

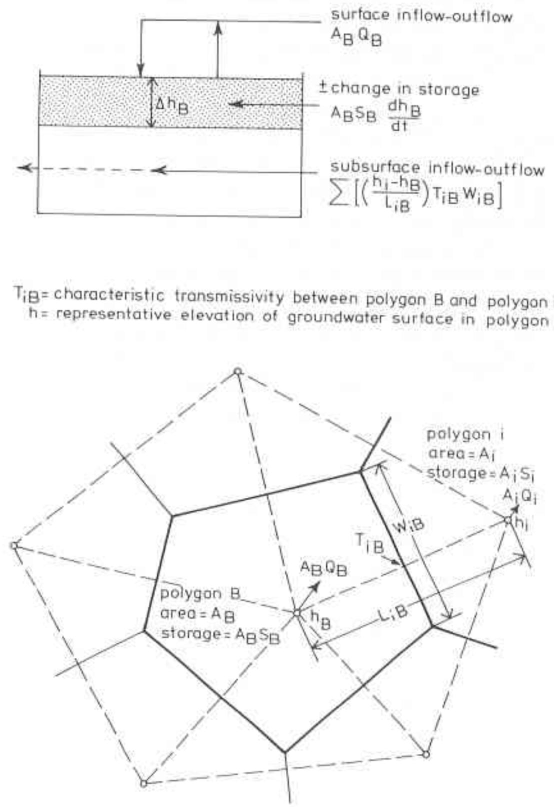

Figure 4.
Scheme of a polygon with the different flow components.

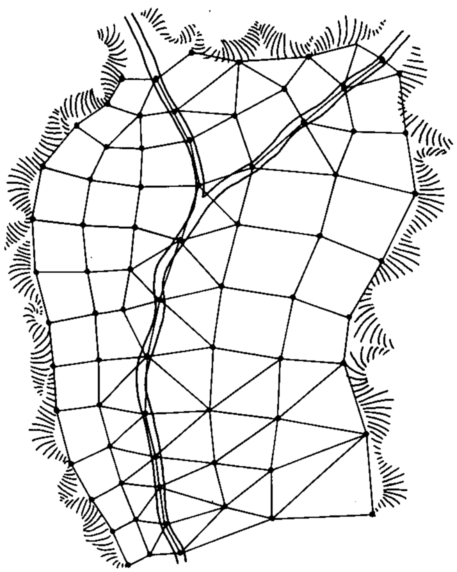

Figure 5.
A finite element network superimposed on the same river valley as shown in Figure 3.

The *finite element method* was developed by COURANT (1943) in a study to find solutions to problems of equilibrium and vibrations, although, he did not yet use the term 'finite elements'. The technique received its name from TURNER et al. (1956) in a study that approached a continuous structure by 'finite elements'. In a later stage the method was rediscovered when it was found to correspond closely with 'variational calculus'. It was ZIENKIEWICZ et al. (1966) and ZIENKIEWICZ (1971) who played a decisive role in indicating the possibilities offered by the technique in solving different kinds of groundwater flow problems.
In the finite element technique the differential equations are also replaced, but now by a 'functional'. A functional can be regarded as some sort of an energy equation that must be minimized. The flow system is considered to be a general system of energy dissipation for which the head solution is found as the head distribution that minimizes the rate of energy dissipation (BOUWER 1978).
The finite element method also requires that the flow domain be discretized, i.e. divided into a number of sub-areas, or 'finite elements', that can have different shapes: triangles or quadrilaterals, joined by nodes at the boundaries of each element. The elements should be as disordered and non-uniform as possible to prevent solutions from going into preferred directions (Figure 5).
As with the finite difference method, a number of simultaneous equations, readily solved by a computer, are produced.
Although the finite element method is somewhat less transparent than the finite difference method, which is fairly simple and straightforward, it is nowadays used to solve a wide variety of groundwater flow and quality problems. MARINO (1976), for example, used both the finite difference and the finite element techniques to solve the problem of contaminant transport in groundwater systems. For a review of the literature on the use of the finite element technique in modelling contaminant transport in groundwater, the reader is referred to GRAY (1976).

