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Management of regional multiple quality water supply systems

URI SHAMIR
Faculty of Civil Engineering, Technion - Israel Institute of Technology, Haifa 32000, Israel

ABSTRACT Models for planning, design, and operation of regional water supply systems are used to yield the capacity expansion and seasonal operation of sources, treatment, storage and conveyance facilities which deliver water to consumers. We focus on regions with sources of different qualities, in which consumers are able to use water of various qualities. The result is a multiple quality water supply system. Quality considerations appear in either the constraints of the management model or in the objective function, or in both. In order to maintain a tractable dimensionality of the model, it can either allow only a small number of quality parameters, or one must combine several parameters into "quality indices". Quality considerations introduce nonlinearities into the management model. If one seeks to use linear programming, then approximations must be used. Several examples of modelling for management of regional multiple quality water supply systems are described. Emphasis is placed on the approach and methods for incorporating quality considerations in these optimization and simulation models.

Aménagement et exploitation d'un système régional d'alimentation en eau de qualités variées
RESUME Les modèles pour planifier, projeter et exploiter les systèmes d'alimentation régionaux sont utilisés pour produire l'expansion de la capacité de production et l'exploitation saisonnières des sources d'alimentation en eau, le traitement des eaux, leur mise en réserve, les structures pour acheminer ces eaux et les livrer au consommation. Nous travaillons plus particulièrement sur des régions avec des ressources en eau de qualité différentes où les consommateurs peuvent utiliser des eaux également de qualités différentes. Le résultat est un système de fourniture d'eau de qualités différentes. Les considérations de qualité des eaux apparaissent soit dans les contraintes du modèle d'exploitation, ou dans la fonction objective ou dans les deux. Afin de conserver au modèle des dimensions qui permettent pratiquement de le mettre en oeuvre, il peut soit: admettre seulement un petit nombre de paramètres de qualité soit combiner plusieurs paramètres en "indices de qualité". Les considérations de qualité introduisent la non linéarité dans le modèle d'exploitation. Si on cherche à utiliser la programmation

linéaire on doit utiliser des approximations. On décrit plusieurs exemples de modèles pour l'exploitation de systèmes régionaux d'alimentation en eau de qualités variées. On insiste sur l'approche et les méthodes pour incorporer des considérations de qualité dans ces modèles de simulation et d'optimisation.

INTRODUCTION

We focus attention on regional water supply systems in which water quality plays an important role. Consider an area, typically several hundred square kilometres, in which there are a number of consumers and sources. The consumers - domestic, industrial and agricultural - need water, and may be able to use waters of different qualities, either in a blend or as separate quantities of the various qualities. These demands may be considered given, as exogenous variables in the analysis, and are then expressed as fixed values. Otherwise, they may be decision variables, so that their magnitude is to be determined as part of the analysis.

A separation of the supply by quality is obviously necessary only if there exist sources of different qualities. These may include, for example: fresh groundwater, (here, too, we find sometimes large variations in quality), brackish groundwater, surface waters of various qualities, reclaimed sewage at different treatment levels, desalinated brackish groundwater or sea water.

There are basically three ways for dealing with waters of different qualities in regional systems:

(a) treating all waters, at their sources, to a common quality, and then having a single-quality distribution system,

(b) blending waters of different qualities, to meet quality constraints at the consumers' nodes,

(c) separate supplies of different qualities, meeting components of the consumers' demands by the appropriate water - separately, or as a blend.

Water quality is a vector of parameters, relating to its bacteriological, chemical and physical properties. Choice of the quality parameters appropriate for the system under study may be a complex problem, which will be considered in the following section. In principle, we may separate the quality parameters into two categories:

(a) Parameters for which maximum limits are given, possibly different limits for the various uses of the waters. These limits are not to be exceeded, and no cost or benefit information is given for exceeding these values or dropping below them. This is typical for standards on potable water quality, but similar situations may arise for chemical and physical properties of water for industrial or agricultural use.

