Application of operations research in Israel's water sector

Uri SHAMIR
Technion-Israel Institute of Technology, Haifa, Israel

Israel's water sector has moved from a period of development, which ended in the mid-1960's, to an era of scarcity. Over 95% of the natural water potential is already being utilized, and there is severe competition for this scarce resource between economic sectors and geographic regions. Management of development, design and operation of the water systems is therefore an acute problem, with implications ranging from national policy to efficiency in daily operation. Operations research methodologies have been developed and applied quite extensively over the last 15 years in Israel's water sector, dealing with the full range of its problems. The paper is a survey of these applications, aimed at providing a realistic assessment of their value, from which water resources systems analysts in other countries may derive some guidelines for their own work.

1. Introduction

Located on the Eastern coast of the Mediterranean Sea, Israel has a total area (excluding administered territories) of some 20 000 square kilometers. Over the 500 km of the country's length, the climate changes from arid (10 mm/year of rainfall or less) in the South to a relatively humid area (1000 mm/year and more) in the North. The irrigated area is somewhateover 2 million dunams (200 000 hectares), a little more than 10% of the total area. Irrigated agriculture is located primarily in the Center and near South of the country. The population, over 3.5 million, is largely concentrated along the coastal plain, in the central part of the country.

The proven natural resources of Israel amount to approximately 1700 million cubic meter (MCM) per year. 25% is surface water, most of it from Lake Kinneret in the watershed of the Jordan River (Fig. 1). 60% is fresh groundwater, primarily from the coastal aquifer and a limestone aquifer adjacent to it on the East, called the Yarkon–Taninim quifer. 10% is brackish groundwater, used directly in irrigation and industry, or desalinated for domestic use. The remaining 5% is water which is economically useable from flash floods.

Over 95% of this potential is already being used. Total consumption in 1976 amounted to 1667.3 MCM, including 1534.7 MCM of fresh water and 132.6 MCM of brackish water (defined as having more than 2 000 mg/l of Cl^-). 76.2% of the consumption was for agriculture, 18.3% for domestic use, and 5.5% for industry. The percentage of agricultural consumption has been decreasing somewhat in recent years – from 8.3% in 1962 – while the domestic and industrial consumption have increased over the same period, in both absolute and relative terms (14.9% for domestic and 4.5% for industry in 1963).

Israel's modern water system, shown in Fig. 1, has been developed over a relatively brief period of the last three decades. It evolved from a random collection of rather outdated local systems, based primarily on shallow wells, to an integrated system, designed and operated according to policies promulgated by central authorities.

On the supply side, sources have been developed and integrated into the system, and the aquifers are also being used as operational reservoirs. Desalination of brackish groundwater and of sea water augments the natural supplies in a few problematic areas of the arid South. Reclaimed sewage is already being used to some extent, and is expected to provide up to 300 MCM/year. This reclaimed sewage, after secondary treatment, will be directed mostly for irrigation. Appropriate sewage treatment methods are being developed and implemented, and re-use is increasing. Cloud seeding has been shown, in a 10 year experimental program, to result in as much as a 15–20% increase in rain yield. It is therefore being exercised operationally, especially over the Jordan watershed above Lake Kinneret.

Dramatic changes have taken place over the last two decades on the demand side. Though much remains to be done, Israel is a model of efficient water utilization (Arlosoroff [6]; Anon [5]). Flood and furrow irrigation of the past have been replaced by advanced sprinkler and drip irrigation systems, designed to increase productivity per unit of water applied. Irrigation systems are being automated, using

European Journal of Operational Research 5 (1980) 332–345

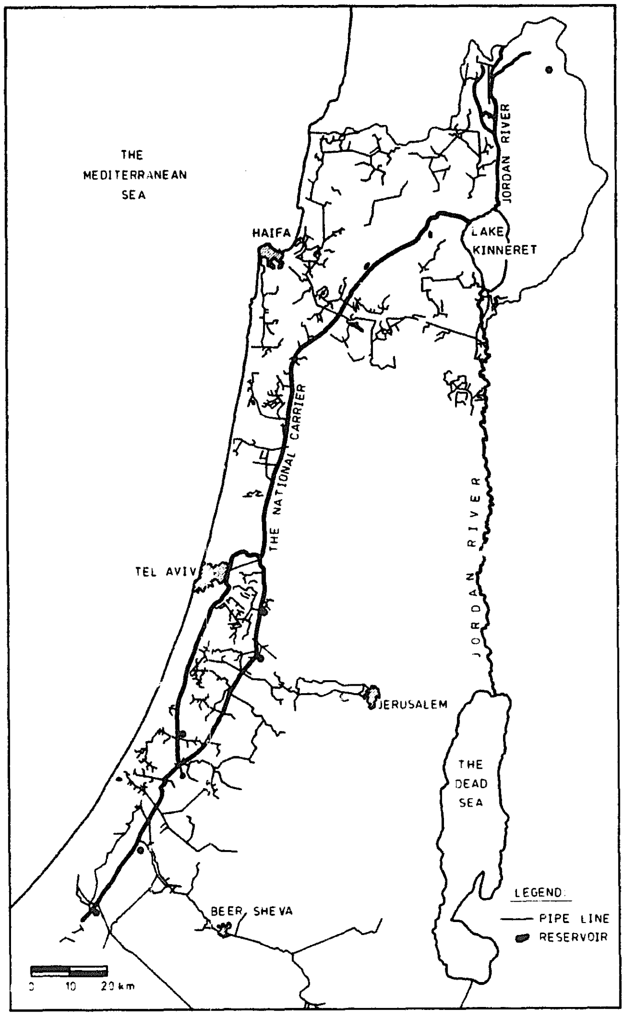

Fig. 1. The Israeli water system.

a wide variety of sophisticated hydraulic equipment, which can be connected to a control center to be operated remotely, often through a computer. Industries are recycling and re-using wastewater, thus saving water and some processed materials. Water saving devices are introduced into homes.

Israel's water sector has had to face many problems. Some of the main issues are:

(1) The main sources are in the North and Center of the country, while much of the demand is in the Center and South. The National Water Carrier (Fig. 1), some 250 km long, carries annually around 350 MCM from the Kinneret to the Center and South. It links along its way some 25 regional water systems, allowing for coordinated management of much of the country's water resources. Completed in 1964, it is the backbone of the national water system.

(2) Precipitation occurs only in winter, while demand is largest in summer. There are large fluctuations in annual water yield. Seasonal and over-year operational storage is therefore needed. The Kinneret provides only part of this storage reservoir, especially for long-range needs.

(3) Water quality in the Kinneret was endangered for many years. Diversion of saline springs which entered the lake, controlled operation of the lake and watershed management have resulted in an acceptable, reasonably stable, water quality.