Model calibration

In spite of the advances made in developing numerical and electric analog models of extensive groundwater basins, many of these models often fail to serve as reliable planning and management tools. There are several reasons for this:
- oversimplification of the groundwater system
- erroneous assumptions underlying the model
- uncertainties in the hydrologic input data
- scarcity of and uncertainties in the values of the basin's parameters.

All these factors may be responsible for the wrong predictions of watertable behaviour that these simulation models may produce. Any kind of model must be verified or validated if the predictions or generated data are to have a meaning. Verification thus means that the model must be proved to be true. This is commonly done by 'history matching' which means that unknown or uncertain parameter values, such as permeability

and storativity, are determined by the closest fit of measured and calculated watertable elevations.
In large groundwater basins, the aquifer permeability or transmissivity and storage coefficient are known from a few sites only. If these parameters were found from, say, properly conducted pumping tests they may be sufficiently accurate and reliable. Similar values, however, are also needed for all the nodes of a network or all the sides of the squares or polygons, but these data are usually not available.
Recent developments in solving this calibration or 'inverse problem' have been the introduction of various automatic and semiautomatic calibration techniques. One of these is the 'indirect' approach, which is merely an automatic trial and error procedure that tries to improve an existing estimate of the parameters in an iterative manner until the model response is sufficiently close to that measured in the real aquifer. Another approach is the 'direct' one. It treats the model parameters as dependent variables in a formally posed 'inverse' boundary value problem of the Cauchy type (NEUMAN 1976; NEUMAN and KAFRI 1976).
CHEN et al. (1974) and CHAVENT et al. (1975) applied optimization techniques to obtain a detailed adjustment of the transmissivity map of oil basins. YEH and YOON (1976) introduced a procedure based on scattered observations of head variations within the aquifer. This technique seeks to improve the method of subdividing a given inhomogeneous aquifer into piecewise homogeneous subregions, each subregion being characterized by a single parameter. In regions where the parameters are accurately determined, subdividing is refined. Coarse grids are developed where parameters are ill-determined.
By using one or more of the above techniques it is possible to find a good set of aquifer parameters. 'Good' means that if we feed these values into the computer, the computed nodal watertable fluctuations may be very close to those measured in the field. But this does not necessarily mean that we have now proved that the model is 'true' and that it can unconditionally be used as a predictive tool for planning purposes.
Apart from the aquifer parameters, the net recharge term may also contain uncertainties or severe errors. The net recharge term is the algebraic sum of all the external flows, which in most groundwater basins are not known precisely. The net recharge from rainfall and/or irrigation is often ill-determined, or at worst just a guess, and so are the losses from evaporation and pumpage.
A verified model need therefore not necessarily be a true model. Used as a predictive tool, as all these groundwater simulation models commonly are, they may have limited value.
In referring to the difficulties that arise in an attempt to fix criteria for when a model is verified, NAYLOR and FINGER (1967) quote the philosopher Karl R. Popper, who suggested that we concentrate on the degree of confirmation of a model rather than whether it has been verified.
Popper stated: 'If in a series of empirical tests of a model no negative results are found but the number of positive instances increases, then our confidence in the model will grow step by step'.

Where do we go from here?

The tremendous progress made in developing different types of models is one of the main achievements in the management of groundwater resources over the last 25 years. The progress in this field far surpasses that in field techniques, although no one would wish to deny the great advances made in the use of satellite photographs, radio-isotope analysis for age determination of the groundwater, and geophysical methods for exploring aquifers and aquitards and determining their porosity.
To-day's problem, however, is not a lack of appropriate mathematical tools, but a lack of quantitative field data that allow groundwater basin parameters to be identified. For the near future there is a need to improve the methods of data collection and data analysis of groundwater problems.
The economic effects of alternate depletion rates and pumping patterns in a groundwater mining situation need further study. More thought must

also be given to the effect that the use of land for agriculture, urbanization, forestry, grazing, and road construction has on water yields, water quality, flow regimes, and groundwater recharge; erosion, flooding, and sedimentation need more consideration. Link-ups between physical, non-physical, and economic models are still rare and may have a great potential.