(b) Parameters which determine the value of the water, usually in economic terms, but sometimes in terms of the water as a habitat for wildlife, for recreation, etc. Limit values may also be given in these cases, but what characterizes the situation is that losses resulting from exceedance of these limits, and/or benefits from reducing concentrations below them, are given, and these are used as a component in the objective function.

Management of regional multiple quality water supply systems may

be performed as one of three cases:

(a) cost minimization, under constraints which specify that demands are to be met and that quality is to be within the given limits;

(b) benefits maximization, with the quantities and/or qualities of water supplied as decision variables. Benefit and cost of water quality data must be available for such an analysis;

(c) trade-off between costs, benefits and quality criteria.

In the next section we discuss the issues of selecting water quality parameters, defining appropriate quality indices for water resources management models, and for including quality as constraints and/or objectives in such models.

The following section then contains several examples of regional multiple quality water supply systems, in various countries. Emphasis is placed on the approach taken to the quality issue in the overall water management situation, and the methodologies used.

Conclusions drawn from these experiences are presented in the final section, which also contains recommendations pertaining to methodologies for analysis and optimization of multiple quality water systems.

WATER QUALITY: PARAMETERS, INDICES, OBJECTIVES

A complete specification of water quality requires many parameters. Water quality standards list dozens of parameters, and fix limits on their values for different uses of the water. In the sources of one region it is sometimes possible to find waters of widely varying qualities. Thus the quality is an important factor in determining which sources are to be developed, how the conveyance and distribution system will be constructed, and the treatment to be given to waters from the various sources.

For models of regional water resources management it is necessary to select a relatively small number of quality parameters. It does not seem feasible to consider explicitly, for a planning analysis, the full list of quality parameters which exist in the regulations. It also does not seem necessary to do so. A limited list of the most important parameters, can be considered. These will play an *explicit* role in determining the plan, the design and the operation of the water supply system. The remaining parameters will, so to speak, "take care of themselves". By this we mean that the system will be able to meet the standards on these parameters - either by the treatment and other facilities determined in the solution of the reduced (with respect to the parameter list) problem, or by adding some facilities to deal with these parameters, facilities which are "marginal" in that they do not alter the overall solution.

How many parameters should be in the basic list? This depends both on the quality issues in the region and on the management model to be used.

We are quite accustomed to river water quality models in which BOD and DO are the only parameters (Loucks *et al.*, 1981, chapters 9 and 10; Beck, 1978a) and lake water quality models in which nitrates, and sometimes phosphates, are the only parameters (Loucks *et al.*, 1981, sections 9.6 and 10.5; Howard & Shamir, 1976).

This is done in situations where there may be many more quality parameters of concern, but the ones selected are felt to be the most crucial and/or the ones which determine the solution.

Another approach is to combine a number of quality parameters into a single index. In the IODZH study (drinking water supply for the Province of South Holland, discussed later) two quality indices were defined. Each was computed by a simple linear equation, combining in one 12 and in the other 14 quality parameters, as listed in Table 1. The general water quality index IK is computed as follows:

$$IK = 1 - \Sigma_{i=1}^{12} W_i \frac{N_i - \mu_i}{N_i} \qquad (1)$$

where:
W_i = weight of the i-th parameter ($\Sigma W_i = 1.0$),
N_i = standard value,
μ_i = mean value in the water under consideration.

This index is applied to waters after treatment, in which the mean concentration of each parameter, μ, is always lower than the value set by the standard, N. Therefore, IK is always between 0 and 1. For situations where $\mu > N$ is possible, a different formula for IK must be devised.