(4) Groundwater quality is deteriorating. Return flows from irrigation and urban areas, as well as some uncontrolled sewage flows, are causing a steady increase in the concentration of several solutes and trace materials in the groundwater. This problem is of great concern, because of long term effects and the great difficulty in reversing the processes.

(5) The national water system carries water of essentially a single quality, suited for human consumption. This means that the quality criteria of 5–6% determine the quality standards for the entire quantity. Multiple (dual or even more) systems, each carrying a different 'Type' of water, must be considered at the local, regional or even national scale – as an alternative. Many health, engineering and economic questions have to be faced by such plans, but it seems that this option will have to be used more widely as time goes on.

(6) Extensive exploitation of groundwater in the past has lowered water levels in the aquifers. Sea water has intruded to considerable distances into the coastal aquifer – in some locations as far as 2000 meters and more – removing some wells from production. Lower levels throughout the aquifers are also of concern because of the reduced quantity in storage, because some wells may dry, and the cost of pumping increases.

(7) Development of new sources – the few remaining conventional sources, reclaimed sewage, desalination – and delivery of their waters to consumers require substantial capital expenditures and operantional costs, and thus compete for scarce funds with many other items of high national priority. Tight budgetary constraints greatly influence expansion and improvement plans for water systems.

(8) Radpidly rising energy costs, which are a major component in the overall cost of producing and distributing water, require careful planning and control of the operation.

(9) Reliable supply for irrigation is crucial in securing revenue from agriculture so important to the farmers, as well as to the national economy. Agricul-

tural products are an important export item, and foreign exchange is affected by any change in quantity of the exported produce.

(10) A constantly rising population and the natural rise in the standard of living require an ever larger proportion of the water to be delivered for domestic and municipal use. Industry is expanding and also needs more water. This increase must come from reduction in the allocation of potable water to agriculture. Economic considerations and a national policy for dispersion of the population throughout the country dictate that agricultural production must not only be kept at its present level but that it must be expanded. The reduction in supply of potable water for irrigation must therefore be compensated by an increased supply of low-quality water – reclaimed sewage and/or brackish groundwater – and by increased productivity of water in irrigation. Technical and economic issues have to be resolved for this transformation to water of different quality to be effective.

(11) All the above points to serious competition between consumers, giving rise to problems of national policy regarding allocation of water and of funds.

(12) Water pricing policies are also controversial issues of national policy – differential pricing and/or subsidies, graded pricing according to quantity consumed and to its temporal distribution, etc.

(13) Administration of the water sector is based on three bodies. The Water Commission, headed by the Water Commissioner, who is a government appointed official in the Ministry of Agriculture, is legally responsible for all matters pertaining to water. Much of the planning and design is done by TAHAL - Water Planning for Israel Ltd. – a publicy owned company. Construction, management and operation of the water systems is by Mekorot Ltd. – the national water supply company. This legel and administrative setup, which evolved during the era of rapid expansion in supply and construction of the national water system, may need revision and adaptation to the present and future era of scarcity.

(14) Today's decisions and actions affect the quantity and quality of the water resources we will pass on to future generations. Many effects, primarily those relating to quality, have a long time scale and are very difficult, or even impossible to reverse. An evaluation of immediate benefits versus the value of the remaining resources is implicit in any decision on development or operation of the system. An explicit evaluation is difficult as well as controversial, since it involves estimation of an uncertain hydrologic and technological future and calls for value judgements.

The above list contains but the more prominent and global problems. Others are too numerous and specific to detail here. They all point to the need for good planning and proper management.

Leaders and directors of Israel's water sector must be credited with foresight and an understanding of the role that basic and applied research must play. Since the early days of modern development in the water sector, for over two decades now, research has proceeded in parallel with development of the water systems. This has resulted in knowledgeable, foreward looking research and development teams within the water sector's organizations, and at research institutes and universities.

Early efforts to develop and apply OR techniques to Israel's water resources problems date back more than 15 years, to the early 1960's (Amir and Kally [4]; Dean and Buras [22]; Yosupovits [50]). Several nion-Israel Institute of Technology and the Hydrologic Service of the Water Commission, plus some activity in other groups. As many as 50 people are involved, to a greater or lesser degree, in OR work relating directly to the water sector. The list of publications at the end of this paper – which contains only those reports and scientific papers relating to cases of actual applications – is an indication of the extent to which OR has been used in Israel's water sector.

This paper is a review of these applications. I have tried to give a realistic assessment of successes and failures – one as devoid as possible from 'Wishful thinking', which, as a proponent of OR, I am likely to adopt. But this is not easy; the benefits derived from development and use of OR techniques are not all specific and visible. One cannot judge the benefits merely by observing whether or not a particular model is being used regularly for decision making. Models which failed in this respect may nevertheless have contributed very significantly to the decision making process, by educating everyone through the process of constructing and exercising the model, by pointing out important and/or irrelevant aspects, and even through the analysis of the reasons for the effort's failure.

The ensuing review is therefore a subjective analysis, by a water resources systems engineer with a strong conviction that OR techniques have an important practical role to play. It offers practitioners in other countries an account of our experience, which, it is hoped, will aid them in their own work.

2. Model hierarchy

From the foregoing discussion it is clear that the management problems in Israel's water sector cover a wide range. Obviously, it cannot be expected that a single model could address all these problems, and thus many models have been developed over the years. Some are so widely different, in terms of the problem they solve, that each operates quite independently from all others. At the same time, however,

