

## THE USE OF COMPUTERS IN WATER RESOURCES DEVELOPMENT AND WATER SUPPLY PLANNING

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### ABSTRACT

There is an urgent need for a new approach and the application of modern techniques in solving the problems of future water supply. More than is the case at present, proper planning must relate the physical, environmental, economical and social factors involved. But integration of the various elements encounters some major difficulties of which insufficient data and lack of an exact and comprehensive methodology are the most serious.

In the last few years there have been a series of important developments in, total water resources management methods and water supply optimization techniques. Basic to these developments in total water resources management methods disciplines as Operations-Research and Systems Analysis, and the availability of high-speed electronic computers.

Planning techniques based on the computer's ability to process vast amounts of information enables the engineer to check a certain solution by arbitrary variation of the given or assumed parameters of his model. The water demands of an area can be met either by delivering surface water, or groundwater, or by an almost infinite number of possible combinations of these two resources. But water should be supplied economically without causing harmful effects within the area or its surroundings. To achieve this objective the technique of linear programming can be applied, as it allows to find for each plan an optimum solution of water supply under the given constraints. Then, using a digital computer model of the groundwater basin, which is capable of simulating the extraction and replenishment flows, the consequences of future water engineering works can be determined. The unique feature of these two models is that the output of the linear programming model can be used directly on the groundwater basin model to test the physical validity of the economic solution.

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### INTRODUCTION

The rapid rate of the population growth and the consequent growing water demands of urban and rural areas give rise to almost overwhelming problems of planning future water supplies. In semi-arid regions, where the water resources are limited and often variable optimum conjunctive use of surface water and groundwater is imperative. Decisions have to be made as to location, size and timing of future surface water and groundwater facilities in order to satisfy economically the water demands of agriculture and urban areas.

The planning of future water supplies in humid, densely populated areas is an equally complex undertaking, especially when the most desirable sites for groundwater extraction are limited or depleted and a further increase of groundwater extraction would cause damage to landscape and agriculture. Hence it may be of more than academic interest to know where and to what extent the extraction of groundwater can be increased without causing harmful effects to the environment and agriculture.

More than is the case at present, proper planning of future water supply and distribution should relate the physical, environmental, economical and social factors involved. The integration of these various elements encounters some major difficulties of which lack of real and effective team work, insufficient data, and lack of an exact and comprehensive methodology are the most serious.

In planning, it is essential that the overall long-

range objective be clearly understood and kept in sight by all members of the interdisciplinary team. It requires the full utilization, interaction, and cooperation of men in the technical disciplines related to geology, hydrology, hydraulics, mathematics, electronics, agronomy and economics.

The lack of sufficient basic data always is a serious problem. But planning cannot be postponed indefinitely or till the last information has been collected. We thus face the problem of uncertainties in our proposals and plans. But these uncertainties can be considered as a wide range of possibilities, whose upper and lower limits can be measured or estimated with sufficient accuracy. The entire range of possibilities can be considered as alternatives for which simulation tools have been developed to test their reliability. In a similar way planning techniques based on the computer's ability to process a vast amount of information enables the engineer to check a certain solution by arbitrary variation of the given or assumed parameters of his model.

Finally there is the problem of methodology. Integrating vast amounts of very different data to find the best plan requires an exact and comprehensive method. In the last few years there have been a series of important developments in, what may be called, total water resources management methods and water supply optimization techniques. Basic to these developments have been advances in such different disciplines as Operations-Research and Systems Analysis, and the availability of high-speed electronic computers.

The purpose of this paper is to set forth the basic principles of these techniques, which are not as esoteric or complex as their names would suggest. Operations-Research refers to an economic model and includes application of the technique of linear programming to find optimum plans of water distribution. Systems Analysis refers to a digital computer model of a groundwater basin that can be used to determine the consequences of future water engineering works. The unique feature of these two models is that the output of the linear programming model can be used directly on the groundwater basin model to test the physical validity of the economic solution.

## THE NATURE OF WATER RESOURCES PLANNING

Planning for water resources development is a

complex problem because of the interaction of surface water and groundwater. Therefore, water resources development should be an integral part of total water resources management, including the planning, organization and control of activities directed to develop water resources economically without causing harmful effects.