TABLE 1 Parameters and weights for the quality and public health indices in the IODZH study

Quality index - IK		*Public health index - IV*	
Parameter	*Weight*	*Parameter*	*Weight*
Temperature	*0.0303*	*Viruses*	*0.1213*
Color	*0.0279*	*Clostridium botulinum*	*0.0647*
Total hardness	*0.0371*	*Toxin forming algae*	*0.0525*
TOC	*0.1114*	*Haloforms*	*0.0709*
Suspended solids	*0.0346*	*Other halogens*	*0.0907*
Natrium (Na^+)	*0.0512*	*Polycyclic aromates*	*0.0520*
Fluor (F^-)	*0.0667*	*Organic nitrogen compounds*	*0.0774*
Total phosphate (P)	*0.0192*	*Genotoxins*	*0.1470*
Ammonium (N)	*0.0654*	*Radioactivity*	*0.0506*
Nitrate (N)	*0.1067*	*Taste and smell*	*0.0420*
Cadmium (Cd)	*0.2307*	*Cadmium*	*0.0737*
Lindan	*0.2189*	*Faecal coli*	*0.0701*
		Natrium	*0.0410*
		Nitrates	*0.0437*

A low value of IK means good water quality. The overall water quality index in the region, for a given water supply plan is computed by:

$$TIK = \Sigma_{k=1}^{K} IK_k * Q_k \quad (2)$$

where:
IK_k = quality index for the k-th supply (after the water treatment plant, where relevant),
Q_k = quantity supplied by the k-th source.

The other index has to do with public health. It is called the "public health reliability index", and is computed as follows:

$$IV = 1 - \Sigma_{j=1}^{14} W_j C_j \quad (3)$$

where:
W_j = weight of the j-th parameter ($\Sigma W_j = 1.0$),
C_j = relative concentration of the j-th parameter.

The overall public health reliability index, TIV, for the region is computed similar to TIK in equation (2).

The weights are given by a group of experts in consultation with the water resources analysts, using an appropriate technique such as the Saaty method (Saaty, 1980). The weights shown in Table 1 should be viewed as an example, not as a definite and final statement of the opinions which prevailed in the IODZH study.

Equations (1), (2) and (3) are based on the assumption of linear additive utility (or, rather: disutility). This has the advantage of generating a quality index which is easy to formulate and to comprehend. The disadvantages are that linear additivity may miss important features of the quality issues - notably the case when the index is low, i.e. quality is acceptable, although one particular contaminant has a high concentration and the quality is therefore not acceptable. Proper weights are supposed to take care of some of this; however, because the weights are given by the experts under "normal" conditions (i.e. relatively low concentrations) the resulting index may not "perform" well when more critical concentrations of certain contaminants are encountered.

Another approach altogether is to leave the water quality unspecified, in terms of its parameters, and merely give it a general tag of "potable", "sub-potable", "non-potable", etc. This is the approach taken in the WESTON study (WESTON, 1977) and by Alkan & Shamir (1980). The supply system may contain water treatment plants, which convert water from one "type" to another, or deliver water directly to consumers, either of a single "type" or as a blend. The detailed water quality characterization and the exact nature of the treatment processes are not present in the model. They are represented via the aggregate "type" index and appropriate cost functions for treatment.

For domestic and industrial uses it can always be assumed that the necessary treatment will be introduced. The problem of finding the least cost system remains, but there is no question that the quality standards will be met, by treatment. For agricultural uses and for many non-consumptive purposes, such as river habitat and recreation, water quality may be a decision variable. Salinity and nutrient concentrations are typical parameters in such cases (Yaron, 1981; Howard & Shamir, 1976). Benefit functions for water quality

are difficult to obtain, and their validity is often restricted to specific locations and limited in time.

In simulation models it is feasible to deal with several quality parameters, individually or grouped into indices, as explained earlier. If an optimization model is to be used, the dimension of the quality parameter vector is a crucial determinant of the model's viability. A multiple quality model is actually a multiple commodity system, if we have to track the quality parameters through the treatment, storage and distribution facilities. It does not seem feasible to do this for more than very few - probably no more than two or three - quality parameters. This seems to be the state of the art, and is not expected to change in the coming several years and probably longer. As was already stated in the opening of this section, models which contain only two or three quality parameters may be perfectly adequate for general water resources management modelling.

