Water Management and Policy: Rules vs. Discretion

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Abstract

Where natural water sources are used to capacity, varying precipitation and replenishment of the reservoirs entails fluctuations in available supply. Emergency measures are often taken as the shortages are realized. This is management by discretion. The paper argues for a different policy approach: management by rule. A stochastic model of water supply is formulated as dynamic programming in Markov chains. The model is illustrated with data for the water economy in Israel where agriculture has served as a buffer—allocation to the sector was curtailed in times of shortage. The major findings of the analysis are that, to serve as a buffer, agriculture need not be a large user of water, and that supply can at least be partly stabilized with flexible seawater desalination, activated to recharge deficient reservoirs.

Introduction

In this paper we are trying to address two issues. The first is management of the water economy under uncertainty; the second issue is the mode of management: we suggest management by rule. The analysis and the argument are supported by a case study of the water sector in Israel.

Water resources are common pools; they must be managed collectively. In Israel, by law, all water sources are publicly owned and their utilization is under the control of the State, managed by the Water Commissioner. The Commissioner is given a set of powerful instruments to enforce the law and the chosen management policies. The law, however, does not specify the desired policy or the duties of the Commissioner. The implication of this omission is that the lawmakers trusted the Commissioner to manage by discretion, to use professional judgment in formulating policies and directing the sector. Experience has taught, however, that management by discretion has often failed. Throughout the years, the Commissioner allowed over-drafting, the water sector was brought at least twice in recent years to a severe crisis, and the reservoirs have been depleted and polluted. Moreover, facing strong resistance of the farm lobby, the Commissioner has been only partly successful in implementing austerity measures in emergency drought periods. We present here a model of management under uncertainty and in the last section of the paper discuss the possibility of this model to be the basis for management by rule.

Water in Israel[1]

Israel is a dry country, half of it is desert. Rain comes only in the winter and in the north. Water accumulates in a lake, the Sea of Galilee (Kinneret), and in groundwater reservoirs. The two largest reservoirs are the mountain aquifer, running from north to south in the middle of the country, and the coastal aquifer, close to the Mediterranean; others are relatively small. The functions of the water economy is to store water from the winter to the summer and from rainy to dry years; to move water from the north to the

[1] For a survey of the major issues in the water economy in Israel, see Kislev (forthcoming).

centers of population on the coast and to the south; to collect and treat the sewage and recycle the effluent; and, recently, to desalinate seawater. The National Water Project (Carrier) is a system of conduits running west and south from the Sea of Galilee and connecting most of the sources and users of water in the country. Two thirds of the water in Israel is supplied by the largest water utility and the company also operates the National Project. Others are private suppliers and regional cooperatives; several municipalities also supply water to their residents from wells they operate.

The total safe yield supply of fresh water from natural resources is estimated as 1,550 MCM/Y (million cubic meters per year). Agriculture used to be the largest consumer but, with population expansion, fresh water was diverted to urban use; some of it replaced by recycled effluent.

Three Nested Circles

The analysis in the paper is based on programming performed in three nested stages. The inner circle in Figure 1 stands for the dynamic programming in a Markovian model serving as a formal representation of management under uncertainty. It will be explained below. The second circle represents the analysis of the optimal size of agriculture and seawater desalination. The desalination plants considered in this circle are dedicated to reduce fluctuation in water supply to agriculture and they can be planned for either continuous or flexible activation—the latter only in periods of shortage. The external circle in the diagram represents the excess demand of water over and above natural sources; it will also be satisfied by seawater desalination.[2] This demand is determined by the size of agriculture and the projected growth of the urban sector.

Agriculture plays two different roles in the water economy. Agriculture is a consumer of water and the larger the farming sector, the more water it uses. With limited natural resources, the size of agriculture determines—together with urban demand—the timing and scale of desalination, excess demand in Figure 1. The second role that agriculture

[2] The desalination plants in the two circles may not be distinguished "on the ground," but they are planned separately in the program of the water sector.

may perform is as a reserve for emergencies. Water allocation to agriculture can be cut in dry years to avoid difficulties in urban supply. In other words, agriculture may serve as a buffer. The two roles are connected: agriculture can serve as a buffer only if its water use in regular years is large enough to be a basis for cuts.