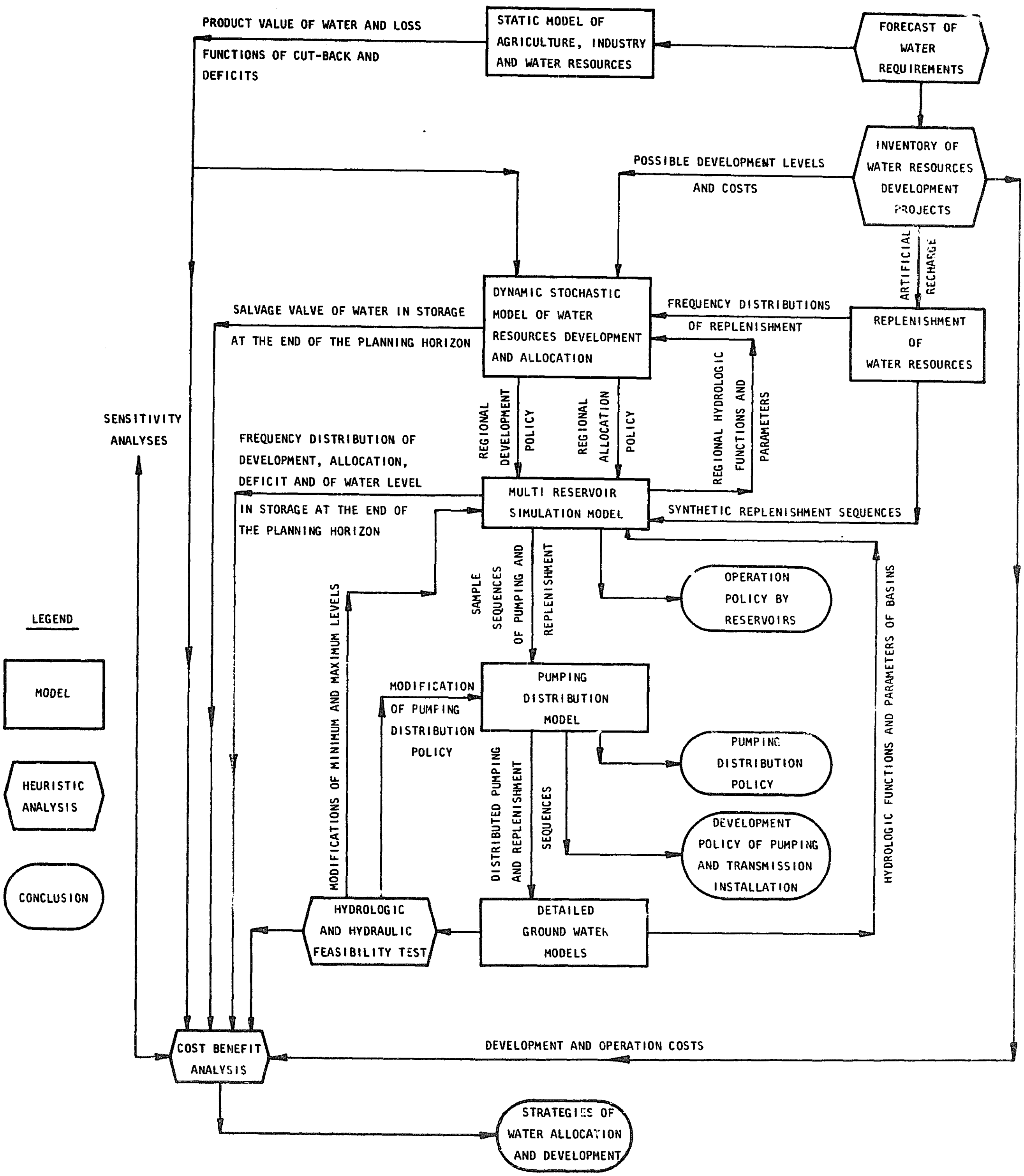

Fig. 2. The hierarchy of models.

there is a 'family' of models which are inter-related. These are models which deal with the national water system – either with the entire system or with some subset of its major components.

Models of the national water system differ from each other in the level of geographic and physical detail, the time horizon and its division into time periods, the objective function, etc. It is useful to view the models as belonging to a *hierarchy*, in which they are arranged in a 'vertical' order, as shown in Fig. 2. In the earlier days of model building we planned to construct a formal mathematical hierarchy of models, in which the individual models were actually linked, feeding each other with data and results in a programmed fashion. With further progress it became evident that building such a formal hierarchy is not warranted, because it would be too complex and unwieldy. A major effort would be needed to construct, maintain and coordinate the programs, the hierarchy would be too expensive to run on a regular basis, and the results would be very difficult to comprehend and interpret.

Still, we have retained the idea of a hierarchy, but more as a framework than a formal programming structure. The links between the models in the hierarchy are maintained essentially by the way the models are exercised, the use of common data bases and the use of results from one model as data for others. Each model in the hierarchy can be characterised according to the following list:

(a) Content: the part of the system with which the model deals;

(b) Time-scale: the time horizon covered, and its division into time periods;

(c) Outputs: the results produced by the model, and specifically the decisions which it is expected to provide;

(d) Internal constraints: conditions imposed explicitly within the model on the decisions and other variables;

(e) Directives: constraints imposed by the 'higher-up' models, which the model in question has to comply with as directives, even though it is clear that they actually represent objectives at a higher level and not 'real' (say, physical) constraints;

(f) Objectives: this is the 'driving force' of the model in question, and is a measure of how 'good' a solution is;

(g) Data: describing the state of the system at a point in time (e.g., network, storage, water quality), hydrology, demands, etc.;

(h) Frequency of use: how often the model has to be run, and the urgency with which its results are required;

(i) Algorithm: the hierarchy contains optimization models, using a number of optimization techniques, and simulation models.

Fig. 2 is one version (taken from [39]) of the model hierarchy. The following chapters will discuss in more detail some of the models, and explain how their use is integrated.

3. Models at the national economy level

Until the mid-1960's the supply of water to consumers was determined largely by the capabilities of the national water system. By the end of the 1960's the situation had changed. The national water carrier went into operation in 1964, and provided the means for integrating the entire system. The water systems could then extract and deliver more water than is available on a long term sustained basis. Problems of access to water which characterized the earlier period were now replaced by problems of shortage, a shortage expected to become more acute with time.

A linear programming formulation, based on an input–output model, was used to develop a policy of water allocation under conditions of scarcity (Chayat et al. [14]; de Button et al. [21]). The input–output model detailed 30 activities (4 in agriculture, 17 in industry and 9 in services), and four geographic regions. The decision variables are the allocations of water to each activity in each region i.e. some 120 allocations. The objective function is maximization of total income attributable to water. Constraints reflect the availability of water and of other resources – land, labour, capital – and the overall transport capability of the water systems. The results were viewed as a policy for minimizing the damages due to curtailment of supplies – a measure that had to be considered in light of the over-exploitation of the water potential and the predicted shortages.

A comprehensive study was undertaken at TAHAL, called "Study and Planning of the National Water System in Anticipation of Extreme Conditions Expected to Develop in the 70's and 80's". Many of the models discussed herein, and the hierarchial model structure, resulted from this work.

A stochastic dynamic programming model was developed to study the overall development of water supply to agriculture (Schwarz et al. [38,39]). The decision variables are total water supply to agriculture in each time-period of the planning horizon and the level of development of the overall supply capacity of the entire water system in each time period. Natural replenishment of the system's reservoirs, represented in the model by a single aggregate reservoir, was taken as a random variable with a known probability distribution. The objective function is maximization of present net benefit over the entire planning horizon, including a salvage value assigned to the water systems and to the water in storage at the end of the planning horizon. Constraints are: storage is to be within physically realizable limits, projected domestic and industrial demands are to be met before allocations to agriculture, supply cannot exceed the developed supply potential and must also be within bounds dictated by administrative considerations, development of the system's capacity is limited by the availability of funds. A hydrologic continuity function is also given, through which storage at the end of a time-period is related to the storage at the beginning, withdrawals, natural replenishment and losses.