The techniques discussed in this paper have been applied in a study concerning water supply of the Varamin Basin, a semi-arid area of Iran (de Ridd er, 1968, de Ridd er et al, 1969). In rural areas of this climate the main objective of water supply is often the development of irrigated agriculture. Because of low rainfall, agriculture is only made possible by irrigation from either surface water or groundwater resources.

In the Varamin Basin river water of good quality is available but the discharge of the river varies not only from one month to another but also from one year to another. In spring floods may occur and these flood waters recharge the groundwater reservoir to some extent. An important recharge takes place by the presently uncontrolled irrigation and seepage losses from unlined canals. Abundant groundwater resources of good quality exist but there is also saline groundwater in the adjacent areas. The danger of salt water intrusion exists if the basin would be over-pumped.

The depth to water table varies from one part of the area to another because of differences in land elevation. Thus the cubic meter price of well water varies throughout the area. The cubic meter price of surface water increases with the distance from the diversion dam to be built in the river because the transportation network should be lined in order to prevent the seepage. The water shortage of the area could be alleviated by importation of surface water from another catchment area but this requires the construction of a long tunnel through the mountains which makes this water more costly than local water.

To arrive at a most economical and efficient plan of optimally coordinated use of surface water and groundwater resources, many complex and inter-related elements must be considered and integrated. These elements include, amongst others: the water demand of the area, the available water, water rights and water prices, possibilities of importation of water, the demand function of imported water and its marginal returns per cubic meter, supply of river

water and groundwater by means of a simple distribution system, alternative plans of groundwater basin operation and physical responses of the basin to such plans, costs of supply facilities and operation, economic return to the farmer after sale of agricultural products, and resettlement of farmers.

All these elements should be properly integrated. Computers are tools that can be used for examining a range of alternative solutions and consequences. The results of such a study can be used as a guide to manage both surface water and groundwater resources effectively and to correct or minimize the undesirable effects of overdraft conditions and possible associated salt-water intrusions.

### GROUNDWATER BASIN COMPUTER MODEL

Since the problem of total water resources management is complex, a systems approach can best be applied. Systems analysis is a general approach aimed at understanding more clearly the combination of elements which, taken together, form a complex that can be designated as a system. Characteristic of the system approach is that it tries to isolate the essence of a complex physical entity or system, to describe its structure and explain its internal cause and effect relationships. When applied to a groundwater basin the procedure is to represent the relationship between components and their assemblage into a system, using quantitative models. Such models usually take the form of mathematical equations.

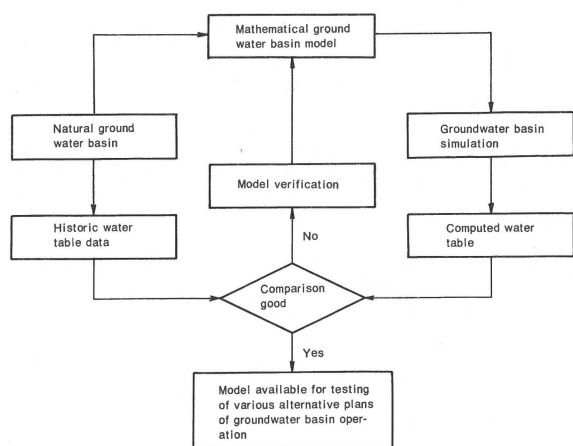


Fig. 1  
Scheme for model analysis of groundwater basin.

The various models of the system components and their interrelationships may be simulated by a computer. As is shown in fig. 1, the data from this simulation are compared with the actual system performance as developed from historic records. In the case the computed data compare adequately with the recorded historic data, the system simulation is said to be verified. If the comparison is not good, the individual models must be modified until the computed and historic data compare adequately.

The demands for water may be met by an almost infinite number of possible combinations of surface and groundwater facilities. If a series of alternative economical plans of water supply and delivery has been developed, each of them can be expressed in terms of groundwater basin operation and adapted to the model of the groundwater basin itself. The model may then be used to investigate physical system responses to each plan.

The mathematical groundwater-basin computer model was initially developed by H.N. Tyson, Data Processing Division of I.B.M. Corporation in Los Angeles, in cooperation with engineers of the California Department of Water Resources (Chun, Weber and Mido, 1963; Weber, Peters and Frankel, 1968), and was successfully applied by the author in Iran (de Ridder, 1968) and recently by others in Libanon and Greece.

