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Agricultural Systems 64 (2000) 115–130

AGRICULTURAL SYSTEMS

www.elsevier.com/locate/agsy

Response of near-optimal agricultural production to water policies

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Received 20 May 1999; received in revised form 9 September 1999; accepted 31 March 2000

Abstract

The paper presents a study triggered by water policies, imposed by the Israel Water Commissioner on agriculture to cope with a shortage of water. Those policies were a combination of price policies and quantity restrictions. We analyze them for the case of the Jezreel Valley district, using a deterministic linear programming optimizing model. The optimal solution finds the mix of crops that maximizes the net income of the district. The results show that a mixture of policies to attain a single end is not efficient and can have unintended side effects. In particular, when water quotas are binding, raising water prices does not increase water productivity and merely places a tax on farmers. The response of Jerzreel Valley agricultural to water quota policy is affected significantly by the presence of unirrigated winter crops as an alternative to water-using crops. The model provides a useful decision-support tool for analyzing water policies.

Keywords: Water policies; Optimisation models

1. Background

In Israel, water is controlled by a governmental authority — the Water Commissioner (IWC). The IWC's responsibilities include mining, supplying and distributing all types of water (fresh, recycled, brackish, surface) to all water-consuming sectors: households, industry and agriculture. The renewable yearly amount of water in Israel is almost totally dependent on rainfall and, thus, is subject to irregularities, drought years and severe uncertainty regarding amounts, places and timing. More than 95% of that total yearly amount is already being used (Kally, 1997).

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0308-521X/00/$ - see front matter
PII: S0308-521X(00)00018-4

There are three main means by which the IWC controls water: water quotas, prices and administrative limitations on crops. The legal basis for the IWC capacity, responsibility and power is the Israel Water Law. Regarding water pricing, that law (paragraph 112) suggests, among other procedures, that the minister in charge of IWC will decide on water prices after considering the ability of water users to pay (free translation).

As a water-consuming sector, agriculture has the following characteristics: (1) it uses approximately 65% of Israel's total water amount (Kally, 1997); (2) it can use low quality water; (3) agricultural demand for water is not steady, fluctuating considerably in time and space; (4) the required dependability of water supply for agriculture is by far lower than that for the other sectors; (5) agriculture's ability to pay for water is significantly lower than that of the other sectors; (6) agriculture is very flexible in water use and can be adapted to rapid changes in water supply patterns (Amir et al., 1991, 1992).

Resulting from several consecutive drought years, a water crisis occurred in Israel in 1990. Among others, three measures were taken by the IWC to cope with it: (1) a significant reduction of water quotas for agricultural use; (2) increase of water prices; and (3) administrative limitations on certain crops (cotton in particular).

These measures resulted in a very noisy and bitter dispute between the authorities and the farmers' organizations. That dispute provided the incentive for us to analyze quantitatively the water policy measures involved.

To do this an optimizing model was formulated and run on the agricultural production systems of 12 kibbutz settlements in the Jezreel Valley, one of the agricultural districts in Israel. These 12 systems, which were planned and operated separately, were aggregated to one unit for this model. The reason for doing this is that water policies and water supply systems are planned and operated on a district level.

The model was run using 1989 data. After the calibration stage of the model (see further explanation below) it became apparent that the actual agricultural production of the combined production system was close to the optimal production suggested by the model. The analysis regarding water policy for near-optimum agricultural systems showed three main points: (1) limiting water amounts can be a suitable measure to cope with water shortage, provided that the policy is based on an economic analysis; (2) increasing water prices, as a policy, does not necessarily lead to an increase in the productivity of water use, as is commonly known or assumed (Eckstein and Fishelson, 1994); raising prices when water quotas are binding acts as an unjustified penalty, especially on efficient farmers; and (3) limitations on certain crops (e.g. cotton) should be very carefully examined to avoid undesired effects on water use under certain conditions.

As we shall see, the simultaneous use of more than one method of limiting water use can lead to a situation in which one or more methods turns out to be redundant. In such a situation, there can be unintended side-effects.

This paper presents a model of a near-optimal agriculture production system and uses it to analyze the system's response to changes in water amounts and prices and to administrative limitations on crops. We do this to focus decision-makers' attention when considering water-pricing policies.

2. The model

The model is aimed at providing a quantitative analysis of the sensitivity of agricultural production to changes in water amounts, water prices and area limitations on crops.[1] The analysis is carried out using an optimizing model activated under a systematic series of reducing water amounts, increasing water prices and with or without cotton. The optimizing model is formulated using the linear programming method (LP). Its elements are detailed as follows.