The hydrogeology of low-permeable layers (aquitards) needs further attention in view of the severe problems resulting from contamination of groundwater and from land use practices. Little is known to what extent confining layers serve effectively as retardation zones for toxics or other contaminants. Finally, there is still a need for practical guidelines in planning the use and management of coastal aquifers.

REFERENCES

AMBROGGI, R. P. (1978). Underground reservoirs to control the water cycle. *Ground Water 16,* 158–166.

BEAR, J. (1960). *The transition zone between fresh and salt waters in coastal aquifers.* Ph. D. Thesis, Berkeley, California.

BEAR, J. and G. DAGAN (1962). *The steady interface between two immiscible fluids in a two-dimensional field of flow.* Haifa, Technion, Israel Inst. of Tech.

BEAR, J. and G. DAGAN (1964). *The unsteady interface below a coastal collector.* Haifa, Technion, Israel Inst. of Tech.

BEAR, J. AND G. DAGAN (1968). Solving the problem of local interface upconing in a coastal aquifer by the method of small perturbations. *J. Hydraul. Res. 6,* 16–44.

BEAR, J. (1972). *Dynamics of fluids in porous media.* Elsevier, New York.

BOUWER, H. (1978). *Groundwater hydrology.* McGraw-Hill, New York.

CHAVENT, G., M. DUPUY, and L. LEMONNIER (1975). History matching by use of optimal theory. *J. Soc. Petrol. Eng. 15,* 74–86.

CHEN, W. H., G. R. GAVALAS, J. H. SEINFELD and M. L. WASSERMAN (1974). A new algorithm for automatic history matching. *J. Soc. Petrol. Eng. 14,* 593–608.

COLLINS, M. A., L. W. GELHAR, and J. L. WILSON (1972). Hele-Shaw model of Long Island aquifer system. *J. Hydraul. Div. 98,* 1701–1714.

COURANT, R. (1943). Variational methods for the solution of problems of equilibrium and vibrations *Bull. Am. Math. Soc. 49,* 1–23.

FAYERS, F. J. and J. W. SHELDON (1962). The use of a high speed digital computer in the study of the hydrodynamics of geologic basins. *J. Geophys. Res. 67,* 2421–2431.

FREEZE, R. A. (1972). *A physics-based approach to hydrologic response modeling:* phase I: Model development. Completion Report. Off. Water Resour. Res., Washington D.C.

GLOVER R. E. (1964). The pattern of fresh-water flow in a coastal aquifer. In: *Sea water in coastal aquifers,* U.S. Geol. Survey Water Supply Pap. 1613-C, 32–35.

GRAY, W. G. (1976). The finite element method in groundwater transport. In: *Adv. in groundwater hydrol.* Ed. Z.A. Saleem. Am. Water Resour. Assoc. Minneapolis, Minnesota, 130–143.

GROVE, D. B. (1976). Ion exchange reactions important in groundwater quality models. In: *Adv. in groundwater hydrol.* Ed. Z.A. Saleem. Am. Water Resour. Assoc. Minneapolis, Minnesota, 144–152.

HALL, W. A. and J. A. DRACUP (1970). *Water resources systems engineering.* McGraw-Hill, New York.

