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A SUSTAINABLE SALT REGIME IN THE ISRAELI COASTAL AQUIFER

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ABSTRACT

Water utilization, particularly in dry areas, augments the accumulation of salts in soils and groundwater. This chapter reports a study of the economic aspects of maintaining sustainable salt concentrations in the reservoirs and in water supplied to agriculture and urban consumers. The study has two major purposes, to stress the need to remove salts, an expensive process, and to point to the water sources from which salts should be removed. The analysis is of the Coastal aquifer in Israel and the area above it and on data forecasted for the year 2020. The total amount of salts that can be expected to reach the coastal region in that year is 120,000 tons chlorides; the same quantity has to be removed yearly for a sustainable salt regime to be maintained. A third, perhaps even half, the salts imported to the region will be removed in the natural outflow to the sea or in water exported to other regions, as fresh or recycled water. The rest, tenths of thousands tons per year, will have to be removed actively.

The study is done under simplifying assumptions and it should be taken as a first step. A more detailed analysis will incorporate additional hydrological and engineering considerations and perhaps also other sources of contamination. But it seems that the major conclusions, on the need to remove the salts and the efficient way of doing it, will not be modified significantly.

A. INTRODUCTION

Israel has three major water reservoirs: Lake Kinneret (the Sea of Galilee) in the north, the Coastal aquifer along the shore of the Mediterranean Sea, and the Mountain aquifer further east, partly under the hills of the West Bank.[1] Most regions of the country are covered by a grid of pipelines connecting water sources with areas of utilization. The major conduit is the National Carrier moving water from Lake Kinneret to the central and the southern regions of the country. The coastal region, the focus our analysis, receives water from all three

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[1] For a survey of the water economy of Israel, see Kislev (2006).

reservoirs—Kinneret, Mountain, and the Coastal aquifer itself. It is expected that in the future it will also receive desalinated seawater. The water is supplied to the region's urban centers and agriculture.

The reservoirs are replenished yearly by precipitation: rains and some snow in the Kinneret's watershed drain into the lake in rivers and springs and the aquifers are fed with rainwater falling directly on the land surface above them. The replenishing water carries salts to the reservoirs, in Lake Kinneret from salty springs, and in the aquifers from ocean spray. Additional sources of salts are underground brines and seawater intrusion. As a result, the water stored in the reservoirs contains significant quantities of salts. Irrigation with water imported to the coastal region from Lake Kinneret or the Mountain aquifer adds further amounts of salts. [2] Another source is effluent: salts used in households and manufacturing are carried in the sewage and increase the mineral concentration of the effluent.[3] They are added to the groundwater wherever crops are irrigated with effluent. The salts are harmful to soils and crops and also, when their concentration is large, to households and industry. Hence the need to halt their accumulation.

Salts also leave the reservoirs—in water outflows. From Lake Kinneret with the water drained to the Jordan River and pumped into the National Carrier and sent southward. As a result, salt concentration in the lake's water is stable (the stability is stochastic, reflecting fluctuations of the precipitation).

In the past, before the development of intensive agriculture, the concentration of salts in the aquifers was also stable: all the replenishment water left the aquifers, either in springs or under the ground through the seawater-freshwater interface; in this way salts entering the reservoirs were flushed away and minerals did not accumulate. Irrigation modifies this equilibrium: most irrigated water evaporates, either directly or through the plants, and the natural outflow from the aquifer is then reduced. Unlike water, salts do not evaporate; they remain on the surface of the land or in the subsoil and are carried back into the groundwater with rainwater and irrigation return flow. Consequently, minerals accumulate in the aquifer wherever irrigation is practiced. In the coastal aquifer, as indicated above, the accumulation is augmented with salts imported with water from non-coastal sources and salts added to the effluent.

The future will see two parallel but opposing processes in the water economy of Israel. The first will be an increased provision of freshwater and effluent; the added freshwater will be mainly desalinated seawater (the first large scale desalination plant commenced operation in summer 2005) and the quantities of the effluent will grow as the population and urban water use increase.

The second process will be active removal of salts. The increased supply of freshwater answers needs created by expanded population and growing demand; the removal of salts is necessary for the sustainability of the reservoirs.

Actually, there are two alternative policy options in reaction to the accumulation of salts. One, let salts accumulate in the aquifers and replace gradually water from natural sources with desalinated seawater. The second option is to remove actively the salts and maintain a sustainable water economy of natural water. This article is about the second option but toward

[2] Salts are not the only pollutants of the aquifer. Mercado (1980) discusses nitrates and chlorides and many more pollutants have been found in the water since his writing.

[3] Households include, in the terminology of the water sector, family dwellings and also places of commerce, workshops, hotels and other water users in the urban sector.

its conclusion we also indicate that the first option, neglecting the reservoirs, is not efficient economically.

Our analysis is limited to the Coastal aquifer and we examine alternative salt concentrations and compare the cost of these alternatives and cost of alternative ways of salt removal.

Under the assumptions of the analysis and with the information at our disposal, our main conclusion is that the efficient alternative is to remove the salts by desalination fresh water from natural source (particularly from the Coastal aquifer). However, even if the removal of the salts is conducted efficiently, it will increase significantly the total cost of the water economy of the country.

B. ASSUMPTIONS

We are not the first to deal with the accumulation of salts and the need to remove them.[4] But earlier studies did not examine alternative ways to treat the salts and did not consider the economic implications of these alternatives. We are expanding the analysis.

The forecast for the area west of the water divide of Israel is that by the year 2020 total water supply will be 2,206 MCM/Y and of those 1,135 MCM/Y from natural sources (fresh and saline), 621 MCM/Y effluent, and 450 MCM/Y desalinated sea water. [5] Salts added are expected to reach 272,000 tons per year from natural sources and effluent and 9,000 tons from desalinated water (the concentration of salts in the desalinated water is 20 ppm of chlorides).[6]

It is expected that 126,000 tons chlorides will be added in 2020 to the Coastal aquifer. The analysis is based on a set of simplifying assumptions to be described below, we shall remark on several of the assumptions at the conclusion of the article.

The movement of water in the coastal aquifer is slow and the reservoir is therefore often visualized as made of separate cells. Still, for simplicity, the aquifer is taken here as if it was a single cell reservoir into which all the salts deposited on the surface of the land are drained with rainwater and irrigation return flow.

We assume complete mixing of the salts with the water in all the active volume of the aquifer. It is reasonable to expect changes in the coastal region after 2020: there will be expansion of the supply of both desalinated water and effluent, and the area covered with buildings will increase; the amount of salts added to the aquifer will therefore also increase. However the additional quantities will be relatively small and therefore, and for simplicity, we are conducting the analysis for constant quantities of water and salts; in other words, the analysis is conducted for a steady state.