The source of uncertainty in the water economy lies in the underlying nature of the sector. As indicated above, precipitation, in varying amounts, comes in the winter, while most of the utilization is in the summer. The appropriate time to inform the farmers about cuts in supply—if needed—is in the fall, when spring planting can still be adjusted. But the decision in the fall is done under uncertainty, before the winter rains. The solution in the Markovian model is simple: decide on allocation for the summer according to the condition of the reservoirs in the fall. When the reservoirs are relatively full, allocation is large; supply to agriculture is cut when the reservoirs are low. The contribution of programming is in formulating an explicit policy—management rules that are expressed as quantitative relations between water in the reservoirs and allocation to agriculture.

Seawater desalination may modify the policy. Desalination plants, operating continuously or activated in times of emergency and shortage, will reduce or even eliminate the need to cut agricultural allocation. In this way, the planning of supply under uncertainty, here in the Markovian model, is connected to average supply and to the decision on desalination plants and their destiny—for continuous or flexible operation.

Framework and Assumptions[3]

The programming horizon in the analysis is 20 years.[4] For simplicity and clarity of exposition, programs were constrained at this stage to a relatively narrow framework and to a small number of alternatives. The dynamic programming of management under uncertainty covers the water economy of the National Project, which supplies

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[3] Only the salient features of the model and the data are presented here; readers interested in further details can inquire with the second author.

[4] Extending the horizon of the program to more than 20 years did not change the plan for the first several years. It can be safely assumed that with changing future conditions, programming will be repeated. Hence a 20-year horizon is sufficient for our problem.

approximately two thirds of the water in the country. We view all reservoirs as if they were a single cell and disregard differences in enrichment or extraction in the separate reservoirs. It is common in Israel to assign to each reservoir a water level (in the aquifers it is measured in specified wells) designed as *the red line*. Extraction management is supposed to prevent the crossing of the red lines; not always is this possible.

The water level in the reservoir (again, assuming a single unit) is an indication of the amount of water stored. Accordingly, the state of the reservoir is defined for the month of September every year, and the reservoir may be, by assumption, in one of the following states: *High* +200; that is, the amount of water in the reservoirs exceeds by 200 MCM the amount associated with the red line. *Intermediate* 0; the red line. *Low* –200: water in the reservoirs is 200 MCM less than the red line and over-utilization has occurred.

Replenishment is the amount of water added yearly to the reservoirs. Relying on a 60 years statistics of replenishment, we adopted the following values and their probabilities: dry year 1,050 MCM (with probability 0.10); average year 1,550 MCM (0.80); rainy year 2,000 MCM (0.10). We could not find autocorrelation in the precipitation data; that is, rain in a future season cannot be predicted from information on rain in earlier years.

The size of agriculture is defined here (disregarding livestock production) by the amount of water allocated from the National Project. *Basic agriculture* is the amount of water allocated to agriculture in regular years. In emergency and shortage, allocation may be curtailed temporarily. The reference for the analysis is the situation in 1998 when basic agriculture, as defined here, was allotted 700 MCM/Y and the program examines 8 level of basic agriculture 0, 100, …, 700 MCM/Y.

The size of basic agriculture, plus the allocation to agriculture outside the National Project and the growing urban supply, will determine the total quantity demanded of fresh water and hence excess demand—and desalination. For example, basic agriculture of 700 MCM/Y requires immediate (1998) construction of desalination plants of 300 MCM per year; however, if basic agriculture is of 300 MCM/Y, the first desalination plant ought to be constructed in 2006 and with a smaller capacity of only 50 MCM per year.[5]

By the model, the Water Commissioner has at his disposal a set of possible actions. The decision on a policy is a choice of actions to be associated with the states of the reservoirs. These actions are then the chosen policy rules. In connection with management under uncertainty of supply from natural sources—in the two internal circles of Figure 1—the alternative actions are:

a. Construction of desalination plants to reduce variability of supply. We shall analyze two alternatives, continuous and flexible operation.

b. Temporary curtailment of supply to agriculture in dry spells.

c. Over-utilization of the reservoirs, below the red lines, up to 400 MCM.

d. Shortage in urban supply. This alternative is taken as a choice of the last resort. Shortage occurs only if the reservoirs were over-utilized by 400 MCM and there was not enough water to provide for urban demand.

The Objective Function and the Cost of Policy

The objective of the program is to minimize cost measured as expected capitalized value for 20 years. The chosen policy is the set of management rules that achieves this goal.