HENRY, H. R. (1959). Salt water intrusion into fresh water aquifers. *J. Geophys. Res. 64,* 1911–1919.
HUISMAN, L. (1972). *Groundwater recovery.* Macmillan, London.
KASHEF, A. A. I. (1976). Theoretical developments and practical needs in the field of salt water intrusion. In: *Adv. in groundwater hydrol.* Ed. Z.A. Saleem. Am. Water Resour. Assoc. Minneapolis, Minnesota, 228–242.
MARINO, M. A. (1976). Numerical simulation of contaminant transport in subsurface systems. In: *Adv. in groundwater hydrol.* Ed. Z.A. Saleem. Am. Water Resour. Assoc. Minneapolis, Minnesota, 113–129.
MEINZER, O. E. (1932). *Outline of methods for estimating groundwater supplies.* U.S. Geol. Survey. Water Supply Pap. 638-C.
NAYLOR, Th. H. and J. M. FINGER (1967). Verification of computer simulation models. *Management Sci. 14,* B 92-B 101.
NEUMAN, S. P. (1976). The inverse problem of groundwater hydrology. An approach based on parametric linear and quadratic programming. *IBM Workshop on Groundwater Modelling,* Venice, Italy.
NEUMAN, S. P. and U. KAFRI (1976). The AM.FM concept in parameter identification. In: *Adv. in groundwater hydrol.* Ed. Z.A. Saleem. Am. Water Resour. Assoc. Minneapolis, Minnesota, 83–101.
PINDER, G. F. and H. H. COOPER (1970). A numerical technique for calculating the transient position of the salt water front. *Water Resour. Res. 6,* 875–882.
POLUBARINOVA-KOCHINA, P. Y. (1962). *The theory of groundwater motion.* Princeton Univ. Press, N.J.
PRICKET, T. A. (1975). Modeling techniques for groundwater evaluation. In: *Adv. in hydrosc.* Ed. V.T. Chow, Academic Press, New York, *10,* 1–143.
PRICKET, T. A. (1976). Advances in groundwater flow modeling: In: *Adv. in groundwater hydrol.* Ed. Z.A. Saleem. Am. Water Resour. Assoc. Minneapolis, Minnesota, 102–112.
RICHARDSON, L. F. (1910). The approximate arithmetical solution by finite differences of physical problems involving differential equations, with an application to the stresses in a masonry dam. *Trans. Phil. Royal Soc.* Ser. A. *210,* London 307–357.
SANTING, G. (1958). A horizontal scale model based on the viscous flow analogy for studying groundwater flow in an aquifer having storage. *Publ. 43, Int. Assoc. Sc. Hydrol.* 105–114.
SHAW, F. S. and R. V. SOUTHWELL (1941). Relaxation methods applied to engineering problems; VII. Problems relating to the percolation of fluids through porous materials. *Proc. Royal Soc.* Ser. A. *178,* London, 1–17.
TODD, K. D. (1953). *An abstract of literature pertaining to seawater intrusion and its control.* Tech. Bull. 10, Sanitary Eng. Res. Project, Univ. of California, Berkeley.
TODD, K. D. (1959). *Groundwater Hydrology.* John Wiley and Sons, Inc., New York.
TURNER, M. J., R. W. CLOUGH, H. C. MARTIN, and L. J. TOPP (1956). Stiffness and deflection analysis of complex structures. *J. Aeronautical Sci. 23,* 805–823.
TYSON, H. N. and E. M. WEBER (1964). Groundwater management for the nation's future. Computer simulation of groundwater basins. *J. Hydraul. Div. 90,* 59–77.
VERRUIJT, A. (1972). *Theory of groundwater flow.* Macmillan, London.
YEH, W. W. G. and Y. S. YOON (1976). A systematic optimization procedure for the identification of inhomogeneous aquifer parameters. In: *Adv. in groundwater hydrol.* Ed Z.A. Saleem. Am. Water Resour. Assoc. Minneapolis, Minnesota, 72–82.
ZIENKIEWICZ, O. C., P. MAYER, and Y. K. CHEUNG (1966). Solution of anisotropic seepage by finite elements. *Proc. Am. Soc. Civ. Eng. 92, EM 1,* 111–120.
ZIENKIEWICZ, O. C. (1971). *The finite element method in engineering science.* McGraw-Hill, London.