2.1. The objective function

The objective function, Z, is the net income of the entire unit, to be maximized by selecting the optimal mix of crops under existing limitations.

$$\max.\ Z = \Sigma X_j \times [\mathrm{WRC}_j - \Sigma(P_i \times W_{ij})], \tag{1}$$

where X_j is the area of the j-th activity (dunam[2])—the decision variables; P_i is the price of 1 m^3 of water of quality i (fresh, recycled); W_{ij} is the water demand for water of quality i by one dunam of the crop j; and WRC_j is the water-related contribution (income) per area unit of crop j.

WRC_j is defined as the gross income of an area unit of the activity j minus all direct expenses (machinery, labor, materials, fertilizers) other than the expenses for water (the net income would then be WRC minus water expenses). It measures the maximum ability of the activity to pay for water. (Note: such a contribution could be defined also for labor and machinery if they are the main concern of the problem.)

2.2. The constraints

The constraints reflect the size of land area, amounts of water and labor available for the agricultural production system under consideration.

2.2.1. Land constraints

The equations for the land constraints are of the form:

$$\Sigma X_{jk} \leqslant A_k, \tag{2}$$

where X_{jk} is the area of activity j in the category k (see below); and A_k is the total area available for category k.

[1] For a detailed discussion of this model and its application to other Israeli districts, see Amir and Fisher (1999).

[2] A dunam is one-tenth of a hectare, or 1000 m^2.

The categories (k) are:

1. all activities (irrigated and unirrigated);
2. all irrigated activities (including fish ponds);
3. crops of the same group (field, orchards, flowers, non-irrigated);
4. crops irrigated by the same water quality (in Jezreel Valley there are two qualities, namely fresh and a mix of recycled, brackish and surface water);
5. crops grown during the same season; and
6. Unirrigated winter crops on irrigable land.

Example: when category k is all irrigated activities, the relevant constraint, Eq. (2), reads that the sum of all irrigated crops j is limited by the total land area available for irrigated crops in the production system under consideration.

The set of land constraints, expressed by Eq. (2), ensures that the sum of the land areas of the crops under each category k will not exceed the area available in the district for that category.

2.2.2. Water constraints

Water constraints are of the following general form:

$$\Sigma W_{ij} \times X_j \leqslant W_i, \tag{3}$$

where W_{ij} is the demand for water quality i (fresh and recycled) by a unit area of the crop j; and W_i is the total amount of water of quality i available.

These constraints ensure that the sum of amounts of water of quality i, required by all crops j, will not exceed the total amount of water of quality i available in the district.

Another water constraint ensures that the total of the two water qualities will be limited by the total water available, either existing or imposed administratively:

$$\Sigma W_i \leqslant W, \tag{4}$$

where W_i is the total available amount of water of quality i, and W is the total amount of water available.

2.3. Inputs

The inputs consist of data on crops per unit area and per unit water, as well as data for the entire district on land and water resources and additional water-consuming activities (such as livestock). The inputs include:

1. water demands per unit area;
2. water-related contribution (WRC) of each crop;
3. the availability of water, land and labor in the production system; the 1989 land area of perennials, orchards, unirrigated crops, greenhouses and fish-ponds; and
4. actual income, water uses and labor in the district.

2.4. Outputs

The outputs are the optimal solutions calculated by the model:

1. optimal land use for a mix of crop areas that maximizes the net income of the district;
2. optimal use of water and labor;
3. post-optimal sensitivity analysis providing the shadow prices of the binding constraints and ranges in which the optimal basis is maintained in spite of changes in the input data (Sher and Amir, 1993); and
4. several tables of calculated factors for the analysis (e.g. income per water, income per land, percentage of fresh and recycled water).

3. Application

The model was run in two stages. The first stage was calibration, aimed at examining and evaluating the formulation of the model and the values of the factors entered as inputs. The calibration stage was done by comparing the actual data of the year 1989 with the model results for the same input data both per unit area and unit water, as well as for total water and land use (further explanation below). The second stage, carried out after the calibration stage had shown acceptable results, was to run a series of systematic changes in the two policy-making decision variables, namely water amounts of fresh water (quotas) and water prices. The systematic runs were aimed at simulating and analyzing the trends of the response of agricultural production to these variables. While for the first stage the list of crops was obviously limited to the existing ones in 1989, for the second stage — simulation of future scenarios — more crops were added to that list. Additional runs were carried out to analyze the case in which cotton was not allowed.