The concept of cost in the analysis is differential. We measure *changes* in cost caused by changes in the program of the water economy. The reference for comparison is the water sector of 1998 when allocation to agriculture from the National Project was 700 MCM and there was no desalination of seawater. The differential cost may have several origins: reduction of the size of basic agriculture (from 700 MCM/Y) reduces the product of the sector, this is taken as cost; cuts in supply to agriculture in emergency are costly; we give a monetary value to over-utilization of the reservoirs and to shortage in urban supply. An additional component is the cost of seawater desalination. Details follow.

[5] Not withstanding our recommendations, the first large-scale (120 MCM/Y) seawater desalination plant in Israel is expected to reach full capacity operation in the spring of 2006.

Basic Agriculture: Farmers in Israel have not used all their water quotas in recent years; we therefore accepted the price they paid as the value of marginal product (VMP) of water at the basic quantity (700 MCM/Y). Deducting the variable cost of water transfer and adding a sum for social contribution of green agriculture, we arrive at NIS 1 per CM.[6] When calculating VMP of lower quantities, we assumed unitary elasticity of demand.

Emergency cuts in Allocation: In emergency, unexpected cuts will damage expensive crops and idle irrigation equipments and other production assets. We took the value of NIS 2.20 per CM for unexpected cuts in allocation of water to agriculture.

Over-utilization: It was assumed that over-utilization of the reservoirs will require desalination of part of the water supplied for 15 years. Accordingly, we constructed a rising cost function approximated by $y = 2.21x + 0.00003x^2$ where y is cost in NIS per CM and x is over-utilization in CM.

The Urban Sector: To represent the high cost of shortage in the urban sector we took the value of NIS 40 per CM.

Seawater Desalination: Fixed cost, capital and labor, of desalination is expected to be NIS 1.60 per CM. Variable cost, of energy, is taken as NIS 1.20 per CM.

Markov Chains and Policy Choice

The stochastic model of the water economy is a finite Markov chain.[7] The states are defined by the amount of water in the reservoirs in the fall of every year. The transformation from one state to another, from one year to the next, is determined by precipitation and water utilization. The states are defined, high=1 (+200), intermediate=2

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[6] NIS is New Israeli Sheqel, approximately $0.25 at the time of the analysis.

[7] The first to suggest and formulate a Markov chain model of a single cell aquifer in Israel was Levin (Bear and Levin, 1966). To our knowledge, his model has never been applied in the country's water economy.

(the red line), low=3 (-200). We write now and explain two Markov matrices P for two alternative policies for basic agriculture of 600 MCM/Y and the corresponding cost vectors C.[8]

Policy a: Never cut allocation to agriculture, not even if in the fall the reservoir is low. The policy matrix and the cost vector are

(1) $$P_a = \begin{bmatrix} 0.9 & 0 & 0.1 \\ 0.1 & 0.8 & 0.1 \\ 0.1 & 0 & 0.9 \end{bmatrix} \qquad C_a = \begin{bmatrix} 95 \\ 590 \\ 1,637 \end{bmatrix}$$

In a Markov matrix, the rows indicate the state the process is in and the columns mark the state the reservoirs will reach by the next period. The entries are the probabilities of transition from one state to the other. Thus in P_a, if in the fall the reservoir is in state 1 (+200) and policy a is followed, the reservoirs will be in the next fall in state 1 with probability 0.9, it will have no chance of moving to state 2, and will be in state 3 with probability 0.1. Similarly, given Policy a, the reservoirs will move from state 2 to state 1 with probability 0.1, to state 2 with probability 0.8, and to state 3 with probability 0.1. The probabilities in the matrix were constructed by combining the information on the replenishment with the effect of the given policy.

For simplicity and ease of computation and exposition, the reservoirs can be in one of three states. However, even with only three possible replenishment levels, the reservoir can be seen as moving to more than three states. As an example consider the transition in P_a from state 3 to state 3; depending on the replenishment, a reservoir with -200 MCM can move to either of two realizations by next fall: -200 MCM with probability 0.8 and -700 with probability 0.1. Both will be regarded as state 3, and therefore the probability of the transition from 3 to 3 is the sum 0.9. This observation means that not one but two cost components are associated with the above shift from 3 to 3: NIS 308 million (when the reservoirs reach –200) and NIS 13,904 million (for –700). The expected value of the

[8] Given a policy matrix, a cost (expected) is associated with each state.

cost is NIS 1,637 million, and this is the third component in C_a. Similarly in other transitions, cost was calculated as the expected value for the realization aggregated into a single state (affected mostly state3).