A steady state is a characterization of a sustainable system and its implication here is that at any time, year in and year out, the same quantities of water and salts are added to the aquifer and identical quantities leave the reservoir.

[4] Hebrew references will not be quoted in the paper; they can be found in Goldfarb and Kislev (2002).

[5] Water units are: CM cubic meter, MCM million CM, and MCM/Y MCM per year.

[6] The most prevalent salt in the water is table salt (sodium chloride). Sodium is the element causing most damage, but it is more convenient to test for chlorides. The unit of measurement is ppm, parts per million. It is useful to remember that one ppm is one ton per MCM.

There is no accumulation, negative or positive, of water or salts. Because of the stochastic nature of the precipitation and other factors, even if a steady state prevails, it will be a stochastic steady state: the quantities entering the aquifer and the quantities leaving it will not be identical every year; the equality will be maintained only for the average. But, at this stage, we are disregarding the between years variations, and conduct the computations as if the years were identical.

C. MODEL I

This section of the chapter opens the conceptual discussion of the study with agriculture as the single water-using sector. Expanded models are introduced below. The models are presented in the chapter as diagrams, in algebraic terms, in equations, and in balanced tables.

In Model I (Figure 1.1) precipitation is added to the groundwater (replenishment), part of the water is withdrawn for irrigation and the rest is outflow to the sea. Irrigated water is evaporated from the surface of the land and through plants and part of it reaches the groundwater as irrigation return flow.

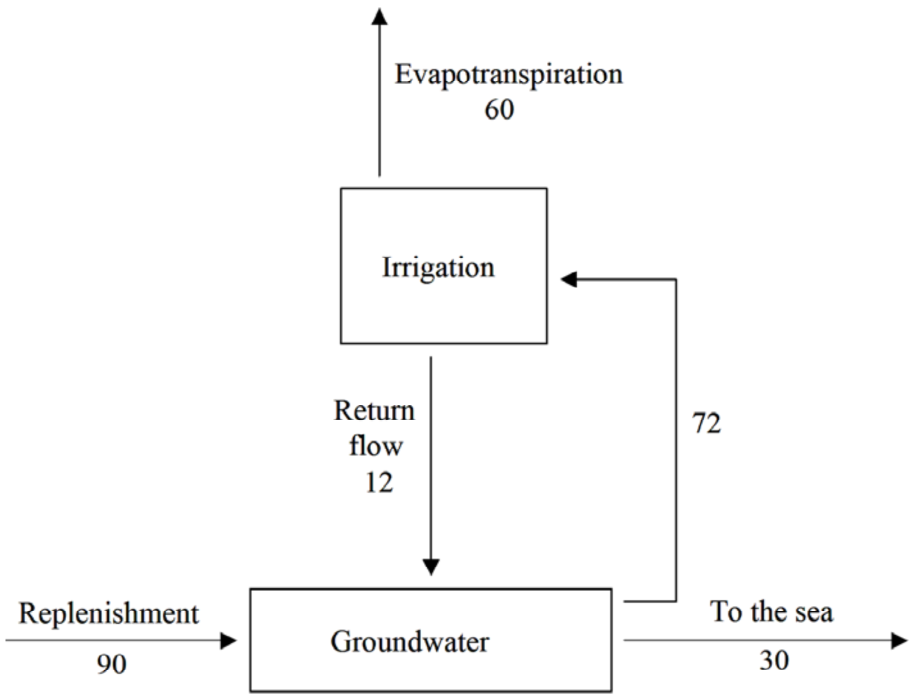

Figure 1.1. Model I, water flows.

C.1. The Algebraic Model

Quantities in the model are flows per year. The variables are

	Water in MCM	Salts, chlorides in tons per year
Replenishment	R	M_R
Irrigation (fresh water)	H	M_H
Irrigation return flow	Z	M_Z
Outflow to sea	Y	M_Y
Evapotranspiration7	E	

The balancing equations are
Water balance

$$R + Z = H + Y \tag{1}$$

Salt balance

$$M_R + M_Z = M_H + M_Y \tag{2}$$

Irrigation return flow

$$Z = 0.17H \tag{3}$$

Irrigation water balance

$$H = E + Z \tag{4}$$

Equations (1) and (2) describe the entry of water and salts into the reservoir and exit away from it. The water supply is augmented with the irrigation return flow. There is some arbitrariness in the division of the salts to the different flows as salts deposited on the surface of the land are drained into the subsoil both with rainwater and with irrigation return flow. For convenience, we combine in M_R salts added with rain (ocean spray), from underground brines, and from other sources. All these quantities are taken as salts coming with the replenishment. Salts deposited on the surface of the land with irrigation we see as if it was all drained to the subsoil with the return flow. Equation (3) defines that the return flow is 17% of the quantity of water in irrigation (an assessment received from hydrologists). The last equation, (4), completes the picture, it separates irrigation water to the part evaporated and the part returning to the reservoir.

To illustrate the model, let us assume (water in MCM/Y; salts, chlorides, in tons per year): replenishment R=90 with salt concentration of 50 ppm; that is, M_R=4,500. Groundwater outflow to the Mediterranean Sea Y=30. As indicated, entering quantities are identical to quantities leaving the aquifer. The balance for water is

$$90 + 0.17H = H + 30$$

hence irrigation H=72, return flow Z=12, evapotranspiration E=60 (Figure 1.1).

We turn now to the calculation of the concentration of salts in the flows of water in the model. In the steady state, all the salts in the irrigation water reach the reservoir; that is M_H=M_Z and therefore M_R=M_Y. In words, all the salts reaching the reservoir leave the aquifer in the water drained to the sea (salts in harvested crops are disregarded). Define the concentration of salts in the outflow to the sea as *P* and write the equality $M_R = M_Y$

$$90 \times 50 = 30P \qquad (5)$$

The solution to the equation is *P*=150; that is, the concentration of salts in the outflow to the sea is 150 ppm chlorides. Also, since groundwater is the source the outflow, the concentration of chlorides in the groundwater will be 150 ppm as well, and this will also be the concentration of salts in the irrigation water.

C.2. The Balance Sheet

The balance sheet (Table 1) summarizes inflows and outflows of water and salts and it is ordered in accordance with the construction of equations (1) and (2). However, the quantities in the table are only quantities of water and salts *added* to the aquifer; for example, there is exit of salts in irrigation, this exit is not recorded in Table 1 since, by assumption, all salts leaving the reservoir in water used for irrigation above the aquifer return to the reservoir—they are drained, with rainwater and in the irrigation return flow, back into the groundwater. Still, because of its significance, we do report in the table the concentration of salts in the irrigation water, 150 ppm chlorides.