4. Calibration — a comparison with 1989 data

The purpose of the calibration process is to examine the model ability and its dependability to reflect the real system as a decision support tool. Basically, the calibration is done by comparing the actual performance of the system in the year 1989 with results provided by the model. For this purpose the majority of the model input data used are forced to take the 1989 actual values, whereas the others are allowed to deviate from those values. The deviations of the entire system from the actual performance, due to changes in part of the input data of the model, enable examining the formulation and the input data of the model used. In our case, certain deviations from 1989 data were allowed in water requirements, WRC and total areas of crops. The allowed crop area deviations were ±15% for perennial high investment crops (such as orchards and greenhouses) and ±50% for vegetables. The industrial crop and grain areas, being low investment and very flexible crops, were free decision variables, meaning that they could have taken any value within the system framework. The comparison between the results of the model and the actual 1989 data in the calibration procedure is presented in Table 1.

In Table 1 the following two main features can be noted:

1. The differences between actual and optimal areas of all crops are within the range of about ±23%, in spite of the fact that field crops, fodder, cotton and maize, which occupied 90% of the total crop area, were allowed to change freely. The orchard area was forced to remain unchanged.
2. The difference between actual and the optimal incomes (for the same amount of water) was 1.46%. The calculated average net income per cubic meter, obtained by the actual and the optimal plans, were 0.915 and 0.928 NIS/m^3, respectively. Taking into account the inaccuracies of the input data and the limitations of a model in reflecting reality, such a difference can well be ignored. It certainly means, however, that the 12-kibbutz unified system managed to use their water quotas very efficiently. This was an exceptional achievement by itself because, in reality, all of the kibbutzim acted separately; unifying their separated systems was a model artifact. The fact that one can treat the district as an aggregate suggests that the overall water quotas for the district were distributed over the individual kibbutzim in a way that did not interfere with district-wide efficiency.

As a very important part of the calibration procedure, the results of the calibration runs were presented to, and thoroughly discussed with, several managers of the agricultural production units under consideration. They approved the data, the results and the dependability of the model.

Table 1
Comparison between actual data and model optimal solution — Jezreel Valley, 1989[a]

Item	Unit	Actual 1989	Model optimum	Difference (%)
Irrigated winter crops	Dunam	20 569	17 738	−13.76
Industrial crops	Dunam	47 680	46 418	−2.65
Vegetables	Dunam	2190	1696	−22.56
Orchards	Dunam	12 333	12 333	0.00
Total irrigated land	Dunam	82 772	78 185	−5.54
Total unirrigated land	Dunam	75 884	80 471	6.04
Total land use	Dunam	158 656	158 656	0.00
Total fresh water	mcm	21.586	21.586	0.00
Total recycled water	mcm	10.586	10.586	0.00
Total water	mcm	32.172	32.172	0.00
Total net income	Million NIS	29.422	29.853	1.46

[a] In 1989, the prices of fresh and recycled water were 0.23 and 0.17 NIS/m^3, respectively. Dunam, 1000 m^2; mcm, million cubic meters.

5. Simulation of agricultural production — systematic runs

After the calibration stage, systematic runs of the model were carried out to simulate the optimal agricultural production response to reducing water quotas and to increasing water prices. Selected data for Jezreel Valley, relevant to the analysis of its near-optimum agricultural production response, are presented in Table 2. Values of income versus water amounts for the two sets of prices, taken from Table 2, are presented in Fig. 1.

6. Analysis

The analysis includes discussions of the three measures taken by the IWC, namely water quotas, water prices and land limitations on crops (cotton).

6.1. Water quotas

From Table 2 and Fig. 1 several aspects can be deduced. Income decreases with water quantities. For P1 the decrease of income is from 29.852 to 22.508 million NIS, or $\Delta In = 7.344/29.852 = 24.6\%$, whereas the decrease in water amounts is from 32.170 to 19.586 million m^3 (mcm), or $\Delta W = 12.584/32.170 = 39.11\%$. The decrease of the income (24.6%) is lower than the decrease of water amounts (39.11%). The marginal production per water unit within the range of water amounts is $\Delta In/\Delta W = 7.344/12.584 = 0.584$ NIS/m^3. Such a marginal production is quite low. It is about half the production per water unit of each of the crops, the average of which