The problematic aspects of this model are the assessment of benefits from water supply in agriculture, the damages due to curtailment of this supply and the salvage value of the water systems and of the water in storage at the end of the planning horizon. There is no agreement regarding the appropriate methods to be used in computing these values, nor are there adequate data to be used in their estimation. The effect of the salvage values can be reduced by taking a sufficiently long planning horizon. Other parameters which are uncertain are the interest rate, budgetary constraints, domestic and industrial demand forecasts and future availability of additional water, such as from reclaimed sewage. Still, the model has proven useful as a means of obtaining an optimal global policy for development of the water systems and supply to agriculture under any selected set of economic functions.

4. Models of the national water system

The national water system, as shown in Fig. 1, has three major reservoirs: the Kinneret and the two aquifers. These are linked by the national carrier, starting at the Kinneret, connecting some 25 regional water systems along its way, and reaching the Negev region in the South. The regional water systems contain wells in the two aquifers, used for pumping and/or recharge of groundwater.

Several models of the national system exist. They differ in their purpose, in the level of spatial and temporal detail, and in the algorithm used. We shall proceed from the longer-term, aggregate model, to the one with finer resolution in time and space.

Models dealing with the operation of Lake Kinneret and the aquifers need hydrologic data on the natural replenishment. Inflows into Lake Kinneret have been recorded regularly since 1928. Monthly water balances are computed, and the result is a table of net montly inflows (inflow plus precipitation on the Lake minus evaporation). These data have been used (Kahan [29]) to formulate a model for generating synthetic data. Each month's inflow is given by an autoregressive equation, with up to four monthly lags. The number of previous months retained in a month's equation is determined by the autocorrelation coefficients computed from the historical data. 900 years of synthetic data have been generated by the model and are accepted as the data base for all studies. Some adjustments in model parameters have resulted from incorporation of new data, and from discovery of certain of deficiencies in the old data.

The monthly net inflows into Lake Kinneret are also used as the basis for generating natural recharge sequences for the aquifers. Water balance studies were performed for the aquifers, using the period for which sufficient data are available. Cross-correlations between these inflows and the concurrent ones into Lake Kinneret were computed, and used as the basis for a model which generates a 900 year sequence of monthly inflows into the aquifers on the basis of Lake Kinneret inflows.

4.1. The multi-reservoir model

Shown schematically in Fig. 3, the model uses a highly aggregated representation of the national water system. There are three main reservoirs: Lake Kinneret, the coastal sand aquifer, and the Yarkon–Taninim limestone aquifer. The coastal aquifer is subdivided into two (and in some versions of this model into three) cells: a main storage cell, and an interface cell (a third cell is sometimes added between them, as a 'transition' cell). The interface cell represents a strip of 1–3 km width along the shoreline, in which the sea water intrusion is contained. Early formulations of the model (Amir and Kally [4]; Dalinsky et al. [16]; Dalinsky [17]; Gablinger [24]) contained only two or three main reservoirs. Later versions [27,38] subvided the coastal aquifer into two or more cells, and also

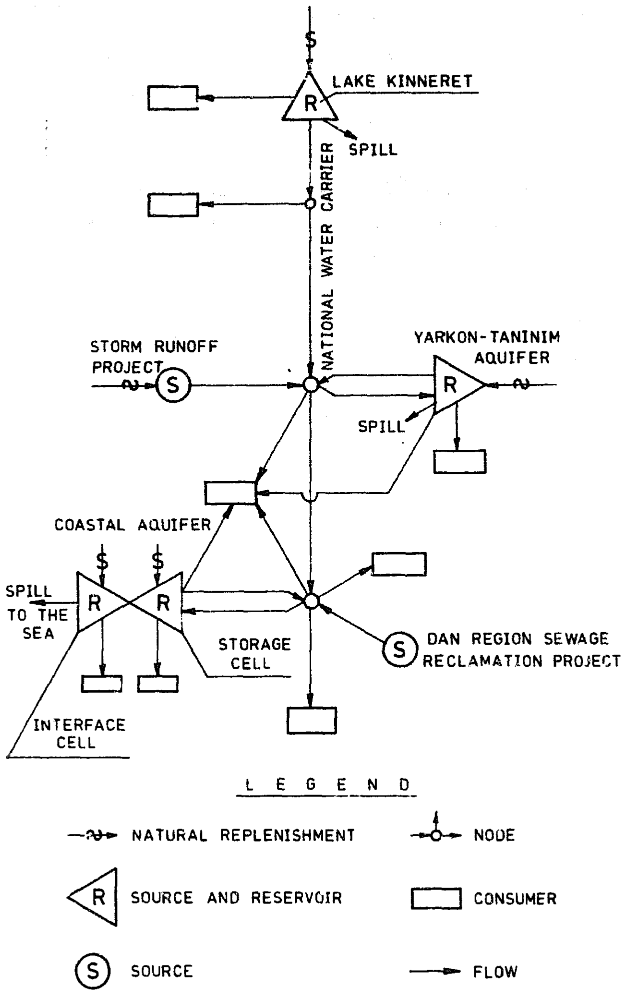

Fig. 3. The multi-reservoir model.

added several other features, e.g. the Dan sewage reclamation project. Because its early version had three reservoirs, it is often referred to as the Three-Reservoir Model.

The multi-reservoir representation of the national water system has been used both in an optimization and a simulation model. Amir and Kally [4] and Dalinsky [16] investigated the operation of Lake Kinneret and the aquifers, using simulation. Gablinger [24] developed a deterministic linear programming optimization model, for the three reservoir representation of the system, wherein the objective function is minimization of damages due to shortages in supply. Evaluation of the damage function, for various levels of curtailment of the supply was a crucial component of model formulation. Improvements in model formulation and in data were subsequently introduced. (Ringler and Galinger [36]), including consideration of sea water intrusion in the coastal aquifer, introducing flood water interception, reclaimed sewage and desalination as potential new sources, adding detail to the hydraulic system and refining its representation in the model, and improving the hydrologic data used for the natural replenishment of the reservoirs and demand forcecasts. The model gives the optimal policy for operating the system in each year of a 15-year planning horizon, assuming perfect knowledge of future hydrology (i.e. deterministic inflows). The model is run for a number of 15-year inflow sequences, using historical and synthetic data.

The performance of various operating policies was investigated with an improved version of the simulation model (Shweig [49]), with monthly time steps. Each policy is run with a number of 15-year synthetic inflow sequences, and the results are analyzed statistically. The simulation model, being more detailed and accurate in its representation of the physical systems than the LP model, can also detect whether a policy which is deemed feasible by the LP model is actually not. The optimization and simulation models are thus complementary: the optimization model is prescriptive, i.e. determines what to do, but somewhat approximate, while the simulation model is only descriptive, i.e. computes what happens if a policy is actually adopted, but more complete and accurate.

4.2. Annual operation models

The multi-reservoir model gives the total annual quantities of water to be taken from the Kinneret, to be pumped out of each aquifer and/or recharged into it, and to be moved in the hydraulic system. Below the multi-reservoir model in the hierarchy are models which determine how best to carry out these annual directives – if at all possible. There are a few such models, with different emphasis in each.