Table 1. Model I: balance sheet of water and salts

Entry to the reservoir				Exit from the reservoir			
	Water	Salts	Concentration		Water	Salts	Concentration
Replenishment	90	4,500	50	Irrigation	72		150
Irrigation return flow	12			To the sea	30	4,500	150
Total	102	4,500		Total	102	4,500	

C.3. Remarks

1. The total quantities of water in Table 1, 102 MCM/Y on each side of the balance sheet, are sums of flows. These values are larger than the quantity of water utilized in the model economy (72 MCM/Y).
2. The concentration of the replenishment, 50 ppm chlorides, is not rainwater concentration; it is an artificial average, the ratio of salts coming from several sources to the volume of the replenishment.
3. In the model and in the steady state, the flows of water and salts come and go year in and year out. In reality, the salts move through the subsoil slowly and therefore salts added to the groundwater in a certain year were deposited on the surface of the land several years beforehand. In the steady state, a given quantity of salts is deposited on the land every year (4,500 tons in model I) and an identical quantity is added to the groundwater.

4. The replenishment and the withdrawal determine simultaneously, in the steady state, both the outflow to the sea and the level of the water table in the reservoir. A comprehensive model would therefore have included equations determining the quantity of the outflow to the sea. Here we assume, for simplicity, given quantities of replenishment and withdrawal and hence also a given outflow to the sea.

C.4. Intuition

For an intuitive grasp of the concept of the steady state it is useful to notice that the endogenous variable in the model is the concentration of salts in the groundwater. The following three examples should clarify.

Example 1. Assume that exit of water to the sea is not 30 MCM/Y but 25 MCM/Y. The solution of equation (5) will now be 180 ppm chlorides (not 150). With a smaller quantity flowing to the sea, the concentration of salts in the aquifer is larger; the larger quantity ensures that, even with a smaller outflow, all the salts added with the replenishment are flushed to the sea (180*25=4,500).

Example 2. The calculation of the steady state can be reversed to compute the quantity of salts added to a reservoir. We do it for the entry of salts to Lake Kinneret. Chlorides concentration in the lake has been, for the past several decades, approximately 230 ppm; outflow to the river and the National Water Carrier is 418 MCM/Y. This means that on average 96,140 tons of chlorides exit the lake annually. Assuming a steady state, the annual entry into the lake is also 96,140 tons chlorides.

Example 3. Here we are returning to Model I and its arbitrary data; we shall exhibit dynamics, examine the first stages of the move from a given initial condition to the steady state. Assume that the initial sate is an aquifer with chloride concentration of 100 ppm, the total volume of the aquifer is 300 MCM. All other data are as in Model I.

The quantity of salts entering the aquifer this year (as in any year) is 4,500 tons. The quantity leaving in the outflow is 3,000 tons (30 MCM with a concentration of 100 ppm). Consequently, the net addition to the aquifer in this year is 1,500 tons; this addition increases the chloride concentration to 105 ppm. The quantity of salts entering next year will again be 4,500 tons. Exit will be 3,150 tons (30 MCM *times* 105 ppm). Hence the quantity added to the groundwater will be 1,350 tons chlorides and its concentration will reach 109.5 ppm. In this way the reservoir will converge gradually to the steady state in which chloride concentration in the groundwater is 150 ppm.

The last example demonstrates that the volume of the reservoir (the active volume) determines the *rate of convergence* toward the steady state; it does not affect the steady state itself. This is why the volume of the aquifer did not appear among the variables in Model I and its steady state analysis.

D. MODEL II

Model II is broader than Model I in two aspects: it is real and it deals with magnitudes that will serve for the extension of the analysis to the Coastal aquifer—including water use in the urban sector, desalination and utilization of effluent—and it also incorporates active removal of salts. Figure 1.2 will be explained below; it describes the flows of water and the concentrations of salts in the model. The removal of salts in Model II is by desalinating water from natural sources (Lake Kinneret and the aquifers) other alternatives will be examined in the next section of the chapter. The desalination reduces the quantity of salts in the water, but it also modifies the water balance since 10% of the water to be desalinated is removed to the sea as concentrate. We assume that this amount will be replaced by an identical quantity of desalinated seawater. In this way, there will be in the model (in the year 2020) two factors determining the quantity of seawater desalination; one is the aggregate demand for water in the country that will be, by forecasts, larger than the supply of water from natural sources; part of this desalinated water will reach the coastal region. The second factor will be desalination to replace the concentrate of the desalinated natural water.[7]

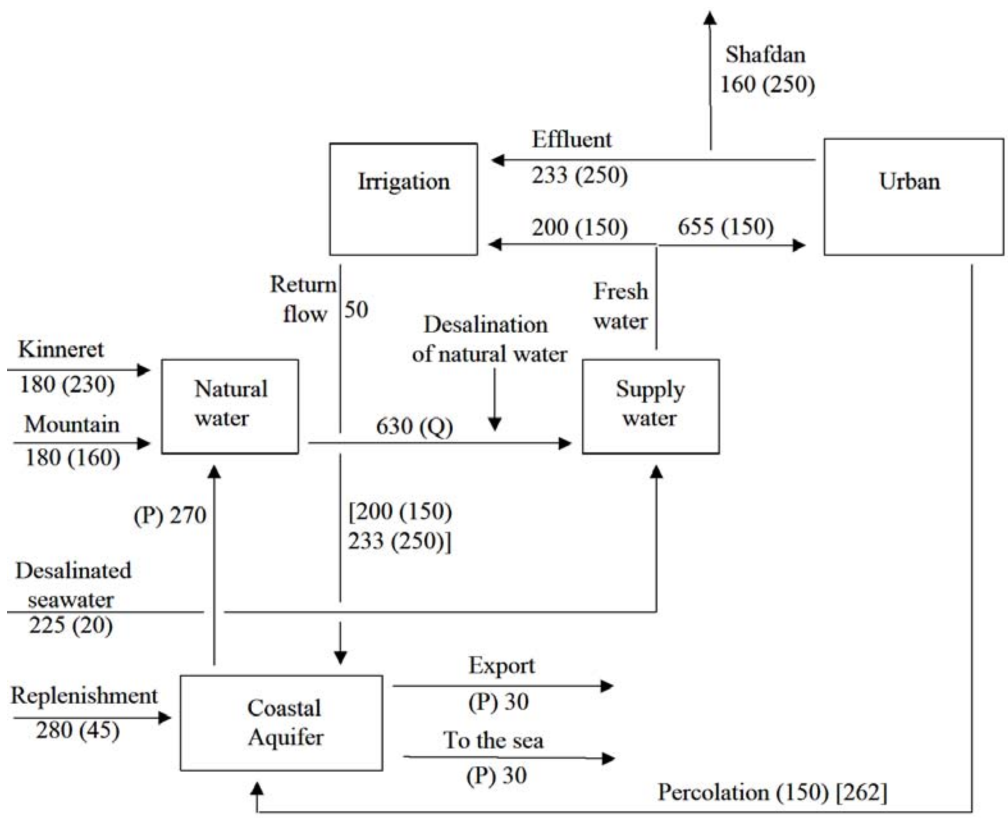

Figure 1.2. Model II, water flows and salt concentration.