Table 2
Optimal water amounts, water-related contribution and productivity for Jezreel Valley for two sets of water prices[a]

Water amounts (mcm)	Net income		Water expenses		Productivity, E		
	P1 (million NIS)	P2 (million NIS)	P1 (million NIS)	P2 (million NIS)	P1 (NIS/NIS)	P2 (NIS/NIS)	Ratio E(P1)/E(P2)
9.000	22.508	19.602	3.870	6.776	6.82	3.89	1.75
12.000	24.389	20.973	4.560	7.976	6.35	3.63	1.75
15.000	26.165	22.239	5.250	9.176	5.98	3.42	1.75
18.000	27.874	23.438	5.940	10.376	5.69	3.26	1.75
21.586	29.852	24.806	6.764	11.809	5.41	3.10	1.75

[a] P1, fresh water 0.23, recycled water 0.17 NIS/m^3; P2, fresh water 0.40, recycled water 0.30 NIS/m^3. mcm, million cubic meters. Notes: (1) The reduction in the total water amount is due to reduction in the fresh water only. The recycled water amount remained constant at 10.586 mcm. (The quality of water, expressed by the ratio of the amounts of fresh and recycled water, decreases with the reduction of fresh water.) (2) In the paper we assumed the same WRC and water requirement per dunam for fresh and recycled water. This assumption is debatable. It is, however, widely adopted in Israel and in Jezreel in particular.

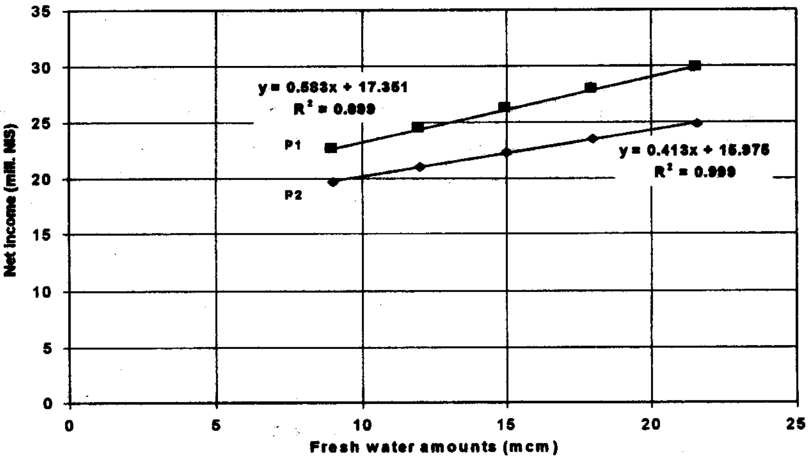

Fig. 1. Net income versus fresh water amounts at two different price sets. The upper curve is for the low water prices of 0.23 for fresh water and 0.17 NIS/m^3 for recycled water, denoted P1 in Table 2, whereas the lower curve is for the high prices of 0.40 and 0.30 NIS/m^3, denoted P2.

(including recycled water) is 1.138 NIS/m^3 (36.616/(21.586 + 10.586)). The analysis showed that the moderate decrease of income, resulting from the low marginal production, could be explained by the fact that unirrigated (rain-fed) winter crops were a feasible alternative to irrigated crops.[3] The relevant values (taken from the model) show that the net income of unirrigated winter crops is 71 NIS/dunam, whereas the WRC per dunam of irrigated winter crops is 168 NIS/dunam, requiring a water amount of 220 m^3/dunam. The net income of irrigated winter grains, for the weighted average water price of 0.210 NIS/m^3 in 1989, was $168-220\times0.210=121.8$ NIS/dunam. The difference in the net incomes between irrigated and unirrigated winter crops was $121.8-71=50.8$ NIS/dunam. Although such a difference in income per dunam was quite significant, the marginal alternative contribution of water was $(121.8-71)/220=0.23$ NIS/m^3, which was quite small. Thus, growing unirrigated winter grains resulted in two outcomes: (1) total income was reduced by 0.23 NIS/m^3; and (2) the reduction in total income, 0.23 NIS/m^3, was relatively small compared to the average income from the crops in the optimal mix.

From the moderate reduction of income compared to the large reduction of fresh water, one may conclude that for Jezreel Valley, in which unirrigated winter crops are a real alternative to irrigated crops, the policy of administrative reduction of water quotas may be economically justified. That is, fresh water can be transferred to other districts that are willing to pay more for fresh water because they do not have the alternative of unirrigated crops.