Mekorot Water Co. Ltd. is charged with operating the water systems. Every year a plan of operations must be prepared, giving the monthly quantities to be delivered from and to regional projects connected to the national water carrier, in the carrier itself and to the consumers. A model to aid in preparing this plan has been developed (Ytzhaki et al. [51]; Meyers et al. [34]) and has been some use. The model is fully operational, and is excercised by the OR group, but the manpower necessary to run and use the model regularly has not yet been found.

The model uses a rather detailed representation of the water distribution system, as seen in Fig. 4. Represented are the regional projects, the aquifers divided

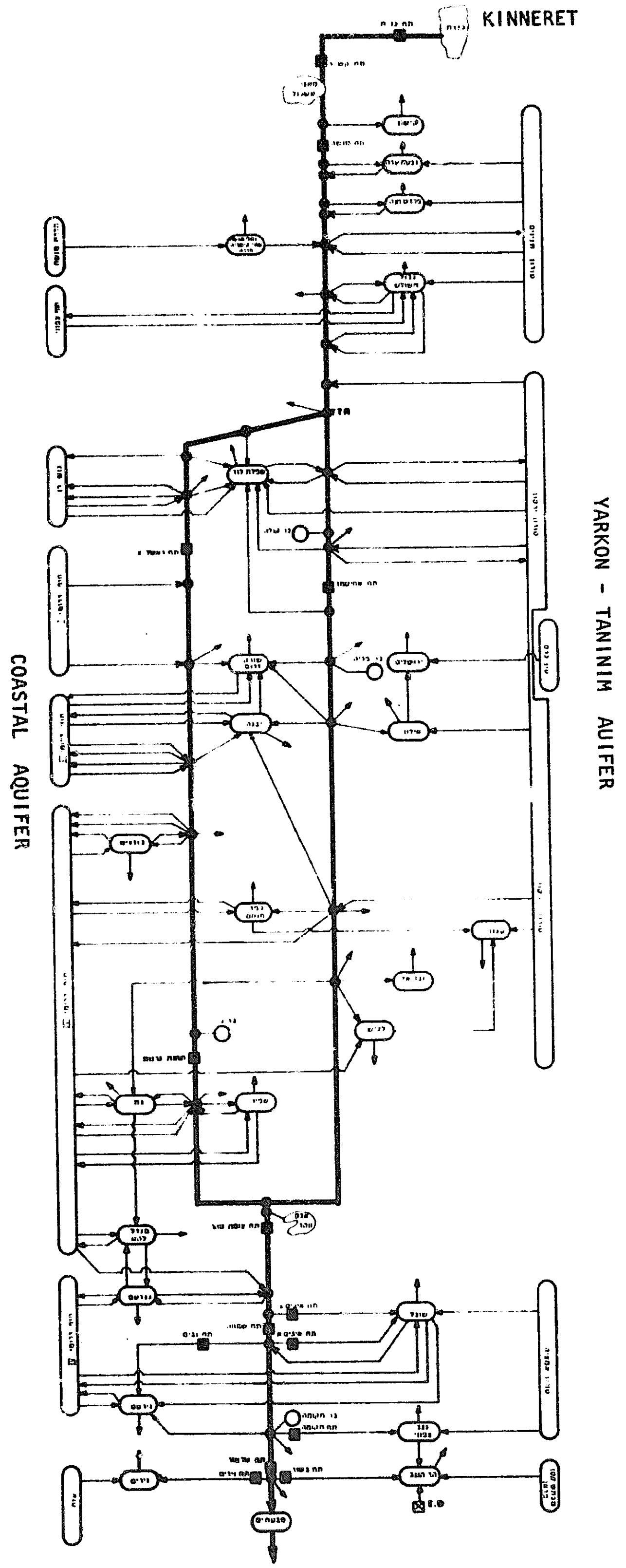

Fig. 4. The national water system.

into cells which belong to the regional projects, the main grid of the national water system and the consumers.

The time horizon is one year, and is divided into months. The decision variables are flows in all links – from and to regional projects, in the national carrier, from and to aquifer cells. Demands are fixed in advance, and have to be met. Total annual quantities of certain variables may be fixed, as given by the multi-reservoir model.

The model is cast as a linear program, with one of a few possible objective functions. One is a measure of how close the aquifer levels are to the ones dictated from 'above' either from the multi-reservoir model or from some hydrological analysis. This is a hydrologic objective function, and may not be well based on economic reasoning. Another is minimization of energy expenditures for pumping from the sources and in the distribution systems. Still another is maximization of the annual amount taken from the Kinneret, following the argument that this is the cheapest water and that any quantity not taken from the Kinneret may be totally lost to the national system through spill.

The constraints in the model represent the hydraulics of the distribution system and the hydrologic balance of aquifer cells. A major effort was involved in linearization of the hydraulics, to provide realistic and accurate constraints on the monthly quantities which are the decision variables. Salinity of the waters differ between the sources, and there are legal bounds on the salinity of water supplied to consumers. At one time the relatively high salinity of Lake Kinneret created a situation wherein mixing of other waters into the national carrier was a major operational consideration. Salinity constraints were therefore also incorporated into the annual operation model, again using an appropriate linearization procedure. Kinneret salinity has been reduced in recent years through the means mentioned in a previous section, and salinity considerations are much less prominent in the operational policy nowadays. The salinity constrains have therefore been made inactive in the annual operation model.

An extensive data base and program management structure have been developed for this model, using MPSX as the optimization package. The program can extract data from various operational files used by Mekorot for management, billing, etc., construct its own LP data, use previous LP solutions to start with a good basis and store the solution for further reference. The output is structured in formats useful and convenient to the operators of the water systems.

At TAHAL–Water Planning for Israel Ltd., more emphasis is put on the hydrology of the aquifers. Detailed models are used to investigate the feasibility of operating the aquifers within the year according to the directives given by the multi-reservoir model. Numerical models have been developed for this purpose (Blank [12,13]) and used extensively. The aquifer is divided into relatively small cells, say 3 km by 3 km, and the overall pumping and/or recharge quantities are distributed in time and space throughout the aquifer, taking into consideration the actual capabilities of the pumping, recharge and distribution systems.

There are simulation models, which have to be exercised iteratively, using experience and understanding of the aquifers to approach feasible operating policies and to improve them. An operating policy for the aquifers is expressed as rule curves, which give the pumping and recharge priorities between the aquifers as a function of average water level in each and of the time of year. These rule curves provide the 'driving force' in the simulation of the aquifers. The results are then analyzed to determine how the rule curves must be changed to meet the desired supply objectives.

These models do not contain an explicit representation of the hydraulic conveyance system. It's capacity, present or future, depending on which target year is being studied, is expressed as upper bounds on quantities moved from one point in the system to another.

The groundwater models are fully operational, and are being used in studies of the development and operation of smaller local aquifers as well.