A recommended approach is to optimize with few quality parameters, then simulate with more parameters (RID, 1981; Bresser & Pluijm, 1981). The simulation serves to check whether the "secondary" quality parameters are within their limits (if such must be met) and/or to determine what kind of treatment processes and attendant costs are involved in meeting their standard values.

When the quality of the water supplied to customers is a decision variable in the model, the issues of benefit and damage as a function of quality must be faced. This is a difficult issue. One way of overcoming the difficulty is to set quality standards which are not to be exceeded, and assume that quality variations below this threshold have negligible effect on the "productivity" of the water in its use. This is analogous to management models for water quantity in which the demands are fixed and the objective is to meet them at least cost.

Setting the threshold values, unless it is anchored in well established standards, is somewhat arbitrary, The threshold values will determine, often to a very great extent, the selected plan and its cost. The question is then raised whether some relaxation of the quality requirements, as long as they remain within the legal standards - when such exist for the specific parameters considered - would not be "better" in some sense. That is, would the savings in cost more than compensate the constituencies involved (the direct consumers of water, the neighbouring residents, society as a whole) for the losses - economic and/or other - due to reduced quality. Curves of cost *vs.* degree of treatment typically show a steep rise as the degree approached full removal, as shown schematically in Fig.1.

Treatment facilities should probably operate somewhere between the flatter part of the curve, where the incremental cost for additional treatment is modest, and the steepest part near full treatment. Setting quality thresholds arbitrarily, without considering the cost functions, may lead to a solution which is either inefficient or unreasonably costly.

The best way would be to have benefit or loss *vs.* quality functions for the consumers. The outcome would then be an optimal system which considers all costs and benefits, both on the demand and supply sides.

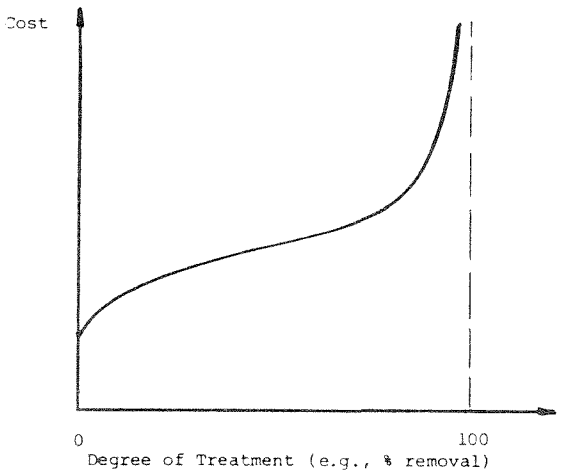

FIG.1 Cost vs. degree of treatment (schematic).

Some data are available on the effect of salinity in agriculture (Hexem & Heady, 1978; Bernstein, 1981; Fishelson & Tolley, 1981; Yaron *et al.*, 1982) but little exists for other uses of water. For recreation, Barnea *et al.* (1976) constructed a utility function for recreational benefits, expressed in monetary units *vs.* water quality in a river. Some assessments have been made of the health risks of water pollution (Office of Technology Assessment, 1981), but their explicit incorporation - in economic terms - in the decison-making process is not well established (Weinstein *et al.*, 1980) and may never be.

This leads to the more general approach of considering quality as a separate objective, in a multiobjective analysis. Quality does not have to be converted into costs and benefits, in monetary units, which are then combined into the single objective of economic efficiency. Quality is expressed in its own units - concentrations or total quantities - and represented as one or more (for several quality parameters) objectives. The multiple objective management model is then used to investigate the trade-offs and aid in the decision-making process. Howard & Shamir (1976) considered land and water use in a region with several lakes, in which nitrate and phosphate concentrations in the lakes are important, by this approach. Shamir *et al.*(1984) used such a multiobjective model for optimal operation of a regional coastal aquifer, in which water quality, expressed by the concentration of some unspecified conservative pollutant, is one of the four objectives (the others being: cost, energy, sea-water intrusion). Alkan & Shamir (1980) developed a multiobjective model for capacity expansion and operation of the sources and two conveyance networks, each carrying a different quality. The quality objective was maximization of sewage utilization, which, in the land-locked desert region which was analysed, means reduction in environmental damages. In the IODZH study (RID, 1981; Bresser & Pluijm, 1981; Shamir, 1983), the objectives are: cost, water quality (equations (1) and (2) above), public health reliability (equation (3)), damage to nature due to water projects and to water quality, reliability of supply, energy consumption.