Basic to the development of the model are the physical characteristics of the groundwater basin to be studied, for example its geometry, structure, boundaries, transmissivity and storage coefficient values. The need for adequate geological and hydrogeological data cannot be emphasized too much including the fact that this information should be presented in quantitative form. In modelling a groundwater basin this is a critical point because geologic information should be presented in such a way that it can be applied and fed into the computer. This means that a stratigraphic sequence must be schematized in terms of aquifers, confining and semi-confining beds, with thicknesses and boundaries expressed in quantitative figures. Aquifer transmissivities and storage coefficients must be available, based on the results of available field pumping tests, estimates from well logs and other lithological information.

The mathematical two-dimensional model was

designed to develop a time history of water table height in a groundwater basin by use of Darcy's equation and the continuity equation. These two equations are combined in a non-linear partial differential equation which models the flow rates associated with a unit area of aquifer, taking into consideration the sum of outward normal subsurface flow rates, flow rates in or out of storage, and inward or outward flow rates external to the aquifer:

$$\frac{g\rho}{\mu} \nabla \cdot k(x,y) h \nabla h - S(x,y) \frac{\partial h}{\partial t} - Q(x,y,t) = 0 \quad (1)$$

where:

$k$  = permeability coefficient;  $h$  = water table height above a datum;  $S$  = storage coefficient; and  $Q$  = net external input;  $g$  = acceleration of gravity;  $\mu$  = viscosity and  $\rho$  = density of groundwater. The term  $g\rho/\mu$  is usually taken as a constant and included in the terms for hydraulic conductivity and transmissivity.

An approximate solution of this flow problem can be achieved by applying a method of finite differences. To this aim the groundwater basin is subdivided into a number of polygonal areas (or squares) whose size and location is chosen on the basis of known variations in replenishment, extractions, transmission, storage, and water levels. If a polygonal network is used, the polygons are constructed according to the Thiessen method. Each polygon (figure 2) has a node point, which is considered as a control point for that particular polygon. In accordance with the theory of finite differences the flow rates in a polygon may be integrated. The finite difference equation for a given node is:

$$\sum_i Y_{i,B} [ h_i(t_{j+1}) - h_B(t_{j+1}) ] = \frac{A_B S_B}{\Delta t} [ h_B(t_{j+1}) - h_B(t_j) ] + A_B Q_B(t_{j+1}) \quad (2)$$

where

$Y$  is a conductance factor made up of transmissivities ( $T$ ), boundary width ( $W$ ), and flow path length ( $L$ ) (see fig. 2).

$$Y_{i,B} = \frac{WT}{L_{i,B}} \quad (\text{linear})$$

$$Y_{i,B} = \frac{W_{i,B}}{L_{i,B}} T_{i,B} \quad \left( \frac{\text{saturated thickness}}{\text{total thickness}} \right) \quad (\text{non-linear})$$