At the Hydrologic Service of the Water Commission still another annual operation model is being studied. It is an attempt to combine detailed hydrology of the aquifers and an explicit representation of the hydraulic capabilities of the system. As in Mekorot's model, it is a linear programming optimization model, but the objective function is of a hydrologic nature. Target levels throughout the aquifers are set, considering long-range objectives – for example those from the multi-reservoir model – and hydrologic consideration based on evaluation of the current status of aquifer water levels and water quality. The objective function of this optimization model is minimization of some norm of the deviations between resulting water levels and their target values in all aquifer cells. To maintain linearity of the objective function the aquifer height is divided into increments, each with its value of the penalty to be assigned if the water level is in this interval, the penalties increasing with distance from the target. Constraints then have to be formulated with the decision variables being the interval in which the level lies.

4.3. Hourly operation model

An attempt to optimize the hourly operation of the national water carrier has failed. Much time and effort went into construction of this model, but when the programming and testing were completed it became obvious that the model is not viable, for computational reasons.

The model, studied at Mekorot Ltd., had as decision variables the operation of wells, pumps and valves on the national water carrier. The time horizon was one day, divided into time periods of one or possibly two hours. The optimization algorithm was a combination of multi-dimensional deterministic dynamic programming for each time period, combined into a heuristic branch-and-bound procedure which advanced the system in time. The stages in the DP were points along the national carrier, and the state variables were:

(a) pressure in the line,

(b) salinity of the water,

(c) the total quantity of water remaining for supply from the carrier in the current time period downstream from the point (stage) under consideration, and

(d) the total quantity of water to be pumped from local sources into the carrier in the current time period downstream from the point (stage) under consideration.

This four-dimensional DP is itself computationally expensive, and several attempts were made to reduce the computational burden through use of experience with the physical system and heuristic rules.

The single time-period model has now got to be 'marched-in-time', to cover the entire planning horizon of one day. A few, say three to five, of the best DP solutions which are closest to the optimum for the first time period are used as starting points for the next time period, providing it with initial conditions in terms of the state variables. For each such starting point there is a new DP to solve, from which several solutions are retained. Using these results of the DP's for the second time period, again only the best three to five are retained, and used as starting points for the next time period. The 'tree' of all possible solutions is allowed at each time period to branch out and is then 'pruned' down to a few remaining branches, based on 'local' criteria for goodness of the solution. Obviously there is no guarantee that this method does not eliminate branches which would later prove to be overall better than some other branch which was retained. Heuristic measures were developed in an attempt to increase the probability of going down the right path.

The idea was that the model would be run in this fashion for a day into the future, but only the results for the first one or possibly two time periods (hours) would be implemented. In the meantime, the model would be run again with updated data, and again only the results for the initial times would be implemented. Inclusion of the later time periods in the model was to make sure the actions taken would not be short-sighted, as would be the case if the DP were to optimize the hour's operation without regard to later consequences.

As stated earlier, when programming was completed and the model was actually tested it turned out that in spite of various 'tricks' to reduce computation time this mode of running the model was not feasible with the computational facilities at our disposal. The project was therefore abandoned.

5. Lake Kinneret operation

Lake Kinneret is the only large surface reservoir in the Israeli water system. It is located in the watershed of the Jordan River, some 210 meters below sea level. Its surface area is around 167 square kilometers and for the allowed operating range of 3 meters it provides an effective storage volume of 500 MCM. The net annual inflows average around 500 MCM, with considerable variability. The annual withdrawals from the Kinneret are: 350 MCM to the national water carrier, 100 MCM to consumers around the Lake, 25 MCM are released downstream into the lower Jordan to augment flows and meet international commitment, 20 MCM are flows of saline springs which used to flow into the Lake and are now captured and diverted around the Lake and into the Lower Jordan (some 60 000 tons of salts are thus prevented from entering the Lake, keeping the salinity below 250 ppm).

As early as 1963, even before the national carrier was completed, attention was given to operating policies for the Lake [22]. The model constructed viewed the national system as having two reservoirs – the Kinneret and the aquifers – connected through a single line with a single consumer, located in the South. The decision variables are the monthly quantities to be taken from each reservoir and supplied, and the demand to be met. Lake level was divided into regions, and an analytical optimization procedure was developed by which the total annual cost of pumping was minimized. Rule curves were constructed, which give the optimal pumping schedule as a function of the time of year and lake level. A dynamic programming optimization model was also proposed, but was not implemented because computer facilities were not available at the time.

The next study of the Kinneret was concerned with optimal spill policies in the winter months [50]. If lake levels are high at the beginning of winter, then large inflows may result in flooding and damages around the lake and along the Jordan River downstream. On the other hand, the water in the lake is a valuable resource and should not be spilled unnecessarily. Difficulties arise in combining damages and the value of water in storage into a single objective function, and therefore the objective function was defined as minimization of the expected spills throughout the winter season subject to a constraint on the probability that flooding will occur.

By this time a computer was already available. A stochastic dynamic programming model was developed, based on a 5-day time interval and covering the entire winter season. This rather fine time-resolution is necessary because floods take place over a few days and a longer time period would not provide an adequate definition of the flow phenomena. The decision variable is the amount to be spilled at any data as a function of water level. Extensive statistical analysis was needed to provide the probabilities used in the model. The model was further refined and improved in subsequent years (Dalinsky [15]), yielding rule curves for water level control before and during the winter season. This policy is called ON–OFF because it gives the levels above which all water is to be spilled (ON) and below which nothing is to be spilled (OFF). While it is indeed important to have this operating policy for spilling, most of the time the situation is that levels are too low rather than too high. Only during the winter of 1968/1969 did flooding occur and some damage resulted. The situation has not repeated since then.

Optimal policies for pumping from the Kinneret were studied again in the early 1970's (Gablinger et al [26]; Kahan and Gablinger [30]), as shortage became more pronounced throughout the water system. A stochastic dynamic programming model was used, wherein the decision variables are the quantities to be pumped to the national carrier in each month as a function of lake level at the beginning of the month and the inflows in previous months (because inflows are serially correlated). The objective function is maximization of total benefit from water supplied over the year. A steady–state operating policy was sought, and the DP solution was iterated until it converged. Two versions of the model were developed: one in which it is assumed that at the beginning of the month the inflow in that month is known in advance and the other without this knowledge. Constraints in this model include spills according to the ON–OFF policy developed in the study mentioned above, local supplies to be met and the pumping capacity of the national water carrier.

The optimal policies from this model were examined [30] to yield probability distributions of Kinneret levels under these policies.

A detailed simulation model of the Kinneret has been developed at Mekorot (Meyers and Shamir [33]) and is being used regularly. Several times during the year, as often as once every few weeks during critical periods, the simulation model is run to examine proposed operating policies. In addition, the model is used to investigate plans for augmenting the pumping capacity of the national water system. The model is based on a two week time period, and uses selected sequences of inflows into the Kinneret, both the historical data and segments of the 900-year synthetic data mentioned in a previous section.