Policy *b*. Do not cut supply to agriculture if the reservoirs are high in the fall, cut 200 MCM if the reservoirs are in intermediate position or they are or low. Here the matrix and the associated cost vector are

$$(2) \qquad P_b = \begin{bmatrix} 0.9 & 0 & 0.1 \\ 0.9 & 0 & 0.1 \\ 0.1 & 0.8 & 0.1 \end{bmatrix} \qquad C_b = \begin{bmatrix} 95 \\ 540 \\ 1{,}036 \end{bmatrix}$$

Comparing equation (1) to (2), one notes the smaller probability of reaching states 2 and 3, intermediate or low reservoirs, in policy *b*. In fact, if policy *a* is followed, state 3 is almost a trap: once in state 3, the reservoir has a probability of 0.9 to return to the same state and only a probability of 0.1 to leave it. Policy *b* protects the reservoir relative to *a*. By policy *b*, allocation to agriculture will be curtailed, at a cost, when the reservoirs are low. However, policy *a* entails a greater probability of over-utilization of the reservoirs. Consequently, policy *a* is, in general, more costly than policy *b*.

Policy choice is the choice of a Markov matrix *P* that minimizes cost. The algorithm was dynamic programming (Hadely, 1964).

The Programs

Programming was done in two stages and 48 combinations of program alternatives. In the first stage we found for each combination the cost minimizing policy. In the second stage we looked for the combination with the lowest overall cost (Table 1 below). Every combination incorporated three alternatives from the following.

Capacity of desalination plants: no plant, 100 MCM/Y, 200 MCM/Y (3 alternatives);

Desalination: continuous, flexible (2 alternatives);

Basic agriculture; 0, 100, ..., 700 MCM/Y (8 alternatives).

Table 1
Total Cost (million NIS, expected present value for 20 years)

Basic Agriculture	0	100	200	300	400	500	600	700
Excess Demand	635	1,905	3,789	6,064	8,729	12,698	16,630	20,022
Reduction of Agriculture	22,938	15,087	10,769	7,236	4,880	2,970	1,400	0
Markov	2,305	3,497	3,953	4,980	6,015	4,835	2,931	2,634
Total	25,878	20,489	18,511	18,280	19,624	20,503	20,961	22,656

Table 1 summarizes the analysis. The table reports cost for 8 alternatives of basic agriculture; form 0 to 700 MCM/Y. The second row, Excess Demand, is the cost of desalination to satisfy the quantities demanded as basic agriculture grows from one alternative to the next. The third row, Reduction of Agriculture, is the opportunity cost of not producing in agriculture, relative to the reference size of 700 MCM/Y.

The fourth row in the table, Markov, is the cost associated with water supply under uncertainty. Here the components are the cost of emergency cuts in supply to agriculture, over-utilization of the reservoirs, and desalination to reduce variability of supply. The entries in the fourth row were constructed in a two-stage minimization process. For each size of basic agriculture, water management policy was chosen in dynamic programming for five alternatives of desalination: no desalination, continuous desalination, and flexible desalination; in both cases desalination of 100 or 200 MCM/Y. The entry in the fourth row is the minimum cost over these five alternatives for each size of basic agriculture. The program suggested no desalination for basic agriculture of 0, 600, and 700 MCM/Y. When basic agriculture is zero, desalination to reduce water supply variability is not needed, and in a relatively large agriculture, desalination is more expensive than cuts in supply during emergency periods. For the other sizes of agriculture, flexible desalination was found less costly than continuous desalination.

The overall minimum in Table 1 is for agriculture of 300 MCM/Y. With 250 MCM/Y outside of the national project, our program recommends fresh water allocation to agriculture of 550 MCM/Y as against 950 MCM/Y that the sector used in 1998.

Remarks

The analysis yielded a rich set of conclusions and insights but most are beyond the principal argument of the paper. Two findings, perhaps unexpected, are worth pointing out. First, a comparison of the relatively small values of the row marked Markov in Table 1 to the entries in the other two rows reveals that incorporating uncertainty into the analysis of the water economy does not modify significantly the optimal plan. Agriculture is not called to act as a buffer for dry spells. Second, by conventional wisdom, desalination plants, being capital intensive, should be operated continuously. We found that flexible operation is preferred. Two advantages make flexible desalination preferred; one, the decision to desalinate can be made in the spring when the winter rains are already known and expensive desalination can be avoided after a rainy season. Advantage two is that over-utilization of the reservoirs does have to be remedied immediately. A relatively small desalination plant can be used to recharge aquifers in deficit over a period of several years.