Note: There are, however, two very serious limitations to the selection of unirrigated crops as an alternative to irrigated crops in Israel: (1) availability of sufficient

[3] Unirrigated crops comprise areas that cannot be irrigated (76 884 dunams) and unirrigated areas in irrigable land (3602 dunams).

rainfall (e.g. more than 300 mm/year for winter grains); and (2) rainfall in Israel is a stochastic resource in its amounts, place and time. Therefore, growing rain-fed crops is risky. When unirrigated crops are considered as an alternative, the risk involved in rainfall should be reflected in the WRC of unirrigated winter crops. The reduction should be a function of the variance of the statistical distribution of rains in the district under consideration.

6.2. Water prices

The difference between the two curves in Fig. 1 expresses the difference of water expenses, D_{we}, for the two sets of the water prices for every water quantity Q (from 9 to 21.586 mcm). It is calculated by:

$$D_{we} = Q \times (P_{a1} - P_{a2}), \tag{5}$$

where D_{we} is the difference between the water expenses; Q is the water quantity; and P_{a1} and P_{a2} are the weighted average water prices of the two sets of prices, calculated by:

$$P_{a1} = \frac{(P_f \times Q_f + P_r \times Q_r)}{(Q_f + Q_r)}, \tag{6}$$

where P_f, Q_f, P_r and Q_r are water price (P) and quantity (Q) of fresh and recycled water types.

From Fig. 1 it can be seen that the differences between the net incomes for the two sets of water prices are around 2 million NIS throughout the entire range of water quantities used. The slopes of the lines are: for P1: (29.852–22.508)/(32.172–19.586) = 0.58; for P2: (24.806–19.602)/(32.172–19.586) = 0.41 NIS/m^3. The difference, 0.58–0.41 = 0.17 NIS/m^3, is exactly the difference between fresh water prices (0.40–0.23 = 0.17). This phenomenon points out the fact that the cropping patterns were the same at both fresh water prices. We discuss this in greater detail below.

Since all quotas of fresh water are used at both prices and the same amount of recycled water is used for all runs, the intercepts are just the expenditures on recycled water for the two prices. This is because the regression assumes that the same fixed expenditure is made independent of water amount. The difference between the intercepts, 1.376 million NIS, is the difference in the recycled water prices multiplied by the (constant) amount of recycled water used (10.586 mcm).

On the other hand, the slopes are not the expenditure on fresh water per cubic meter, because they involve the income being made and the costs of other factors; however, with the same water amounts being used, the difference in the slopes (0.17 NIS/m^3) reflects the difference between the prices of fresh water per cubic meter.

To further analyze the effect of water prices on agricultural production we introduce now, as an economic measure for water, the term 'water productivity ratio'. It is the ratio between the water productivity *E*(P2) and *E*(P1) at prices sets P2 and P1, respectively, as defined above (see explanation in Table 2). Water productivity ratio is calculated for each water amount, using the last two columns of Table 2.

From the solution we see that the WRC for the two sets of water prices remain the same for every fresh water amount. This is a direct result of the fact that the restrictions on the total amounts of water are binding in the solution at both sets of water prices. It also means that the optimal mix of crops does not change with the different price sets. Thus, the policy of raising water prices together with reducing water amounts does not change the near-optimal practice of the production but simply reduces the income of the most efficient farmers. This conclusion can clearly be deduced from Table 3, that for given fresh water amount all crop areas and water amounts are the same. As a result, the water productivity ratio is the same for all water quantities.

The crop patterns that resulted from water limitation suggest the following:

1. Orchard areas are stable as long as fresh water amount is not less than 9 mcm.
2. The first 'victims' of fresh water reduction are winter crops (wheat and barley), which are changed from irrigated to unirrigated winter crops, though still located in irrigable land (from 17 738 irrigated dunams to 0). This is to be expected, because the differences in WRC between the irrigated crops and their alternatives — unirrigated crops — are significantly smaller than the original WRC values.
3. The reduction in industrial crops is moderate, because most of them are irrigated by recycled water, which is not exposed to administrative limitations.
4. The reduction in water amount of 39%, is the weighted average between a reduction of 58% of fresh water (67.1% of the total water amount) and a zero reduction of recycled water.
5. Irrigated land is reduced by 27% whereas the total water amount is reduced by 39%. This means that the average water requirement per area is reduced. Since the water requirements per dunam of all crops are predetermined constants, the reduced average means that there is a shift from more to less intensive, usually less profitable, crops due to the reduction of fresh water. By checking the average WRC for the two extreme amounts of total water (Table 2) it may be seen that the average WRC is reduced by 28%. That is, with the reduction in fresh water, crops of smaller water requirements — which also have lower WRC — are being preferred (e.g. maize is less profitable than cotton per unit area but has a higher income per water unit).