The model is simple and easy to run. It is therefore exercised quite regularly, to answer specific operation and planning questions which are posed. The model first computes the behaviour of the Kinneret under the assumed plan and/or operating policy, and then carries out a statistical analysis of the results – water levels, spills, water supplied, etc. Pumping cost computations have been added to the hydrologic simulation, and allow economic comparison of proposed plans. A recent study was concerned with the best way to augment pumping to the national system. Two basic options exist:

(a) install a fourth pump, with a capacity of around 9 m^3/sec, in the main pumping station on the Lake, or

(b) operate the existing pumps more hours during the day and pay the higher energy costs charged during these times of peak energy consumption in the country.

The simulation model was the main tool in determining that installation of an additional pump (deferred by several years during which some high cost energy will be used) is the better option.

6. Aquifer management

Since the aquifers are such an important component of the Israeli system, which act as both sources and operational reservoirs, special attention has been devoted to special models for their management. The numerical models of aquifer flow mentioned in a previous section are designed to examine in detail the hydrologic regime resulting from a proposed pumping and recharge program. In addition to these methods, which merely describe the aquifer's behaviour and do not attempt to yield an optimal policy, there are optimization models.

A management model, which optimizes the operation by linear programming (Schwarz [40]), uses a multi-cell model. The decision variables are pumping and recharge in each cell during each time period – usually a season or a year – over a given planning horizon. The constraints are the hydrologic continuity equations of all cells, bounds on water levels and on the amounts which can be pumped or recharged. The objective function is minimization of operating costs. These models have not yet become an integral part of the methods used regularly for operating the systems.

7. Development of regional systems

A multi-objective model has been developed for determining the development plan of a regional water system [2]. It is a linear program with six objectives:

(a) min. total cost,

(b) min. operating costs,

(c) max. net benefit,

(d) max. employment in agriculture and industry,

(e) min. import of water to the region from the national water carrier, and

(f) max. utilization of sewage in the area.

The model considers two types of water – potable and sub-potable – delivered via separate networks to consumers – domestic, industrial and agricultural. The decision variables are: additions to the existing capacity of the sources and of the distribution system and the quantities to be supplied to the 'productive' consumers (all but domestic).

An iterative procedure, based on a modification of the STEM method (Benayoun et al. [11]), allows the analysts, interest groups and decision makers to interact and articulate progressively their preferences and compromises in response to results generated by the procedure at each interaction. The compromise solution is approached through this process, which emphasizes the role of communication between the participants and is based on easily understood results generated by the analysis at each iteration.

The model was used to develop a plan for a large regional system in the arid area of the Negev in the South of the country. It is presently being used for a region in the North-West.

8. Design and operation of distribution systems

The water sector is the largest consumer of electrical energy in Israel. Much of the water supplied requires 2 KWH/m^3 and more for pumping by the time it gets to the consumers. With the rapidly escalating cost of energy this becomes a major expense. General scarcity of energy is an added incentive to save energy. At Mekorot, the company charged with operating the systems and delivering the water, a continuing effort is devoted to finding means for saving energy through improved operation, design changes, automation and control.

A simulation model of regional water distribution systems (Dreizin [23]) was used to determine improved control routines, which result in energy savings. The model is based on a hydraulic network solver and a control routine which simulates the operation of the control equipment in the actual system – electrical set points installed in reservoirs, which control the operation of pumps. The model was used in a systematic search for energy efficient settings.

The results obtained for the particular water system which was studied indicated that the potential savings are around 10% of the 'dynamic energy' – that part used to overcome resistance to flow in the system, as distinct from the 'static energy' needed to overcome geodetic difference between source and destination. A survey of the regional water systems shows that dynamic energy is around 20% of the total, and so the potential for energy saving is around 2% of the total. Even this seemingly low saving is worth while, because the total energy bill is very substantial

A special simulation model was developed to derive optimal operating policies for the top section of the national water carrier – the 40 km section starting at Lake Kinneret and including the two main pumping stations (Damelin and Shamir [19]). This section contains open channels, closed conduits and a balancing reservoir, and so a special purpose hydraulic simulator had to be developed.

Reliability considerations in water systems were studied by a stochastic simulator of regional water systems (Damelin et al. [18]). The stochastic events are failures of pumping equipment and of electrical supply.

Optimal timing for overhaul and/or replacement of pumps and of pipes was determined by an analytical procedure applied to an economic model of expenditures (Shimron et al. [47]). The procedure provides the means for examining the extensive population of pumps and pipes in the water systems and arranging them in order of priority for replacement, overhaul of pumps, cleaning and lining of pipelines. Lack of manpower to use the system has prevented its implementation.

The hydraulic simulators are being used regularly to investigate operations and proposed design changes in existing systems. An optimization method has been developed more recently (Alperovits and Shamir [3]) to deal with the design. The optimization is based on a two-level hierarchy. At the lower level the design is optimized by an LP model for assumed flow distributions in the network under each of a number of demand 'loadings'. This optimization also determined the operation (pumps, valves) under each of the loadings. At the higher level of the hierarchy the flow distribution is modified, using the duals and some additional information from the LP, in such a way that the optimal solution for the new flow distribution is better than for the last. The methods is currently used at TAHAL for designeng new systems and additions to existing ones.

9. Conclusion

The foregoing survey does not cover all of the developments and applications of OR in Israel's water sector. It concentrates on those cases where the effort has had some impact on the decision making process. It is hoped this survey will provide practitioners in other countries a case study and some ideas which will aid them in their own work.

References

Note: Material in Hebrew is denoted (H). All other material is in English.