Flexible desalination raises a political issue and an economic question. The first is that once a desalination plant has been constructed, political lobbies will demand that it be operated continuously ("it is a waste to let a plant lie idle"). If this (economically unsound) demand is accepted, agriculture will expand and allocation will have to be cut in emergency periods with all the difficulties experienced in recent times. The economic question is about water pricing. The way the programming was done, desalination was activated when the *variable* cost of desalinated water was lower than cuts in supply or over-utilization. (Total costs were considered in the decision of whether to construct a desalination plant.) If the suggested policy is implemented, farmers will take the desalinated water if its price is equal to variable cost, but then payments for water will not cover total cost. This is a typical case of pricing in the presence of economies of scale, here up to capacity of the plant (Bös, 1994). Extraction levies, reflecting scarcity values, have recently been instituted in Israel. The levies may cover the fixed cost of desalination, but we shall not elaborate here on this issue.

The analysis was conducted as if all decisions are made by the planner and water users act mechanically. However, once the chosen policy is to cut allocation to agriculture in emergencies, and that policy is made public, farmers will plan their operations with this possibility in mind. For example, they may plant, on part of their land, inexpensive crops that are not damaged severely when water is in short supply (Marques, Lund, Howitt, 2005). Another alternative is to institute water markets where farmers in need purchase allotments from others. These adjustments may lower the cost of emergency cuts in supply and may also alter some of the conclusions of our analysis.

Rules Vs. Discretion

When management was by discretion, the Water Commissioner was constantly subject to political pressure to expand supply to agriculture; and indeed, quotas were increased despite professional advice. The ensuing over-utilization resulted in an ever-growing deficit in the reservoirs and a succession of dry years threw the water sector into an acute crisis. When the severity of the situation was realized, the Commissioner tried to curtail supply to agriculture but his efforts were frustrated when the farmers and their political lobby succeeded in dragging the authorities into extended discussions of procedure and compensation.

We envisage management by rule to be implemented along the following general lines: The government will be presented with a program for the water sector. The program will be made of three parts. The core of the program will be a set of management rules and associated costs. The rules and the costs will be programmed in a model similar to the one presented here. Needless to say, if implemented, the model will be more detailed and its assumptions rechecked. The second part of the program will consist of special rules; such as, development plans, prices, or quotas for emergency situation in dry years. The third part of the program will detail the programming methods and the assumptions.

The program will be transparent and subject to public debate. In due course the government will select a *policy*, a set of rules to adopt. The government, guided by general welfare considerations, need not choose the cost minimizing set. Once announced, the Water Commissioner and the public, particularly the farmers, will know the rules in advance and what to expect in rainy or dry years. There will be no need for political bickering when an emergency situation materializes. A water authority will monitor the sector and the implementation of the rules adopted. The Commissioner will be judged by his adherence to the selected policy and the specified goals.

We should be realistic; the best plan can be watered down in the political arena. It should in fact be expected to be watered down: farmers and others, including in some cases the Commissioner himself, will rather have a more flexible policy regime, believing that they may squeeze preferential treatment if the rules are not cut and clear. A realistic outcome will always be a compromise. The question is whether a compromise is worth the effort invested in its implementation. We believe it is.

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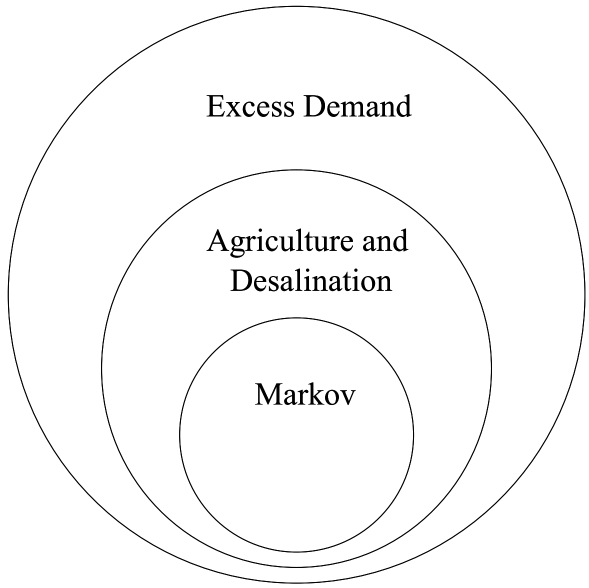

Figure 1: The Three Programming Circles