$h$  = water table height

$A_B S_B$  = storage coefficient for the polygonal area

$A_B Q_B$  = net external inflow for the polygonal area

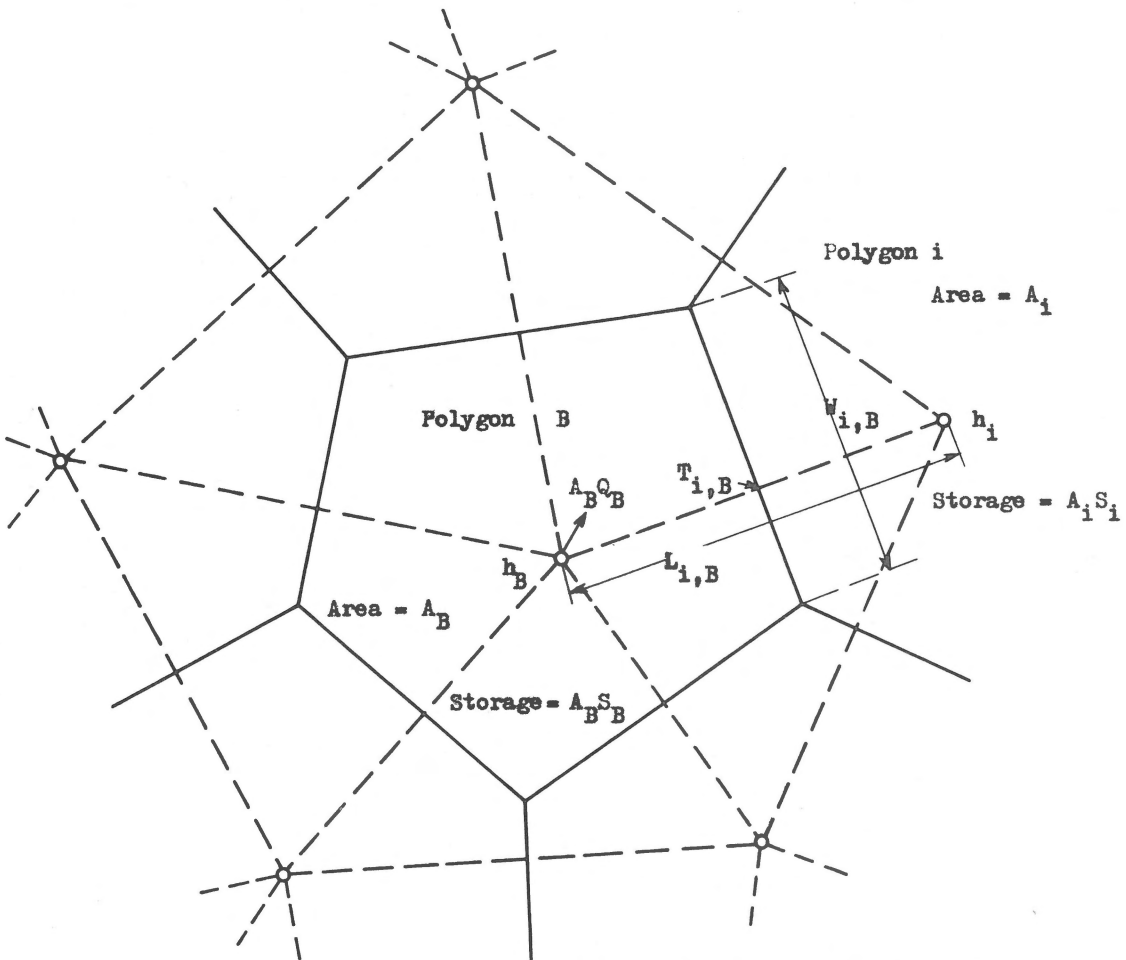
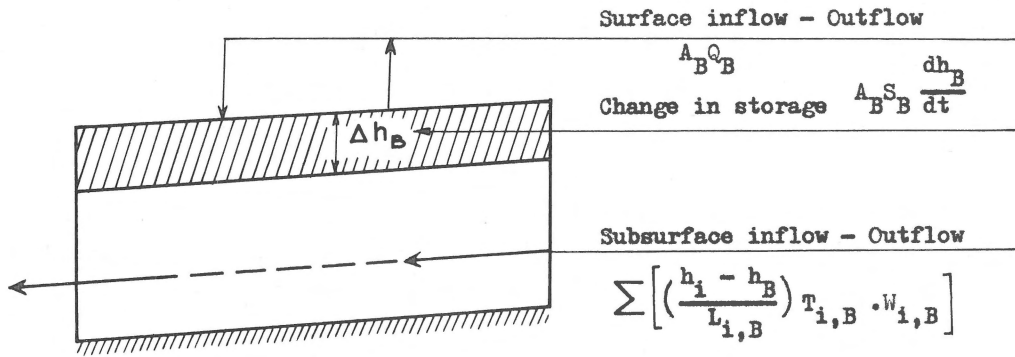
$i, B$  = continuous nodes and the node in question, respectively

$t_j$  = time element

## DEVELOPMENT AND VERIFICATION OF THE MODEL

The general steps taken in developing a mathematical model and verifying its reliability are as follows:

1. The groundwater basin is subdivided into *subareas* (polygons), using the Thiessen method of polygon construction.
2. The *conductance factor* ( $TW/L$ ), which affects the subsurface flow between two nodes, is obtained by using the results of pumping tests and geologic investigation. Well logs are analyzed to delineate the water-bearing zones and estimates of the hydraulic conductivity are made to obtain estimates of the transmissivity of these zones. A transmissivity map is prepared, showing lines of equal transmissivity. For each polygonal side the appropriate value of transmissivity of the aquifer is obtained by interpolation. To obtain the conductance factor ( $Y$ ), the transmissivity value ( $T$ ) is multiplied by the width of the polygonal side ( $W$ ) and divided by the length ( $L$ ) of the flow path between the nodes.
3. The *storage factor* ( $AS$ ) is considered to be a measure of the storage characteristics at each nodal polygon. A specific yield value ( $S$ ) is estimated from well logs and geologic data. To this aim the various lithologies described in drillers' logs can best be grouped in a small number of main groups to which a specific yield value is assigned. Thus a weighted average specific yield value can be calculated for the zone of water table fluctuation. The results of these calculations are plotted on a map and lines of equal specific yield



$T_{i,B}$  = characteristic transmissivity between polygon B and polygon i

$h_{i,B}$  = representative groundwater table elevation in polygon

Fig. 2  
 Element of polygonal network with cross-section.

values are drawn. For each polygon a weighted average specific yield value is calculated, which multiplied with the area (A) of the polygon, gives the storage factor (AS). This factor is considered to be a constant.

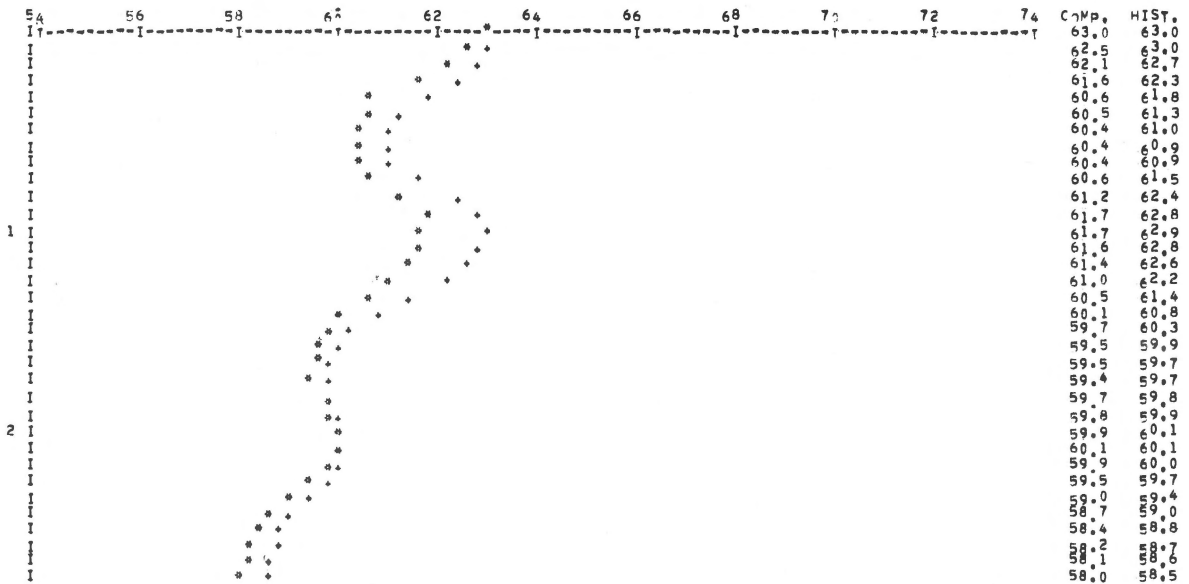
4. The *net deep percolation* (net recharge, AQ) for each polygon is determined by using all information on precipitation, evaporation, stream and canal percolation, effluent seepage, artificial recharge (if any), and groundwater extractions by pumping. The algebraic sum of these replenishment and extraction flows gives the net deep percolation of the polygonal area. It should be determined for the chosen time step (month, season or year).
5. For testing and verification of the model historic water-table elevations are used, preferably for a 5 to 10-year period. For the time step chosen, water table contour maps are prepared and representa-

tive groundwater table elevations for each node in the system are developed by interpolation.

6. The verification of the model consists of matching the water table elevations generated by the computer, using the historic hydrologic input data, with the historic water-table elevations.