7. What explains these results?

We have found that increasing water prices in our results do not affect the cropping pattern or the total amount of water used. Indeed, the only effect of increased water prices is to tax the income of farmers without changing their behavior. What is going on here?

Table 3
Crop patterns at different fresh water amounts and for two water price sets[a]

	Fresh water	$Q=21.586$		$Q=18$		$Q=15$		$Q=12$		$Q=9$	
	Unit	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
Orchards	Dunam	12 333	12 333	12 333	12 333	12 333	12 333	12 333	12 333	11 625	11 625
Irrigated winter crops	Dunam	17 738	17 738	0	0	0	0	0	0	0	0
Industrial crops	Dunam	46 418	46 418	43 441	43 441	36 551	36 551	29 885	29 885	26 062	26 062
Vegetables and flowers	Dunam	1696	1696	1696	1696	1696	1696	1696	1696	575	575
Total irrigated land	Dunam	81 772	81 772	78 795	78 795	71 905	71 905	65 239	65 239	59 588	59 588
Total unirrigated land	Dunam	80 471	80 471	98 209	98 209	98 209	98 209	98 209	98 209	98 209	98 209
Total cultivated land	Dunam	158 656	158 656	155 679	155 679	148 789	148 789	142 123	142 123	136 472	136 472
Total fresh water	mcm	21.586	21.586	18.000	18.000	15.000	15.000	12.000	12.000	9.000	9.000
Total recycled water	mcm	10.586	10.586	10.586	10.586	10.586	10.586	10.586	10.586	10.586	10.586
Total water	mcm	32.172	32.172	28.586	28.586	25.586	25.586	22.586	22.586	19.586	19.586

[a] Dunam, 1000 m^2; mcm, million cubic meters.

The answer can be obtained by examining Fig. 2, which shows the demand curve for water.[4] Here, Q^* is the amount of water allocated to the district, the 'quota'. P_1 and P_2 are the low and high prices, respectively, and Q_1 and Q_2 are the corresponding amounts of water that would be demanded if there were no quotas. Note that these are both greater than Q^*, indicating that the quota is a binding constraint on water use.

In this circumstance, it is clear that raising the price from P_1 to P_2 has no effect on water usage. Instead, its only effect is to increase the payments made by farmers for their allocated quota by$(P_2-P_1)Q^*$.

Furthermore, in our runs, the demand curve generated comes from an optimizing model. Hence, given that Q^* is used at both prices, the model can be thought of as optimizing the cropping pattern with total water use fixed at Q^*. But Q^* is independent of price, hence the optimal cropping pattern must be similarly independent.

What has happened here can be described in a less detailed, but more general way. Setting water allocations (quotas) and setting water prices are two ways to affect the overall use of water. Since these are two policy instruments that act on a single goal, it is likely that one of them will be effective and the other redundant. Where the water allocation is effective and water prices redundant (as a tool), the only effect of a change in water prices will be to change what farmers pay for water without changing their behavior. (In the opposite case, where prices are effective and allocations so large as to be redundant, there will be no parallel side effect.)

A referee has correctly pointed out that the income-transfer effect could be controlled and rationing by price still used if price policy concentrated on setting the price that would make the quantity demanded equal to the quota amount. In Fig. 2,

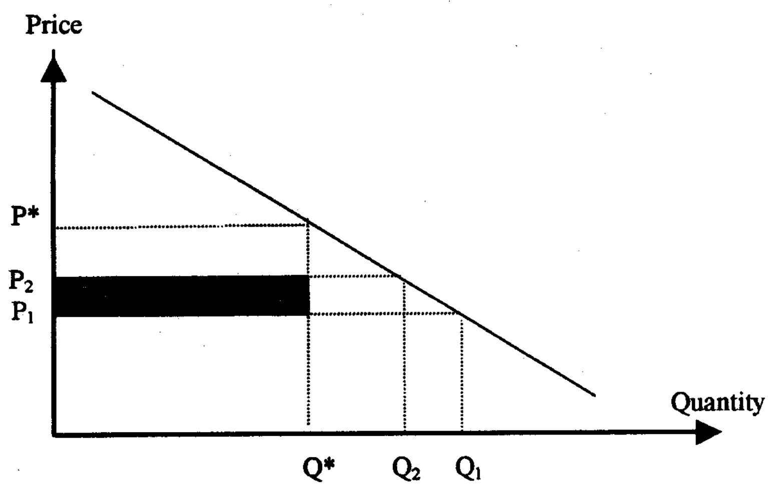

Fig. 2. A schematic demand curve for above-quota water quantities.