[7] Perhaps it need not be added that, as seawater for desalination is external to the model, its concentrate is not replaced. It is only the net quantity that is incorporated into the model's computations.

In the circumstances described above, the magnitudes of the steady state—water and salts—will be found in the solution of a system of three equations in three unknowns. We term the magnitudes that vary with the solution *endogenous variables* and those taken as data *exogenous*. The distinction should become clearer once the variables are displayed in tables and equations.

D.1. Exogenous Variables

Table 2 reports water and salt magnitudes for 2020. The table is divided into three parts: natural water is the water from natural sources utilized above the coastal aquifer, in agriculture and in the urban sector; included here is water extracted from the Coastal aquifer itself as well as water imported from the mountain aquifer and Lake Kinneret. This water carries salts that are also recorded in Table 2. Other sources for water used above the coastal region are desalinated seawater and effluent. The third part of the table reports water use, outflow to the sea, and irrigation return flow (30 and 50 MCM/Y, respectively); for simplicity, we assume that these quantities are given. The last two magnitudes in table 2, export (outflow) of fresh water and Shafdan effluent, indicate use of coastal water and effluent in non-coastal regions. [8] The salts carried with this water will not be deposited above the Coastal aquifer and will therefore not return to the reservoir.

Table 2. Exogenous magnitudes in the Coastal aquifer in 2020

	Water	Salts added	Concentration
Natural water			
Coast	280	12,600	
Mountain	180	28,800	160
Lake Kinneret	180	41,400	230
Total natural	640	82,800	
Other sources			
Desalination (seawater)	225	4,500	20
Effluent	393	39,300	100
Other variables			
The urban sector	655		
Irrigation (fresh water)	200		
Outflow, to the sea	30		
Irrigation return flow	50		
Export, fresh water	30		
Export, Shafdan	160		

Remark: water in MCM, salts in tons chlorides per year, concentration in ppm chlorides.

Water imported adds salts to the Coastal aquifer. For example, salts concentration in the water of the mountain aquifer is 160 ppm chlorides; multiplied by 180 MCM, the imported

[8] Shafdan is the Dan (Tel Aviv) region wastewater reclamation project. Its effluent is delivered to the Western Negev; 100 km and more south of Tel Aviv.

mass is 28,800 tons chlorides. For the Coastal aquifer, water withdrawal and used in the region is forecasted to be 280 MCM. It is estimated that salts *added* from various sources will be 12,600 tons chlorides. The concentration cell is left empty for the Coast row in the table since the entry of these salts into the aquifer is not a function of the quantity withdrawn. Salt content in the aquifer's water is today close to 200 ppm. This magnitude does not appear in Table 2 either as the use of the aquifer's water above the reservoir does not *add* to the reservoir's mass of salts.

The forecast is that by the year 2020 the use of desalinated seawater in the coastal region will reach 225 MCM/Y and this is the magnitude recorded in Table 2 as an exogenous variable. The quantity of effluent was calculated as 60% of the water utilized in urban sector. The concentration of salts in the desalinated water is 20 ppm and 100 ppm chlorides are added in the effluent (added to the background water, to the water supplied to households and manufacturing). The quantities of salts and their concentrations for the section of Other variables are not recorded in Table 2 since these are endogenous variables and will be determined below.

D.2. The Water Sector of the Coastal Region

As indicated, we are examining in Model II a steady state with desalination of natural water in the coastal region. The *quality goal of the water economy* in the model is that fresh water is supplied in chlorides concentration of 150 ppm to all the users in the region—households, manufacturing, and agriculture. Total supply of water and salts, as reported in Table 2, is summarized below. Out of this, the supply of natural water is 630 MCM/Y (640-30-30+50).

	Water in MCM/Y	Chlorides in tons per year
Natural water	640	82,800
Seawater desalination	225	4,500
Effluent	393	39,300
Outflow of fresh water	-30	
Outflow to the sea	-30	
Irrigation return flow	50	
Total	1,268	126,600

To determine steady state magnitudes under the above constraints, define 3 endogenous variables to be the unknowns in the computation,

The concentration of salts in the natural water, ppm chlorides Q
Concentration of salts in the coastal aquifer, ppm chlorides P
Desalination of natural water, MCM/Y D

Turn now to Figure 1.2. Water flows are marked in the diagram by arrows and salt concentration is indicated in parentheses wherever appropriate. The natural water is, as in

Table 2, water from Lake Kinneret, the mountain aquifer and the water withdrawn from the coastal aquifer. (Withdrawal is replenishment *minus* outflow to the sea and to other regions *plus* irrigation return flow.) The concentration of chlorides in the coastal water is marked *P* and it is an endogenous variable to be calculated below. The water supplied for irrigation and the urban sector (households and manufacturing) is natural and desalinated water (the quantity of water desalinated for the removal of salts is not recorded in the diagram, it will be computed below). In accordance with the quality goal of the water economy, the concentration of salts in the water supplied to the urban sector will 150 ppm chlorides. The urban sector produces 393 MCM/Y sewage with salt concentration of 250 ppm chlorides (100 ppm are added to the background water). One hundred and sixty MCM/Y are exported from the region as Shafdan effluent, and 233 MCM/Y of local effluent is utilized for irrigation in the coastal region. Irrigation return flow to the coastal aquifer is 50 MCM/Y, however all the salts in irrigation water, both fresh water and effluent, reach the aquifer. To indicate this, we recorded in Figure 1.2, in brackets by the axis representing irrigation return water, irrigation water of the different kinds and the corresponding salt concentration. We assume that salts reaching households and not leaving in sewage also reach the coastal aquifer. The axis representing these salts is marked as percolation. [The water entering households and not leaving in sewage does not return to the aquifer; its quantity is therefore recorded in brackets (262 is 40% of 655).]