MODELS AND EXAMPLES

Drinking water supply for the Province of South Holland

Consider a region in which there are a number of water sources and consumers. Figures 2 and 3 show the Province of South Holland, in

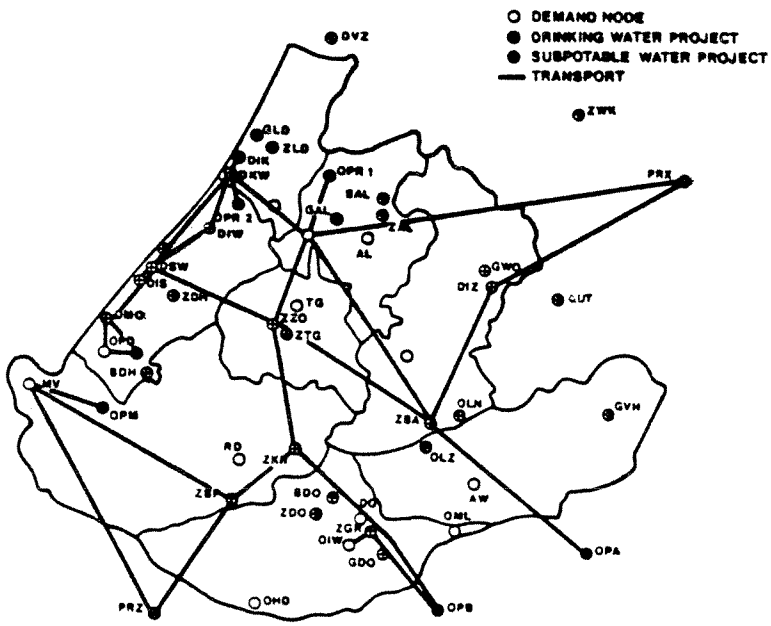

FIG.2 Province of South Holland: sub-potable water system.

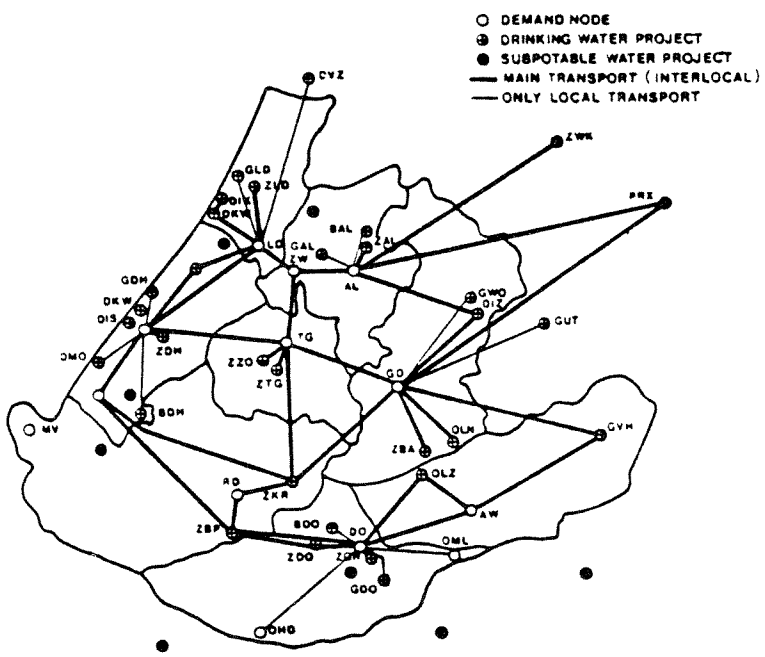

FIG.3 Province of South Holland: drinking water system.

the Netherlands, an area about 3300 km^2 with a population of over 3 million people. The demands amount to 310 x 10^6 $m^3 year^{-1}$, and are expected to rise. Figure 2 contains the elements of the sub-potable (untreated) system - the existing facilities and those considered for development. Similarly, Fig.3 contains the drinking water system. The "drinking water projects", as they are identified in these figures, are treatment plants, where sub-potable water is converted into drinking water, and from where it is delivered to the consumers via a separate transport network.