In general, the water-table elevations generated by the computer match the (measured) historical water-table elevations reasonably well in most polygons, but usually deviations occur in some polygons. To obtain a closer match of the water elevations in all areas, some of the values of storage factors, transmissive factors, and net deep percolation, are adjusted. Too great fluctuations of the computed water levels are due to underestimated values of the specific yield. Such errors can easily be corrected by raising the specific yield value. Similarly, too high computed water levels in a certain polygon and too low

GROUND WATER MODEL FOR MIRES BASIN, CRETE SAMPLE OUTPUT OF FINALLY CALIBRATED MODEL. DATE 10/2/71. RUN NO 19



ELEVATION IN METERS ABOVE SEA LEVEL VS. TIME IN YEARS

Fig. 3 Example of a digital computer output for water level data of the Mires Basin on Crete. In this diagram computed and historic groundwater levels are compared.

computed water levels in an adjacent polygon obviously are due to an error in the transmissivity. Depending on the direction of the groundwater flow, raising or lowering of the transmissivity value will help to obtain a closer match between computed and historic water level elevations in the respective polygons.

To make comparison between computed and historic water level elevations easier, these elevations are recorded graphically by using a digital plotting technique (fig. 3). After the necessary adjustments are made, a new test run on the computer is made and the results examined. This process is repeated until the water levels in all polygons match, or have adequate correlation. The model can then be used for simulating different groundwater extraction patterns by simply changing the polygonal net deep percolation values. For any time period (e.g. 10, 20 or more years) the dynamic behaviour of the groundwater basin under the new conditions of pumping (and recharge) is predicted.

It should be noted that the nonlinear system requires three additional kinds of data: the representative ground surface elevation at each node, the representative base of the aquifer at each node, and the base of the aquifer at the polygonal sides (branches).

### COMPUTER PROGRAMME

To solve the system of differential equations (2) a computer is used. The programme for the computer was written in Fortran. According to this programme all the node-to-node subsurface flows ( $Q$ ) are calculated first and then the storage flows ( $S$ ). Then the flows, subsurface storage and extraction are balanced at each node by setting their sum equal to the residual ( $RES$ ) term. Water level elevation at the node is adjusted by the magnitude of the residual attenuated by a relaxation coefficient. When all the water table elevations have been adjusted, a sum is formed of the nodal residuals. This sum is compared with an error criterium ( $ERROR$ ). This ( $ERROR$ ) value represents the maximum acceptable sum of nodal flow residuals at any time step. If the sum of the residuals is less than or equal to the ( $ERROR$ ) value the calculation of the water table elevation is complete for that time step. If not, the calculation is repeated

as many times as required to reduce the sum of the residuals to a value less than or equal to the  $ERROR$  value. Because of space limitations no further details of the programme are given. The author obtained solutions, for a problem in Iran, containing 27 node points for a given set of boundary conditions, over a period of 4 years, in about 3 minutes, using an IBM 360-65 system, and for a problem in Greece, containing 17 node points, over a period of 3 years, in less than 1 minute, using a CDC 3300 system.

Finally it may be noted that the nonavailability or poor quality of certain basic data, like storage coefficients or transmissivities, does not prevent developing a mathematical groundwater-basin model. The order of magnitude of these hydraulic characteristics can easily be estimated with sufficient accuracy by an experienced geologist. During the verification process the computer is used to check the estimated values of the transmissivity and storage coefficient and adjustments are made as long as required in order to obtain a close match between computed and historic water table elevations. Thus, by means of the computer the geologist can gain insight in the subsurface geology, facies changes and physical characteristics throughout the basin, which he cannot otherwise achieve at such a low cost. Obviously, this does not mean that computers can replace field work and exploration borings. But there is a need for better methods of collecting and especially evaluating the geologic and hydrologic data, as these will improve the quality of the models developed.

### OPERATION-ECONOMIC MODEL

The planning and design of a water supply and delivery system to meet the agricultural demands of an area where water resources are limited and long-distance conveyance facilities are involved, may be considered as an economic optimization problem. The problem has as its basic conditions the limitation of the available water resources and the requirements of the agricultural production schedule, and as its objective the farmer's desire to maximize his gain. A solution that satisfies both the conditions of the problem and the given objective is termed an optimum solution.