[4] To simplify discussion, we ignore the fact that there are two water qualities involved. This can be safely done, since the total amount of recycled water used is the same in all runs.

that price is P^*, corresponding to the quota amount, Q^*. Since demand depends on *marginal* cost, the quota could be enforced without charging so high a price on all units; rather, the price need only be charged for units just above $Q * -\epsilon$, where $\epsilon > 0$ can be as small as desired. Any lower price can be charged for the infra-marginal units. Hence the income-transfer effect can be as large or as small as desired.

This is a good idea. In order to use such a policy, the policy-makers must know the price, P^*. As it happens, this can be estimated. One way of doing that is to run our model without prices but with quantity constrained to Q^* and then to calculate the shadow price of the constraint. We have done this for the 1989 Jezreel Valley data for the case of fresh water (with the quantity of recycled water constrained to the actual amount of 10 586 mcm). We find values for P^* of approximately $0.59 per cubic meter for a fresh water quota of 18 mcm and $0.72 per cubic meter for fresh water quotas of both 12 and 15 mcm.[5]

Note that such a policy may often require a more elaborate investigation, since there is more than one type of water. In the case investigated, we knew (from earlier runs) that a constant amount of recycled water would be used at all prices of interest; hence, we could impose that amount as a quantity constraint. In more general cases, we might have to find appropriate shadow values for both fresh and recycled water in order to use prices to ration both water types. (In even more general cases, more water types and prices would be involved.)

But, if authorities wish to have water rationing and must decide on what prices to be charged, such an exercise appears warranted and far better than arbitrarily setting both prices and quantities. Our model provides one tool with which to ration sensibly. If it is so used, the question of the total amount to be paid by farmers from water can be decoupled from the instruments used to accomplish the rationing.

8. Limitations on irrigated crops

As already noted, the somewhat undesirable phenomena found above occur because two policy instruments act on a single goal — the overall use of water. Where two policy instruments act on different goals, such redundancy as we have observed will generally not happen. Policies that affect crop choice directly can, therefore, be used in addition to overall policies without creating redundancies or side-effects.

As mentioned above, one of the measures used by the Water Commissioner to cope with the shortage of water was to limit certain crops, of which the most significant one for Jezreel Valley, was cotton. In order to analyze this measure, the

[5] The value of P^* is the same for two different quota amounts. This is due to the fact that the same crops (orchards) are the marginal crops in the basis for both amounts. In effect, the linear-programming nature of our model generates a discontinuous demand curve. But real demand curves are not discontinuous. This problem can be overcome by dropping the assumption that all plots planted to the same crop are identical in WRC and water requirements, as discussed in the Appendix to Amir and Fisher (1999).

model was run with and without cotton and with and without replacements for cotton. Selected results of these runs are presented in Table 4.

8.1. Case 1 — Cotton replacement is not allowed

Comparison between runs with and without cotton shows that the reductions in irrigated area and in the amount of fresh water are close to each other (43.88 and 41.69%, respectively). The total use of water was reduced by ((32.172−15.732)/32.172=)51.10%. The income per water unit was increased by 29.03% (from 0.93 to 1.20 NIS/m^3). The reason for this increase is that the average contribution of water of the optimal mix of crops without cotton is higher than the contribution of cotton due to water. (As a matter of fact, this was the main reason for applying the policy of limiting cotton). However, one should take into account that cotton, which occupied 24.33% of the total cultivated area, can be irrigated also by recycled water. Because a part of the cotton in this district was irrigated by recycled water, the main outcome in this respect was that the recycled water amount was reduced by 68.53%. Therefore, the policy of taking out cotton did not in fact reduce the amount of used fresh water, which was the main concern of IWC, but only caused a reduction in recycled water, which the farmers were encouraged to use more intensively. It is, therefore, concluded that the policy of limiting cotton was a mistake for Jezreel Valley. (Note: As a matter of fact, cotton irrigated by other than fresh water types — recycled, brackish and surface — was soon excluded from the list of limited crops by IWC.)

