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Analyzing agricultural demand for water with an optimizing model☆

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Abstract

The paper introduces an optimizing linear model for analysing agricultural production under various water quantities, qualities, timing, prices and pricing policies. The model is designed to serve as a decision-making tool for planners of agricultural production on district and national levels. The output solutions provide the optimal mix of water-consuming activities to maximize the net income of the agricultural production of the districts and the water demands under various prices. It also provides the user with procedures to carry out 'if–then' sensitivity and scenario analyses and to generate optimal water demand curves. The paper presents the formulation of the model, indicating and analysing problems of linearity and scaling, the steps undertaken to examine and verify it, optimal water demand curves for eight districts in Israel (separately and as an integrated unit) and calculated estimates of water demand elasticity.

Keywords: Water demand; Optimizing model; Water policies; Elasticity

1. Introduction

Agriculture, especially in arid and semi-arid zones, requires water for irrigation. It competes for that water with the household and industry sectors. There are substantial differences in the characteristics of water consumption between the various sectors. For example, compared to agriculture, water demands by households are not price sensitive, at least for the high priority uses necessary for human life. On the other hand, while agriculture can utilize low quality water types (recycled, brackish and untreated surface water) the household sector and much of the industrial sector can use only fresh water. Another significant difference is that water supply to households and industry must be extremely reliable, whereas the reliance of the agricultural sector on a dependable supply of water may not be as important, especially when water is to be used for low cash field crops. As a result, agriculture, although the main water-consuming sector, tends to be the most vulnerable one.

On one hand, agriculture is subject to considerable uncertainty as to water supply; on the other

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hand, it has considerable flexibility, often being able to produce a large variety of crops and other water-consuming activities (e.g. fishponds) in the same area. This flexibility is mainly due to annual field crops (e.g. wheat, maize, cotton) that can be grown by using different amounts and qualities of water during different growing seasons. Agricultural planning methods to deal with such issues have been developed and used (Amir et al., 1991, 1992; Sher and Amir, 1993), but the sensitivity of agriculture to water remains an important issue for many countries in formulating water policies.

Agricultural demand for water is an important factor in the Harvard Middle East Water Project (Fisher et al., 1996). That project deals with the economics of water and water policy in general; this naturally requires a detailed treatment of demand by agriculture. For that purpose, a model of agricultural response to water prices and policies has been developed. We refer to that model as the "agricultural sub-model" or AGSM. AGSM has two main goals: (1) to provide district and national level planners with a decision support tool for planning agricultural production under various water amounts, qualities, timing and prices; and (2) to provide the main Harvard model with a soundly based analysis of agricultural water demand. We believe the mode of analysis to be of interest also outside the limits of the Harvard Project.

As explained in detail below, AGSM is an optimizing model of agriculture. It uses data on available land, water requirements per unit land area for different crops, and net revenues per unit of land area generated by the growing of those crops. These net revenues do not include payments for water, which are handled separately. The model takes prices or quantity allocations for water and generates that cropping pattern which maximizes agricultural income. By varying water prices, one can construct demand functions for each water type or for water generally. The model can also be used to examine the effects of water quantity allocations or of non-water phenomena such as changes in the prices of agricultural outputs. In the present paper, however, we concentrate on the demand for water and related matters.

An objection that will naturally occur to the reader has to do with the usefulness of results obtained from an optimizing model. Actual demand curves reflect the behavior of actual people, and actual people may not always respond optimally. To this there are several replies.

First, as shown below, application of AGSM to data for several Israeli districts at least suggests that the model closely approximates the actual response of farmers to water prices. This is borne out by the fact that estimates of elasticity of demand for water obtained from AGSM lie reasonably close to those suggested by Eckstein and Fishelson (1994).

Second, even if AGSM generates results that do not exactly agree with actual behavior, those results can serve planners as an approximation. This is likely to prove particularly useful when econometric studies of water demand specific to a district are unavailable.

Third, a departure of actual behavior from the optima generated by AGSM can serve as a signal to planners that further study is called for.

Forth, AGSM provides a quantitative post-optimal sensitivity analysis that can be used to analyze uncertainty, stability of plans and risks.

Finally (a related point), AGSM can serve as a decision-support device suggesting to planners what crop patterns are likely to prove optimal under various conditions and relating these to different water policies.

2. AGSM in detail

The detailed description of AGSM is specifically tailored to the case of Israel, for which the model was developed.