To arrive at such a optimum solution out of a large number of possibilities, the technique of linear

programming can be applied. Basic to this technique is that a mathematical model or formulation of the problem can be stated, using relationships which are called "straight line" or linear. Hence, there are required sets of linear equations, which include clearly defined physical constraints, alternative activities, physical input-output coefficients and per unit costs. The linear combination of the variables must be optimized by the selected solution. This added condition of optimization enables to select a single solution that satisfies all the conditions of the problem and yields the unique optimum value of the function.

When applied to the present problem the following activities can be distinguished:

1. Inflow of the river to the main diversion point where the water is distributed to various parts of the plain
2. Supply of river water to a certain area (polygon) by means of a canal system
3. Supply of groundwater to a certain area (polygon) by extracting from wells
4. Agricultural production in a certain area (polygon).

These activities have costs, which can be defined as follows:

1. The cost of river water per cubic meter at the diversion structure
2. Based on a new canal system, these costs also represent the maintenance, operation and capital costs of surface water supply
3. The cost of well water per cubic meter, taking into account differences in water table depth and aquifer transmissivity
4. Agricultural production can be considered as negative costs and represents the net return per cubic meter of water. It is based on an optimal agricultural production pattern and the respective water demands of the various crops per hectare. The net return per cubic meter water represents a net residual of the crop value after deduction of purchased input, including interest, labour costs, and capital costs of land levelling. This net return can be considered as the maximal price for water that farmers in a certain polygon can afford if the assumed higher efficiency level will be achieved.

The model is restricted by certain constraints that

are defined as follows:

1. River discharges are variable, especially in semi-arid regions. Different discharges, for instance for average, dry and wet conditions, are incorporated in the model.
2. The maximum water demand of the various subareas (polygons) is restricted. Alternatives are: water is delivered to the best soils only; this implies a resettlement of farmers; water is delivered to each subarea based on the number of farmers living at present in these subareas, and assuming that in the first development phase each family has, say 5 hectares of land; in the next development phase water can be imported from another catchment area, thus more land may be cultivated and each family may have 10 hectares of land.

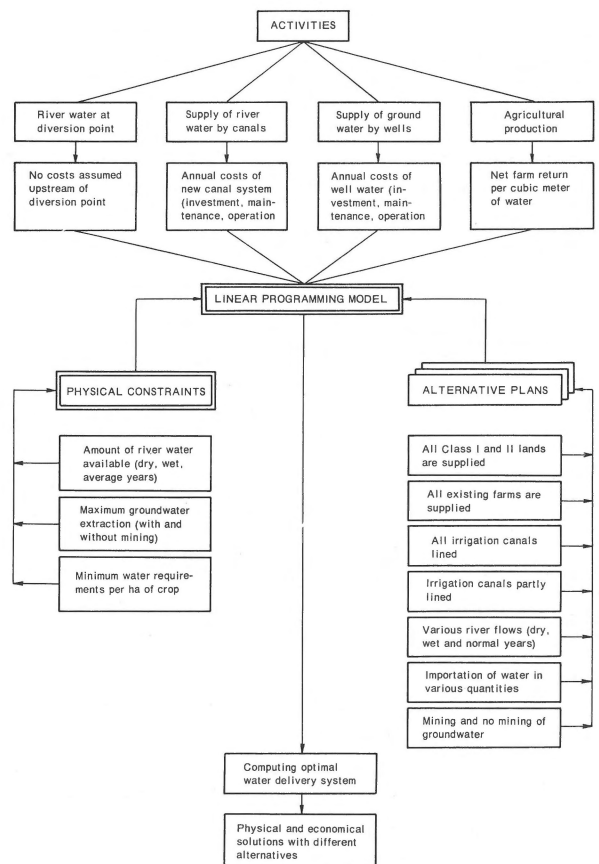


Fig. 4  
Scheme for operation-economic analysis for water supply of an irrigation area.

3. The total groundwater extraction should be smaller or equal to the subsurface inflow into the basin plus the net deep percolation.
4. All surface water distribution activities equal the total river flow.
5. Any level of production in a certain polygon must be supplied by surface water or groundwater.

Figure 4 shows a diagram of the various elements of the linear programme. The unique aspect of this model is that the same polygonal areas are used as for the groundwater-basin model. This allows the optimum solutions of water supply to the plain obtained from the linear programme model to be applied directly to the groundwater model, in order to test their physical validity. Such a testing of the solutions is necessary in order to predict what changes in the dynamics of the groundwater basin can be expected if the plan would be implemented and what corrective measures would have to be taken and at which places, to control the water table.