As the diagram indicates, the desalination for salt removal will be of natural water; as if all sources of natural water are mixed to a uniform quality before any part of it is desalinated. Other possibilities will be examined below.

The steady state magnitudes are computed recursively in three equations. In the first equation we calculate the concentration of salts in the coastal aquifer

$$\begin{gathered} 280\times 45+200\times 150+233\times 250+262\times 150=(270+30+30)P \\ P=425 \end{gathered} \tag{6}$$

The left-hand-side of equation (6) records the salts entering the aquifer: in the replenishment, freshwater irrigation, effluent and percolation. The magnitudes on right-hand-side are the quantities leaving the aquifer: withdrawals, exported to other regions, and outflow to the sea; these quantities are multiplied by the factor *P*, salt concentration of the steady state in the coastal aquifer. By the solution of the equation, the concentration is 425 ppm chlorides.

In the second equation of the model we calculate the concentration of the salts, before their removal, in the natural water

$$\begin{gathered} Q=(180\times 230+180\times 160+270\times 425)/630 \\ Q=293 \end{gathered} \tag{7}$$

In equation (7) we have used the concentration of salts in the coastal aquifer (425 ppm) calculated in equation (6). By the solution, the concentration of the salts in the natural water before desalination is 293 ppm.

We now calculate the quantity of water to be desalinated in the steady state to remove the salts reaching the coastal region

$$160 \times 250 + (30 + 30) \times 425 + (293 - 20)D = 126,600 \qquad (8)$$
$$D = 224$$

In the steady state, 224 MCM/Y of natural water will be desalinated to maintain the goal of supplying freshwater to households, agriculture, and manufacturing with chloride concentration of 150 ppm and still remove all the salts reaching the coastal region. (Recall that in the wake of this desalination there will be a desalination of additional 22.4 MCM/Y to compensate for the concentrate).

The solution of the three equations was reported here in rounded values, in the following calculations we use exact figures. Table 3 summarizes the quantities involved—exogenous and endogenous, the latter are underlined. Thus, for example, outflow of 30 MCM/Y to the sea flushes 12,741 tons of chlorides. The quantity of salts to exit is determined endogenously as it is the product of the quantity of water (an exogenous variable) by the concentration of the salts; the latter being an endogenous variable determined in the solution of the steady state. In the seawater desalination, the quantity 225 MCM/Y is determined exogenously, but the quantity 22 MCM/Y, against the concentrate, is determined endogenously.

The effluent appears in both sides of Table 3. All the quantity of the effluent produced in the coastal region is recorded on the left-hand-side: 393 MCM/Y. On the right-hand-side we write separately 160 MCM/Y of Shafdan water exported from the coastal region with the salts it carries. The rest, 233 MCM/Y of effluent, will be used for local irrigation. Hence the salts it carries do not exit from the coastal region and are therefore not registered on this side of the table.

Table 3. Salts and water in the steady state in Model II

Entering the reservoirs				Exit from reservoirs			
	Water	Salts	Concen-tration		Water	Salts	Concen-tration
Coast	280	12,600		Urban	655		
Mountain	180	28,800	160	Irrigation, fresh	200		
Kinneret	180	41,400	230	Outflow to sea	30	12,741	425
Seawater desalination	225 (22)	4,500	20	Export fresh	30	12,741	425
Effluent	393	39,300	100	Export Shafdan	160	40,000	250
Irrigation Return	50			Effluent in the coast	233		250
				Desalination of natural water	(224)	61,118	293-20
Total	1,308	126,600		Total	1,308	126,600	

Remarks: a. water in MCM/Y, salts in tons chlorides per year, concentration in ppm chlorides.
b. Underlined, endogenous variables.
c. Values in parenthesis are not included in the column's total.

The natural water to be desalinated, 224 MCM/Y, is closed in parenthesis as it does not leave the coastal region; the salts carried in this water do exit. The sum total for the water columns, 1,308 MCM/Y, is larger than the magnitude registered earlier (1,268 MCM/Y) as it includes here the exported freshwater as well (30 MCM/Y).

E. Selection of a Sustainable Alternative

This section examines the cost of 12 alternatives of the sustainable policy. Four are salt removal alternatives:

Desalination of natural water as in Model II (for average concentration of all natural water);
Desalination from a given source of natural water such as the Coastal aquifer or Lake Kinneret;
Desalination of the effluent (the salt concentration of which is relatively high);
Removal of the effluent to the sea and replacement of the same quantity by desalinated seawater.

Likewise, we examine three alternative salt concentrations in the supplied water (for households, manufacturing, and irrigation): 150, 100, or 50 ppm chlorides. As will be explained below, steady state quantities are maintained in all alternatives. Table 4 reports the cost assumptions (in US dollars) for the alternatives to be examined.

Desalinating the effluent improves the quality of the water supplied to agriculture; replacing effluent removed to the sea with desalinated seawater has a similar effect. To bring the other alternatives to a comparable water quality, we add in the following examination the option of upgrading the effluent; adding tertiary sewage treatment to the secondary treatment usually employed. The cost of the option is recorded in Table 4 as $0.10 per CM.

Table 4. Cost of operations

	Cost (US dollar per CM)
Seawater desalination	0.55
Desalination of natural water	0.20
Desalination of effluent	0.40
Removal of effluent to the sea	0.05
Tertiary treatment	0.10

E.1. The Twelve Alternatives

The endogenous magnitudes, the solution values of the steady state equations, are reported in Table 5. The first alternative is Model II that was calculated for the goal of 150 ppm chlorides in the water supplied and for the removal alternative by desalination natural water. As found above, for this alternative there will be a desalination of 224 MCM/Y of natural water and the average salt concentration in the coastal aquifer will be 425 ppm chlorides. Recall that this alternative also involves additional seawater desalination of 22 MCM/Y against the concentrate from the desalination of the natural water. This desalination comes in addition to the desalination of 225 MCM/Y determined exogenously and reported in

Table 3. (The desalination of 225 MCM/Y is not reported in Table 5 as its cost is not included in the comparisons of the table.)