This study employed both simulation and optimization (RID, 1981; Bresser & Pluijm, 1981). The simulation model considers the development of the system over the period 1980-2010. This is done in the "Production and Capacity Module" whose input includes:

(a) the demands for water at each demand node, over the 30 year period;

(b) the existing system; and

(c) a strategy for meeting the demands.

The strategy is specified as a set of priorities for using the various sources to meet each of the demands. The outputs of this module are the capacities and productions of all facilities, over time (treatment plants, pipelines, reservoirs, etc). The capacities are incremented at appropriate time intervals, and the actual annual production of each facility is constrained by the installed capacity.

Quality considerations appear in the simulation model essentially as a "driving force" for decisions on treatment facilities: the model adds-on treatment modules until the treated water meets all quality standards. The result is a capacity expansion and production schedule for all sources, treatment and conveyance facilities.

This capacity expansion and production schedule is next submitted to various other modules, for testing and evaluation.

The outcomes of these analyses are various indices which figure in the objectives, such as: total present value of costs, unit cost of 1 m^3 at each demand point, a reliability index for the quantities supplied, a water quality index, a public health reliability index (the last two were defined in a previous section), energy consumption, a "damage to nature" index, an institutional index (which has to do with the institutional-political viability of the plan, in view of the fact that several government bodies and private water companies are involved).

The optimization model is designed as a screening tool, to provide "good" plans for detailed analysis by the simulation model. It is a multiobjective LP. Its objectives are essentially the same as those of the simulation, except that they may have to be computed in an approximate, linearized, version, to fit into the LP framework.

The constraints are:

(a) demands have to be met,

(b) water mass balances at nodes,

(c) production of each facility is limited by its installed capacity,

(d) certain sources are limited in total capacity.

The optimization model deals with a single time horizon, and has therefore to be run several times, once for each time step (of several years). The simulation model is used to generate data for the optimization model (coefficients for technological and economic

functions) and the optimization model serves to screen the feasible region and provide efficient (in the multiobjective sense) plans for detailed simulation.

Quality considerations appear in the optimization model as objectives: the water quality index and public health objectives defined in the previous section. No constraints are placed on concentrations of the various quality parameters at the points of demand. These are met through the addition of treatment steps - as needed - by the simulation model, as described above.

Har-Ha'Negev water supply system

Alkan & Shamir (1976) used a multiobjective LP model in developing capacity expansion and operation plans for Har-Ha'Negev, a 5000 km^2 region in the desert region of southern Israel. Sources include fresh and brackish groundwater, some flood waters, import from the north via the national water carrier, reclaimed sewage. These are divided into "potable" and "sub-potable" categories. Domestic consumption is fixed, and has to be met. Industrial and agricultural demands are decision variables. They can use low quality ("sub-potable") water, up to a maximum fraction of the total supply, a fraction which is given for each consumer.

The two water qualities are delivered through separate networks, as shown in Fig.4. The two systems touch only at consumer nodes, where the two qualities are "blended" for the supply. No treatment is considered. Treatment plants would create links between the two supply systems, by allowing a transformation of sub-potable water into potable waters.

The model considers two seasons in the year: a 3-month summer, during which the peak demands occur, and the remaining 9-month period of lower demands. The constraints are:

(a) continuity equations, for the summer season and for the yearly totals,

(b) annual and seasonal water potential limitations for all sources,

(c) seasonal production at nodes limited by the developed capacity of the sources,

(d) seasonal transfers through pipelines limited by their installed capacity,

(e) the ratio of sub-potable to potable supply to each consumer is limited, according to the type of use (agricultural, industrial), and

(f) bounds on certain supplies, when non-water considerations (such as the arable land) put a limit on the development of agriculture or industry.