Under the given constraints the computer generates for each alternative plan an optimum solution of water supply. Such a solution shows which polygons should be entirely supplied by river water, which polygons by well water, and which polygons by river water and well water. It also shows the polygons which can not be supplied by either of these waters because of too high costs. The solution may also

include certain areas whose water demands are only partly met, because supplying the total demand would not be economical.

To test the optimum solution obtained from the linear programme model by the groundwater model, a special computer programme has been prepared that converts the linear programme results into terms of groundwater basin hydrology. Through this programme the computer lists at the end of the computations the river water supplies, seepage losses from canals, field irrigation losses and groundwater extractions, for each polygon separately.

The algebraic sum of these flows represents the net deep percolation, which for each polygon is imposed on the groundwater model. As is shown in fig. 5 the model simulates these net deep percolation values and generates the corresponding water table elevations of each polygon for a period of 10 or 20 years, as is required.

For each polygon a nodal hydrograph is made, showing the changes in water table for the chosen time period. The computed water levels are also plotted on a map and lines of equal water table change are drawn (for example the difference in water table after 5 or 10 years of operation). From these maps it can be decided whether the optimum water delivery plan is physically sound, or whether it would cause waterlogging or overdraft conditions in certain polygonal areas.

## CONCLUDING REMARKS

The use of a Linear Programming Model in combination with a Mathematical Groundwater Basin Model employing a computer, is of great advantage in developing and testing of various alternative plans of water delivery and supply. With these tools more alternative plans may be examined than otherwise would be possible.

Linear programming is based on the principle of linear relationships and on certain physical constraints. The results obtained have a deterministic character and they cannot be considered as an optimization of a stochastic problem. For instance, cycling of river flows cannot be built into the model. On the other hand, the linear programming model is

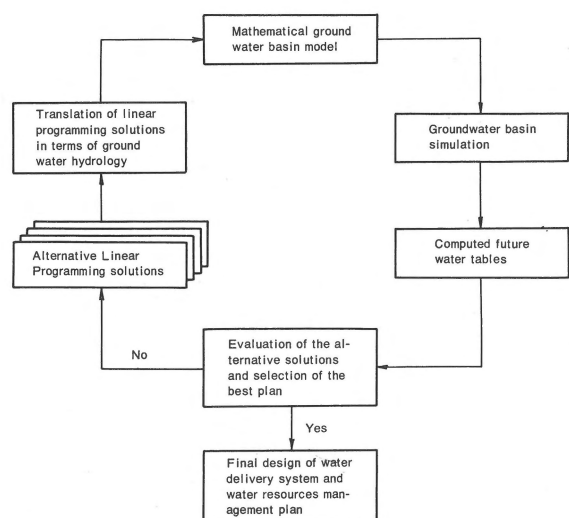


Fig. 5  
Scheme for feasibility analysis of linear programming results adapted to a groundwater basin model.

flexible enough to incorporate, for example, certain groundwater extraction and delivery patterns.

The Groundwater Basin Model has the flexibility of handling any plan of groundwater basin operation, as it is based on nonlinear partial differential equations which model the flow rates. Cycling of flows can be imposed on this model and its effect on the water table can be studied.

To avoid any misunderstanding I wish to stress that the computer results obtained should not be considered as decisions. The results can be used as a guide in predicting the physical and economical consequences of decisions, and in ranking alternative plans according to certain criteria.

The best (economic) solution obtained from the computer may show certain physical shortcomings, e.g. excessive drop rates of the water table in certain polygons, due to high groundwater extraction rates. There may also be legal and social constraints, imposing limits on the most economical system of water distribution. Hence, after selection of the "best" plan its merits and shortcomings should be studied and proposals for corrective measures be made. During this "post-optimization" process the computer model can also be used to test the alterations and corrective measures of the initial plan and determine their effect on the water table.

The techniques discussed here can be applied to

provide a better basis for decisions and a better understanding of some of the complex relationships between water supply and use. For further details of the techniques and the results obtained for a case study, the reader is referred to a forthcoming publication on the subject matter by the author in the series of Bulletins of the International Institute for Land Reclamation and Improvement.

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