Table 5. The twelve alternatives—quantities, concentration of salts in coastal water and cost

Removal alternative	Seawater desal	Natural w desal	Coastal w desal	Effluent desal	Effluent removal	Concentration in Coast aquifer	Cost
Quality goal: 150 ppm chlorides							
Natural water desal	22	224	0	0	0	425	80 (57)
Coastal water desal	14	0	151	0	0	425	62 (39)
Effluent desal	35+7	0	71	233	0	262	131
Effluent removal	233+7	0	71	0	233	262	158
Quality goal: 100 ppm chlorides							
Natural water desal	33	330	0	0	0	319	108 (84)
Coastal water desal	24	0	252	0	0	319	88 (64)
Effluent desal	35+24	0	239	233	0	192	173
Effluent removal	233+24	0	239	0	233	192	201
Quality goal: 50 ppm chlorides							
Natural water desal	49	490	0	0	0	214	148 (125)
Coastal water desal	48	213	270	0	0	214	146 (123)
Effluent desal	35+38	360	19	233	0	122	209
Effluent removal	233+38	360	19	0	233	122	236

Remarks: a. Columns 2-5 MCM/Y, concentration in ppm chlorides, cost in million US dollar per year.
b. In parenthesis cost of alternative without upgrading of effluent.
c. The desalination of natural water in the alternatives of effluent desalination and effluent removal for 50 ppm is of the water of Lake Kinneret and the Mountain aquifer.

The cost of removing the salts in Model II is $80 million per year (Table 5 row 1). This sum includes the cost of upgrading the effluent to tertiary treatment. Without upgrading, the cost is $57 million per year (in parenthesis). The alternative of desalination of water withdrawn from the coastal aquifer is examined in the second row of the table (in Figure 1.2, the desalination arrow is now pointing to the axis going from the coastal aquifer to natural water). Since in the steady state, salt concentration in the coastal water will be higher than in the other sources of the natural water, less coastal water will have to be desalinated to remove a given quantity of salts than in the desalination of mixed water; consequently, the cost of this alternative is lower than the cost of the first alternative.

In the third row, still fort the quality goal 150 ppm, we examine the alternative of salts removal by desalination of the effluent. The effluent to be desalinated is that remaining in the coastal area; the Shafdan effluent will not be desalinated. This alternative creates a difficulty:

given the 2020 quantities, even if all the quantity of the effluent is desalinated, not enough salt will be removed to maintain a concentration of 150 ppm chlorides in the supplied water. This is the reason for the inclusion, in this alternative of 71 MCM/Y of coastal water desalination. There will be also additional desalination of seawater, 7 MCM/Y against the concentrate from the fresh water and 35 MCM/Y against the concentrate of the desalination of the effluent (15%). The total quantity of desalination in this alternative for the coastal region in the year 2020 will be 571 MCM (225+233+71+35+7) and the cost of salt removal will be $131 million per year.

Desalination is even larger in the fourth row, where the alternative is to remove the effluent to the sea.

Desalinated water replaces in this alternative the effluent removed (this is desalination to maintain the total water quantity of the steady state). The cost of this alternative is $158 million per year.

The interpretation of the entries for the other 8 alternatives in Table 5 is similar to that of the alternatives that have been reviewed and, as can be expected, salt removal becomes more and more expensive as the quality goal tightens.

A Remark

The examination of the removal of salts in the steady state in the data for 2020 raises the issue of the salts that had accumulated in the last 50 years, part of this mass is already in the aquifer's water and part is still in the subsoil in the unsaturated zone above the groundwater table. Will these salts not be removed? The answer to the query depends on the choice of the quality goal for the steady state. A goal of 150 ppm chlorides means that a salt concentration of 425 ppm chlorides in the aquifer's water is acceptable (Table 5). If so, not only that salts accumulated in the past will not be removed, but salts will be allowed to accumulate further until the steady state is reached. If however, the goal is 50 ppm chlorides and salt removal is in desalination of the effluent, the salt concentration in the steady state in the aquifer will be 122 ppm chlorides (as against 200 today) and then, as the salts are removed the aquifer will gradually converge toward the steady state in a similar fashion to the way it did in the example presented in section C. That is, in this case the removal of salts will remove both all the salts that will be added in the future and part of the salt accumulated in the past.

Summary

The principal finding of the analysis is that, for all the alternative quality goals considered for the water economy of the coastal region, desalination of the coastal water is the lowest cost option. The cost differences between the alternatives are large and it is therefore safe to assume that a more detailed examination will not modify our principal finding and conclusion.

F. TIMING AND PRICES

The analysis, conducted for the conditions expected to prevail in 2020, raises two economic questions, the timing of salt removal and the implication for prices in the water economy.

F.1. Timing

Salts accumulate gradually; it takes years and even decades for salts deposit on the surface of the land to reach the aquifer's water. The question is then, when should salt removal commence? Could the expensive activity be postponed and left to future generations?

Here is a simple method for the determination of the activation date of salt removal: choose a water quality goal, it could be one of the goals specified in Table 5. The activation date of salt removal will be when chloride concentration in the aquifer's water reaches for the first time the steady state concentration corresponding to the chosen goal. For example, if the chosen goal is 100 ppm chlorides, removal will first be activated when concentration of salts in the coastal water reaches 319 ppm chlorides. In this way, the aquifer enters the steady state on the day the removal is first activated.

The difficulty is that this simple method ignores two aspects of the problem. One, that the removal of the salts improves the quality of the water, the other aspect is that there are now large quantities of salts doing their way toward the aquifer. This is why experts forecast that salt accumulation will accelerate in the coming years; salt concentration of 266 ppm chlorides is predicted for the year 2015. If this "time bomb" is really ticking on its way to the aquifer, the water economy is already in the salt accumulation rates expected for the future. Taking these two aspects of the accumulation problem into account justifies advancing the desalination to a date earlier than when the concentration in the aquifer reaches the chosen steady state.

F.2. Prices

The derivation of prices is presented in the appendix in a programming model. Here we offer a verbal discussion. Water in the model is supplied from the Coastal aquifer, Lake Kinneret, and seawater desalination. There are two consuming sectors, agriculture and urban. Agricultural production in the model is a function of fresh water and effluent. The effluent is a given ratio of the amount of water supplied to urban uses. Salts are removed by desalination of natural water.

The freshwater cost function is increasing: the lowest cost is coastal water, Lake Kinnert's comes next, and desalinated seawater is the most expensive. By assumption, prices are set equal to marginal cost. The appendix considers two cases that differ by the demand for water.

In the low demand case, the coastal region is supplied with fresh water from the local aquifer and from Lake Kinneret; seawater is not desalinated. Salts are removed by desalination of natural water. The price of fresh water is determined by the marginal product of water in agriculture and it is set, in equilibrium (at maximum net income), to equal the cost of moving water from Lake Kinneret *plus* the cost per CM of removing from the water of the Coastal aquifer the salts imported with the lake's water. The price of the effluent is a fraction of the price of fresh water, the fraction representing the comparative productivity of the recycled water.