[1] D. Alkan and J. Schawrz, Optimal operating policies for the Yarkon–Taninim aquifer, P.N. HG/70/01, TAHAL (1970) (H).
[2] D. Alkan and U. Shamir, Multi-objective planning of the Har-Ha'Negev water system, P.N. 1/77, Water Resources Research Center, Technion (1977) (H).
[3] E. Alperovits and U. Shamir, Design of optimal water distribution systems, Water Resources Res. 13 (6) (1977) 885–900.
[4] R. Amir and E. Kally, A model of the national water system used for planning its operation, P.N. 355, TAHAL (1963) (H).
[5] Anon, Water in Israel 1962–1976, Allocation Department, Water Commission, Israel Ministry of Agriculture (1978) (H).
[6] S. Arlosoroff, Israel – A model of efficient utilization of a country's water resources, Paper presented at the United Nations Water Conference, Mar del Plata, Argentina (1977).
[7] M. Avron and A. Mercado, Optimization of pumping and transport in the coastal region under quality constraints, P.N. 01/78/56, TAHAL (1978) (H).
[8] J. Bargur and M. Gablinger, Temporal distribution of water allocation in agriculture, P.N. HR/72/020, TAHAL (1972) (H).
[9] J. Bargur and J. Vanunu, The economic value of water in agriculture – estimation of marginal productivity and of damage to the national economy due to reductions in supply, P.N. 01/75/01, TAHAL (1975) (H).
[10] J. Bear and O. Levin, Optimal utilization of an aquifer as an element of a water-resources system, Project No. A.10-SWC-54, Technion (1968).
[11] R. Benayoun, J. de Montgolfier, J. Tergny and O. Laritchev, Linear programming with multiple objective functions: Step Method (STEM), Math. Programming 1 (3) (1971) 336–375.
[12] D. Blank, Multi-aquifer simulation system (MASS), P.N. 01/78/25, TAHAL (1978).
[13] D. Blank, Aquifer simulation system (AQSIM), P.N. 01/78/24, TAHAL (1978).
[14] M. Chayat et al., Integrated planning of Israel's water resources and agriculture, P.N. HR/72/102, TAHAL (1972) (H).
[15] P. Dalinsky, Optimal operating policy of the Kinneret by the ON–OFF method, P.N. HR/72/051, TAHAL (1968) (H).
[16] P. Dalinsky et al., A simulation model of the Kinneret–Turon system, P.N. 744, TAHAL (1969) (H).
[17] P. Dalinsky, A simulation model of the Three-Reservoir System, P.N. HR/71/057, TAHAL (1971) (H).
[18] E. Damelin, U. Shamir and N. Arad, Engineering and economic evaluation of the reliability of water supply, Water Resources Res. (4) (1972) 861–877.
[19] E. Damelin and U. Shamir, Optimal operation of the pumping stations in the Kinneret-Eshkol section of the national water carrier, J. Hydrology 28 (1976) 271–288.
[20] P. Dar, The evaluation of marginal waters as a natural resource, P.N. 01/76/46, TAHAL (1976) (H).
[21] M. de Button, J. Bargur and M. Gablinger, Analysis of the national economy under a policy of reduction in water supply, P.N. 01/74/09, TAHAL (1974) (H).
[22] B.V. Dean and N. Buras, Effective control and economical scheduling of Lake Kinneret pumping operations, P.N. 282, TAHAL (1963).
[23] Y. Dreizin, N. Arad, U. Shamir and H. Matmon, Evaluation of the potential for energy saving in regional water systems, R.N. 131.105, Mekorot Water Co. (1971) (H).
[24] M. Gablinger, A three-reservoir optimization model of the national water system, P.N. HR/72/089, TAHAL (1972) (H).
[25] M. Gablinger, J. Schwarz and Y. Vardi, Use of systems approaches in planning Israel's water resources management, Internat. Symp on Water Resources Planning, Mexico (1972).
[26] M. Gablinger, J.P. Kahan and Z. Ringler, Optimization model for monthly pumping from the Kinneret, P.N. 01/74/49, TAHAL (1974) (H).
[27] M. Gablinger, Simulation in hierarchial modeling of water resources, in: G.C. Vansteenkiste, Ed., Modeling Identification and Control in Environmental Systems (North-Holland, Amsterdam, 1978) 843–855.
[28] S. Gal, Optimal management of a multi-reservoir water supply system, Technical Report 051, IBM Israel Scientific Center (1977).
[29] J.P. Kahan, Generation of monthly inflows into Lake Kinneret and Yarmouk River, P.N. 01/74/12, TAHAL (1974).
[30] J.P. Kahan and M. Gablinger, Probability distributions of Kinneret levels under optimal policies and expected pumping and spill based upon them, P.N. 01/75/30, TAHAL (1975).
[31] D. Koniak, Optimal operating policy for the Kinneret, P.N. 7/68, TAHAL (1968) (H).
[32] O. Levin, Optimal control of a storage reservoir during a flood season, Automatica 5 (1969) 27–34.
[33] S. Meyers and U. Shamir, Effect of increasing the pumping capacity to the national carrier on operation of the Kinneret, R.N. 231.240, Mekorot Water Co. (1975) (H).
[34] S. Meyers, U. Shamir and N. Meidad, Optimal annual operation of the Israel national water supply system, P.N. 231.254, Mekorot (1979) (H).
[35] A. Reiter and U. Shamir, Optimal operation of the Kfar–Baruch reservoir, R.N. 231.207, Mekorot Water Co. (1972) (H).
[36] Z. Ringler and M. Gablinger, A multi-reservoir optimization model for the nationa system, P.N. 01/73/44, TAHAL (1973) (H).
[37] J. Schwarz, Strategy and management techniques for the integration of groundwater resources in regional planning, Proc. Mexican–Israeli Workshop on Water Utilization and Management, Mexico City (1974).
[38] J. Schwarz, E. Kally and J.P. Kahan, A stochastic dynamic programming model for determining optimal development and allocation policies and for forecasting storage levels in the Israeli water sector (LOTDP), P.N. 01/74/54, TAHAL (1974) (H).
[39] J. Schwarz et al., Models of the national water system – interim conclusions about the system's development and operation, P.N. 01/76/54, TAHAL (1976) (H).

[40] J. Schwarz, Linear models for groundwater management, J. Hydrology (1976) 377–392.
[41] J. Schwarz et al., The use of mathematical models for groundwater in TAHAL, P.N. 01/78/22 and 23, TAHAL (1978) (H).
[42] J. Schwarz, Controlled mining of groundwater, in: G.C. Vansteenkiste, Ed., Modeling Identification and Control in Environmental Systems (North-Holland, Amsterdam, 1978) 856–872.
[43] Z. Shalev and J. Schwarz, Operation of the reservoirs in the national water system under stable conditions, P.N. 01/74/73, TAHAL (1974).
[44] U. Shamir, Optimizing the operation of Israel's water system, Technology Rev. M.I.T. (June 1972) 41–48.
[45] U. Shamir, Mathematical methods applied to practical problems of water resources systems engineering, Proc. Mexican–Israeli Workshop on Water Utilization and Management, Mexico City (1974).
[46] U. Shamir, Water research in Israel – achievements and potential, KIDMA 3 (2) (1977) 11–15.
[47] Z. Shimron, N. Arad and U. Shamir, Optimal timing for renewal of pumps, R.N. 1602, Mekorot Water Co. (1970) (H).
[48] Z. Shimron and U. Shamir, Short range forecasting of water demands, Israel J. Technology 11 (6) (1973) 423–430.
[49] J. Shweig, An improved simulation model of the national water resources system P.N. 01/73/39, TAHAL (1973) (H).
[50] K. Yosupovits, Optimal control of releases from the Kinneret in winter, P.N. 1/67 TAHAL (1967) (H).
[51] Y. Ytzhaki et al., Engineering-economic analysis for development and operation of the national water system, R.N. 1604, Mekorot Water Co. (1972) (H).