Six objectives are considered:

(a) minimum total cost,

(b) minimum operating costs,

(c) maximum net benefit, from agriculture and industry,

(d) maximum employment, in agriculture and industry,

(e) minimum water imports, to reduce the loads on the already stressed sources outside the region, and

(f) maximum utilization of sewage effluents in the region, to reduce environmental damage.

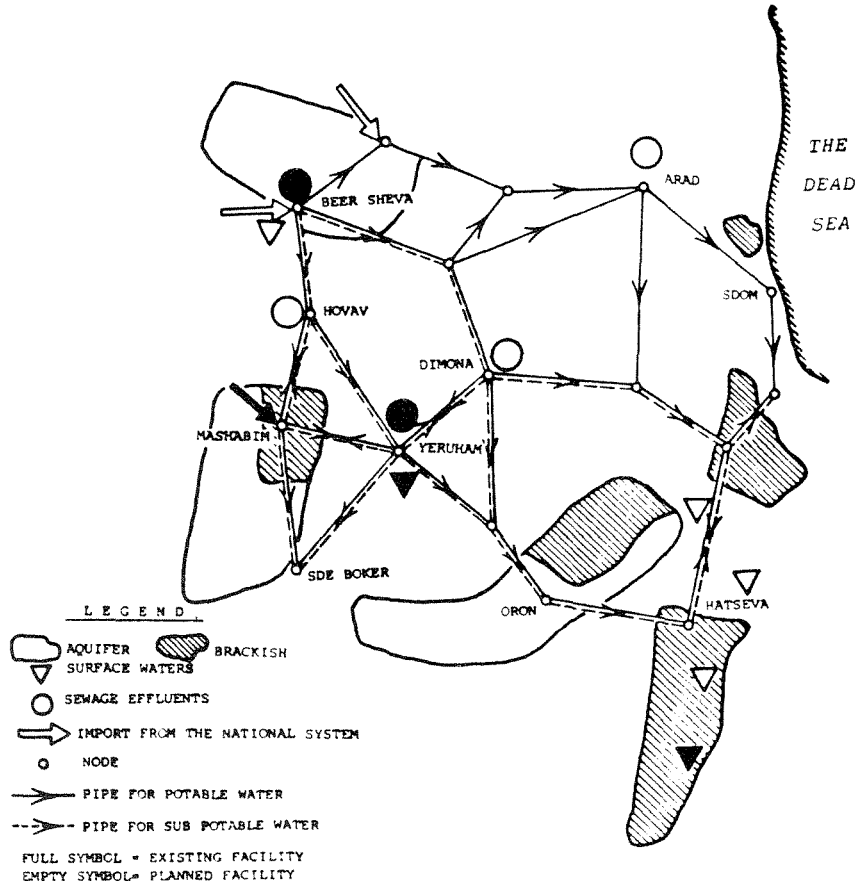

FIG.4 Har-Ha'Negev water supply system.

The TEKUMA model

Schwarz *et al.*(1981) developed a general model, called TEKUMA, which is being used for a study of Israel's national system as a whole, as well as for several regional systems. It is a multi-period linear program in which the decision variables include:

(a) supply to consumers,

(b) development of sources and capacity expansion of the conveyance system,

(c) operating policy of reservoirs and the conveyance system.

The objective function is minimization of the present value of all costs, including damages due to non-supply of the specified demands. The model recognizes several hydrological "states", which can represent average, wet and dry years, and yields a solution which is optimal with respect to the weighted contributions of these states (by their probability of occurrence).

In its basic form, this model considers quality in the same way as in Alkan & Shamir (1980), namely: a maximum blending ratio is given, for each consumer, on low-quality water. The model is presently being revised, to allow incorporation in the linear programming formulation of the nonlinear mixing equations, as shown below.