In this low demand case, only the coastal water is scarce and has, in the model, a scarcity value. This value, and hence the extraction levy of coastal water, is equal to the price of fresh water *minus* the cost of its withdrawal. No scarcity value is attributed to the water of Lake Kinneret. The urban sector is seen in the program as if selling the effluent to agriculture; hence the net price urban dwellers pay for water equals the opportunity cost, the marginal productivity of water in agriculture, *plus* the cost of treating the sewage *minus* the price farmer pay for the effluent (only part of the water ends as effluent).

In the high demand case, seawater desalination is activated and the marginal productivity of water in agriculture is equal to the cost of desalination *plus* the cost of the removal of the (small amount) of salts left in the desalinated water. Desalinated water is supplied when the other water sources cannot satisfy the demand. Hence, in this case, the withdrawal constraint in Lake Kinneret is binding and the scarcity value of its water is positive; it is equal to the marginal productivity of water at the coast *minus* the cost of moving the water from the lake, and *minus* the cost of removing the salts carried in the Kinneret water. It is interesting to examine the difference in the cost of the lake's water in the two demand cases. In the low demand case, the users of water at the coast pay for the removal of the imported salts; the higher salt concentration, the higher the price of water. In the high demand case, on the other hand, water users pay the same price whatever the salt concentration in Kinneret's water. The fisc, the taxpayers, pay for the removal of the salts: the higher the concentration, the lower the extraction levy. The government sells low quality (salty) water and is paid accordingly.

CONCLUSION

Our calculations were based on simplifying assumptions and they should be taken as first approximations. Still, it can be expected that the two principal conclusions we have reached will not change with more detailed analysis. The first conclusion is that salt removal is an expensive operation. To show this, assume that the cost of delivering water to the coastal region is $0.15 per CM for aquifer water (Coastal or Mountain) and $0.30 per CM for Lake Kinneret water. With these magnitudes, the total cost of supplying 640 MCM/Y is $123 million per year. The cost of removing the salts in the steady state (desalination of coastal water), even if the modest quality goal of 150 ppm chlorides is chosen and the effluent is not upgraded, will be $57 million per year. This is an addition of close to 50% to the cost of the water economy.

The cost of removing the salt is high, but the cost of not doing it will be even higher. For example, if we let the aquifer deteriorate until its water cannot be used any more, water will be supplied from seawater desalination; the cost will be $154 million per year, more than twice the cost of maintaining a sustainable aquifer. Salt removal is a precondition for the maintenance of a sustainable water economy and its cost is part and parcel of the cost of the intensive utilization of the water resources. Just as a household has to remove sewage and garbage, so also one of the tasks of the water economy is to remove the salts and prevent their accumulation in the reservoirs.

The second principal conclusion of the analysis is that the efficient way to remove the salts is desalination of natural water from the saltiest source. The reason being that with this alternative the quantity desalinated is markedly smaller than in the other alternatives.

The computations in the analysis were conducted for the steady state in which, for example with the quality goal of 150 ppm, the concentration of salts in the coastal water is

425 ppm chlorides and then the efficient way to remove salts is by desalination of this source. However, if desalination were to commence today, when the concentration of salts in the coastal water is only 200 ppm, it would be advisable to start by desalinating the water coming from Lake Kinneret until the concentration in the Coastal aquifer exceeds that of the imported water. Another possibility, and even more reasonable, is to start desalination in most salty regions in the coastal aquifer itself.

These comments demonstrate, if a demonstration was necessary, that the analysis was preliminary. The continuing analysis will cover the other aquifers and incorporate engineering considerations. Also, the expected rate of desalination and the optimal date for removing the salts will have to be studied in further detail. Another subject for inquiry is the fate of salts exported from the coastal region; for example, will salts have to be actively removed from areas irrigated by Shafdan water?

APPENDIX: PRICES IN THE WATER ECONOMY

The prices are determined in a mathematical programming model of the coastal region in a steady state. The model is both broader and narrower than the framework of the discussion in the chapter. It incorporates agricultural production, that was not included explicitly in the chapter, but import of mountain water and exit of water and effluent from the region are disregarded in the formulation of the appendix. The objective function of the programming model is the value of agricultural output *minus* the cost of the water economy. The sources of freshwater are the Coastal Aquifer, Lake Kinneret, and seawater desalination; effluent is used in agriculture. There are two consuming sectors in the model—urban and agriculture. The urban sector receives a predetermined quantity of water. A given ratio of the water used in this sector is collected as sewage and, after treatment, provided as effluent. Irrigation deposits salts on the surface of the land and identical quantities are added to the water in the aquifer. Additional salts come from autonomous sources (ocean spray and underground brines). Freshwater desalination is used to remove the salts.

A. Functions and Variables

F( )	A well-behaved production function in agriculture (NIS per year)
f( )	Value of marginal product in agriculture (NIS per CM)
b	Constraint or requirement of provision (CM per year)
M	Freshwater (CM per year)
R	Effluent (CM per year)
μ	Salt concentration in water (gram chlorine per CM)
δ	Addition of salt (gram per CM, per year)
Δ	Autonomous addition of salts (grams per year)
λ, ϕ	Lagrange multipliers (shadow prices)
γ	Value of effluent in agriculture relative to freshwater
r	Ratio of effluent in urban water

C	Cost (dollars per CM)
P	Price (dollars per CM)
E	Extraction levy (dollars per CM).

B. Indexes

A	Agriculture
U	Urban
K	Kinneret
H	Coastal region or aquifer
DH	Desalination of coastal water
DK	Desalination of Kinneret water
T	Desalination of seawater
R	Effluent.

C. The Structure of Cost

Average cost is assumed to be constant per source, scale effects are disregarded and the costs rise; the lowest cost is withdrawal of coastal water, next Kinneret's water at the coast, and the most expensive is desalinated seawater.

$$C_H < C_K < C_T$$

D. Resources and Uses, Constraints, and Supply Requirements

D.1. Equality Constraints

Freshwater: provision to agriculture and the urban sector is equal to supply for the coastal aquifer, Kinneret, and seawater desalination

$$M_A + M_U = M_H + M_K + M_T$$

Effluent: supply to agriculture plus removal to the sea is equal to the quantity collected and treated in the urban sector

$$R_A + R_S = rM_U$$

Salt: the quantity added to the coastal region is eliminated by desalination of coastal or Kinneret water (the concentration of chlorides in the desalinated water is 20 ppm)

$$\Delta_H + \mu_K M_K + \delta_R R_A + 20 M_T = (\mu_H - 20) M_{DH} + (\mu_K - 20) M_{DK}$$

Urban water constraint

$$M_U = b_U$$

D.2. Inequalities

Coastal Aquifer, extraction	$M_H \le b_H$
Kinneret, extraction	$M_K \le b_K$
Coast, desalination	$M_{DH} \le M_H$
Kinneret, desalination	$M_{DK} \le M_K$

D.3. Nonnegativity

All the quantity variables are nonnegative.