8.2. Case 2 — Cotton replacements are allowed

The following Table 5 presents results, in the same format as Table 4, where cotton is not allowed but other crops, mainly maize, are allowed as replacements.

Maize and irrigated winter crops replace cotton in the optimal mix of activities. Recycled water amounts remain at 10.586 mcm, but the total income is reduced by 8.9%, compared to the optimal income *with* cotton. Such a reduction in income, in addition to raising water prices, is another penalty inflicted on the farmers, while the

Table 4
Administrative limitation on cotton in Jezreel Valley — replacement not allowed[a]

Item	Area of cotton (dunam)	Total income (million NIS)	Total irrigated area (dunam)	Total recycled water use (mcm)	Total fresh water use (mcm)	Average income per total water (NIS/m^3)
Cotton allowed	35 880	29.852	81 772	10.586	21.586	0.93
Cotton not allowed	0	18.861	45 892	3.146	12.586	1.20
Rate of reduction (%)	100	36.82	43.88	68.53	41.69	−29.03

[a] Dunam, 1000 m^2; mcm, million cubic meters. Note: minus sign in the last row means increase!

Table 5
Administrative limitation on cotton in Jezreel Valley — replacement is allowed

Item	Area of cotton (dunam)	Total income (million NIS)	Total irrigated area (dunam)	Total recycled water use (mcm)	Total fresh water use (mcm)	Average income per total water (NIS/m^3)
Cotton allowed	35 880	29.852	81 772	10.586	21.586	0.93
Cotton not allowed	0	27.197	81 772	10.586	21.586	0.85
Rate of reduction (%)	100	8.90	0	0	0	8.60

effect on water use, which was the trigger of applying water policies, is negligible. It becomes quite clear that the policy of administrative limitations on cotton is wrong, when applied on Jezreel Valley, because of its inefficiency in reducing the use of fresh water and, at the same time, being economically harmful to the farmers. However, it does not necessarily mean that such a policy may not be adequate for other conditions.

9. Conclusions

The effects of water prices, administrative water quotas and limitation of certain crops as water policy-making factors, are analyzed using an optimizing model for near-optimal agricultural production systems. From this study the following can be concluded:

1. The model enables analyzing changes in data, evaluating scenarios and water policies; thus it can be used as a decision-support tool at both district and national levels.
2. When water quotas are binding, raising water prices for agricultural production does not necessarily increase water productivity and efficiency, and thus may be merely a tax on the better farmers — those that practice near-optimal systems. Consequently, instead of encouraging such farmers, the combined policy of quotas and prices may contradict the basic intentions of the decision-makers. This reflects the fact that quotas and prices are two policy instruments acting on the same goal — overall water consumption. Their joint use is, therefore, likely to lead to a situation in which one of them is redundant. When that happens, there may be unintended effects.
3. One way of avoiding such unintended effects would be to use our model to calculate the prices that should be charged *at the margin* in order to accomplish the desired rationing. If this is done, the question of the total amount paid by farmers for water can be decoupled from the instruments used to accomplish the rationing.

4. The response of agricultural production systems to water limitations should be evaluated by the decision-makers by analyzing the marginal reduction of income. In Jezreel Valley, because of the presence of unirrigated winter crops as an alternative to irrigated winter crops, the reduction in income is small compared to the reduction in water amounts. In other words, the shadow price of fresh water is relatively small. In this case the administrative water reduction may well be justified if the water is shifted to other districts, with higher shadow prices, that will be prepared to pay higher prices for water.
5. Applying area limitations on certain crops should take into account the type of water used by the crop under consideration. Where cotton is not irrigated by fresh water, such a policy may be justified when cotton WRC is quite low. In our case, however, limiting cotton was a wrong policy, because it reduced mainly recycled water (rather than reducing fresh water, which was the main reason for applying such a policy).
6. The policy of limiting cotton with the allowance of replacements did not change the crop pattern but put an additional penalty on the better farmers. The magnitude of the penalty was the difference of WRC between cotton and the replacements.

It should be emphasized that the analysis of limiting cotton did not take into account long-term effects, such as existing equipment and other investments. Therefore, the analysis explicitly assumes that limiting crops is a short-term policy, i.e. a policy that is applied only for short terms.

Acknowledgements

We would like to pay our deepest appreciation to Prof. D. Nir of the Technion, Faculty of Agricultural Engineering, for his involvement and vital contribution. Our thanks are also due to the planners and to other experts of Jezreel Valley.

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