At a mixing node the material balance for any conservative quality parameter is:

$$\Sigma_j Q_j C_j = 0 \tag{4}$$

where the summation is over all pipes connected at the node. Q_j is the discharge in pipe j, positive when it enters the node and negative when it leaves the node, and C_j is the concentration of the (conservative) water quality parameter. This nonlinear relation, which is a constraint in the optimization model, is approximated by a linear expression in which each term is:

$$Q_j C_j \cong Q_j C_j^* + Q_j^* C_j - Q_j^* C_j^* \tag{5}$$

Q_j^* and C_j^* are (known) reference values. When the model is constructed they are given initial values, and are updated iteratively. The introduction of equation (5), and a similar expression for any product term in the objective function, turns the optimization problem into a linear program, which is solved iteratively. Some experimentation has shown that the procedure converges quite well. The initial values for Q_j^* and C_j^* are obtained by solving the LP without the quality constraints and then computing the resulting concentrations. The values of the discharges and salinities resulting from this solution are the initial values. In subsequent iterations the values are taken from the solution of the previous iteration.

Optimal re-use of waste water

Ocanas & Mays (1981a, b) developed models for determining the optimal re-use of waste water in a region. Waste water and fresh water are both considered as sources, and each source is characterized by its quantity and quality. The consumers impose certain quality requirements, which the solution must satisfy. Nonlinearities, of various origins, are maintained and the resulting nonlinear optimization model is solved with the large-scale generalized reduced gradient (LSGRG) method (Lasdon *et al.*, 1978), or the successive linear programming (SLP) method (Palacios-Gomez *et al.*, 1982).

In its extended form (Ocanas & Mays, 1981b), this is a capacity expansion model, which considers specifically the construction and operation of water and waste-water treatment plants. Sources include surface and groundwater and waste water. Water and waste-water treatment plants and pipelines connecting sources, plants and consumers are decision variables for each of the time periods of the planning horizon.

BOD is used as the primary quality parameter, but the model is designed to consider several parameters.

The concentrations throughout the system are modified at the treatment plants, and mixed at nodes of the distribution system. Quality constraints are imposed at consumer nodes, and apply to the blend of all waters arriving at a node. In addition, limits are set on the amounts of pollutants discharged into the sources (waste water can be discharged into surface or groundwater, then taken for

direct supply or for treatment).

Nonlinearities in the model are due to mixing of qualities (as in equation (4)) and to cost functions reflecting economies of scale. The nonlinear program is solved by LSGRG and/or SLP.

Real-time control of water quality

Another aspect, which is beyond the scope of this paper, is real-time control of water quality. Work by Beck (1978a, b, 1980) deals with control in rivers and reservoirs. Work by Sinai *et al.* (1984) deals with control of irrigation and water supply systems.

CONCLUSIONS

The experiences reported in this paper indicate that for management of regional multiple quality water supply systems:

(a) it is often sufficient to consider explicitly only a small number of quality parameters in the management models.

(b) More comprehensive water quality indices may be needed under other circumstances. There does not seem to be, as yet, a fully satisfactory way for defining such indices, although some simple definitions have proven useful.

(c) It is feasible to construct and use optimization and simulation models which include water quality in the constraints and/or objectives.

These experiences and conclusions lead to the following main recommendations. Analysis of multiple quality systems is best conducted in two parts: (1) in the first a few quality parameters are considered in a "screening model" which is designed to eliminate inferior solutions and indicate promising ones, and (2) in the second part a more detailed description of water quality parameters is included in the model, and solutions proposed in part (1) are subjected to a more thorough analysis.

An optimization model, even if simplified and approximate, should be used in part (1), while simulation may be the best tool for part (2). The two may be exercised iteratively: the optimization generates candidate solutions for analysis by detailed simulation, and the simulation provides insight, functions and numerical parameters which are then used for refining the optimization model for the next iteration.

Another recommendation is that more work is needed to develop procedures for incorporating quality considerations more accurately in linear optimization models, such as that of equation (5).

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