E. The Programming Problem

Equation (A.1) is the Kuhn-Tucker Lagrangian of the programming problem. Following Simon and Blume (1994), we write specific multipliers for the constraints: λ for equalities and ϕ for inequalities. In this formulation, the quantities are the primal variables, they are the activities of the program; the Lagrange multipliers are the dual variables.

$$\begin{aligned}L &= F(M_A + \gamma R_A) - C_H M_H - C_K M_K - C_T M_T \\ &-C_A R_A - C_D(M_{DH} + M_{DK}) \\ &-\lambda_M(M_A + M_U - M_K - M_H - M_T) \\ &-\lambda_R(R_A - rM_U) - \lambda_D[\Delta + \mu_K M_K + 20M_T + \delta_R R_A \\ &-(\mu_H - 20)M_{DH} - (\mu_K - 20)M_{DK}] \\ &-\lambda_U(b_U - M_U) - \phi_H(M_H - b_H) - \phi_K(M_K - b_K)\end{aligned} \tag{A.1}$$

We skip the derivation of the first order condition and demonstrate application in two cases; the first corresponds to relatively low demand for water in the coastal region; the second case represents conditions of higher demand.

E.1. Case I

By construction, in the solution of this case, extraction from the coastal aquifer is up to the constraint and additional quantities of water are moved from Kinneret; part of the water extracted in the coast is desalinated; fresh water is supplied to the urban sector and to agriculture; effluent is supplied to agriculture.

Writing formally,

$$\begin{aligned}&M_A > 0 \\ &R_A = rM_U > 0 \\ &M_H = b_H > 0 \\ &0 < M_K < b_K \\ &M_U = b_U > 0\end{aligned} \tag{A.2}$$

The value of the primal variables that do not appear in (A.2) is zero.

Combining the first order derivatives and (A.2), the following multipliers were factored out

$$\begin{aligned} \lambda_D &= C_D/(\mu_H - 20) \\ \lambda_M &= f(M_A + \gamma R_A) = C_K + C_D\mu_K/(\mu_H - 20) \\ \phi_H &= f(M_A + \gamma R_A) - C_H \\ \lambda_R &= \gamma f(M_A + \gamma R_A) - C_A - C_D\delta_R/(\mu_H - 20) \\ \lambda_U &= \lambda_M - \lambda_R r \\ &= f(M_A + \gamma R_A)(1 - r\gamma) + r[C_A + C_D\delta_R/(\mu_H - 20)] \end{aligned} \qquad \text{(A.3)}$$

The first shadow price in (A.3) is of desalinated coastal water. It is the cost of desalination of one CM divided by the amount of salt removed; that is, λ_D is the cost of salt removal per gram of chloride.

The multiplier in the second equation in (A.3), λ_M, is the Value of the Marginal Productivity of water in the coastal area agriculture and it is also equal to the marginal cost of water provision. The cost of moving water from Lake Kinneret to the coastal region is higher than the cost of local extraction. Hence, if in the solution of (A.1) water is moved, the marginal cost of freshwater, λ_M, is the cost of the lake's water at the coast and this magnitude is equal to the cost of moving the water from the lake *plus* the cost of removing the salts brought by its water.

The third equation defines the scarcity cost of coastal water, ϕ_H; it equals to the VMP of water *minus* cost of extraction; in other words, to the cost of water from Lake Kinneret *minus* extraction.

The value of the effluent in coastal agriculture is λ_R and it is its VMP (water's multiplied by γ) *minus* the cost of sewage treatment and the removal of the salts added in the urban sector. The cost of water to the urban sector is the opportunity cost of freshwater in agriculture *minus* the value of the effluent the town transfers to the farm sector; that is, the program visualizes the urban sector as purchasing water, treating its sewage, and selling the effluent to farmers at a price equal to its VMP.

Given the multipliers of (A.3), the prices and the extraction levy will be

$$\begin{aligned} P_A &= \lambda_M = f(M_A + \gamma R_A) = C_K + C_D\mu_K/(\mu_H - 20) \\ P_R &= \gamma P_A \\ P_U &= \lambda_U \\ E_H &= \phi_H \end{aligned} \qquad \text{(A.4)}$$

By the first line in (A.4) farmers (and urban users) pay for the transfer of water from Kinneret and also for the removal of the salts carried by the water from this source. The last attribute will be modified in the next case.

E.2. Case II

This case corresponds to higher profitability in agriculture than in Case I and therefore the solution calls for larger quantities of water, the extraction constraint in the Kinneret is met, and seawater is desalinated. Formally, we add to (A.2)

$$\begin{aligned} M_K &= b_K > 0 \\ M_T &> 0 \end{aligned} \tag{A.5}$$

The shadow price of freshwater is now

$$\lambda_M = f(M_A + \gamma R_A) = C_T + 20C_D / (\mu_H - 20) \tag{A.6}$$

The marginal cost of desalinated water is the cost of desalination *plus* the cost of removing the (small amounts of) salts desalinated water adds to the aquiver.

The other multipliers will be in this case

$$\begin{aligned} \lambda_D &= C_D /(\mu_H - 20) \\ \phi_H &= C_T + 20C_D / (\mu_H - 20) - C_H \\ \phi_K &= C_T + 20C_D / (\mu_H - 20) - C_K - C_D\mu_K /(\mu_H - 20) \\ \lambda_R &= \gamma \left[C_T + 20C_D / (\mu_H - 20) \right] - C_A - C_D\delta_R /(\mu_H - 20) \\ \lambda_U &= \left[C_T + 20C_D / (\mu_H - 20) \right](1 - r\gamma) + r[C_A + C_D\delta_R /(\mu_H - 20)] \end{aligned} \tag{A.7}$$

Again, the prices are

$$\begin{aligned} P_A &= \lambda_M \\ P_R &= \gamma P_A \\ P_U &= \lambda_U \\ E_H &= \phi_H \\ E_K &= \phi_K \end{aligned} \tag{A.8}$$

Here, in Case II, the scarcity value of Lake Kinneret water, ϕ_K , is positive; it was zero in Case I. Unlike in the previous case, now the cost of removing the salts carried from the lake is shouldered by the public at large (the fisc) and not just by the users in the coastal area. To see this, examine the components of ϕ_K : the higher the concentration of salts in the lake's water (μ_K) the lower the scarcity value. The government provides the coastal users with water of low quality (salty) and is paid accordingly.

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