AGSM is formulated at the level of a district. Its objective function is the net agricultural income of the district, which is maximized by selecting the optimal mix of water-consuming activities (crops and fishponds). In this procedure, the decision variables are the land areas of the activities. Each activity is characterized by its water requirements per dunam (one tenth of a hectare = 1000 m^2) and the net income it produces per land area—not including water payments. (This construct is called 'water-related contributions' (WRC) and is further explained later.) At this stage, AGSM is a short-term model in the sense that it does not include activities that differ from each other by their capital investment and redevelopment costs. It is also a steady-state model that reflects the current data on a yearly basis.

Each activity can, in principle, use one or more types of water: four water quality types and three seasons. As implemented for Israel, the water quality types are fresh (ground) water, surface water, brackish water and recycled wastewater. There are three seasons: winter, transition (March, April, October, November) and summer. This makes 12 season-quality combinations. AGSM has been formulated to support up to 12 different water prices due to season-quality water types.

The constraints in AGSM are mainly for two factors: water and land area. Regarding water, if the user chooses, there can be constraints on the availability of water by quality and by season. The user does not have to impose such constraints; instead, he or she can choose a pricing policy for water allowing prices to perform any required rationing of supplies. If desired, the user can have a pricing policy and also specify constraints on water quantities. Different prices can also be set (at the district level) for different water quantities (quotas). AGSM supports five different water policies providing a complete optimal solution for each.

The second set of AGSM constraints involves land areas. These constraints are grouped into categories of the total land area available for agriculture, the total land areas suitable for particular crops and for groups of crops. By specifying land-area constraints in this way, the user can account for the fact that not all land parcels are equally suitable for all activities.

For Israel, the categories of activities subject to land-area constraints (denoted k in Eq. (2) are as follows:

1. all activities;
2. all irrigated activities (including fishponds);
3. crops of the same group (field, orchards, flowers, non-irrigated);
4. crops irrigated by the same water quality (fresh, recycled, brackish, surface);
5. crops grown during the same season;
6. unirrigated crops on irrigable land;
7. crop rotation; and
8. recreation.

The objective function that is maximized in AGSM is the total annual net income of agriculture in the district. Net income is considered in two parts. The first of these is what was referred to as WRC. WRC_j, the water-related contribution of activity j, is defined as the gross income generated by activity j per unit area less all direct expenses (machinery, labor, materials, fertilizers) associated with doing so, except for direct payments for water. It measures the maximal ability of the activity to pay for water.[1] WRC enters the objective function positively.

The second component of net income consists of direct payments for water and is subtracted from WRC. It is important to note that such payments do not include water-related expenses such as conveyance and distribution because these are included in the calculation of WRC. This enables us to concentrate directly on the demand functions for water.

There is another aspect of this procedure that deserves mention. Because AGSM operates at the district level, the district is treated as a single unit for most purposes. It means that only one price for each water type (average) prevails within the entire district for all activities. One problem associated with such a treatment is that conveyance and distribution costs within the district are usually dependent on the location and elevation of water sources and on the location of the agricultural plots on which water from those sources is used. To release this limitation AGSM employs two procedures: (1) where costs vary by water source, we define each source as a separate water type and define activities separately in terms of the source used; then the different costs will simply show up as different values of WRC for the source-differing activities; and (2) where certain activities get water from specific water sources at water prices different from the district average

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[1] We have proceeded in this way in order to focus on the demand for water and on water-related policies. A similar procedure could be given to other inputs or outputs, were they the focus of the analysis.

price we introduce a price correction factor for water consumed by these activities that changes their net income. The last procedure is introduced by the following example. Banana groves in the Golan district, which are high water consumers due to climate requirements, are located near Lake Kinneret, 200 m below sea level, and are irrigated directly from the lake. The average water price in the district, however, reflects the average elevation of the district, which is +100 m, with much higher pumping expenses and, consequently, supplied at a significantly higher water price. In this case the high average price of water would cause the banana groves to leave the optimal basis, distorting significantly the optimal mix of activities. Such water price correction factors are formulated in the general format of AGSM. (Note: These correction factors can be an important contribution to model formulation because they enable the user to include in a large-scale model specific data related to smaller scales.)

2.1. Mathematical representation of AGSM

The objective function is:

$$Z = \sum_j X_j \, [\mathrm{WRC}_j - \sum_i (P_i W_{ij})], \tag{1}$$

where WRC_j, as already explained, is the water-related contribution of activity j; P_i is the price of one cubic meter of the ith water type (where i varies by quality and season; $i = 1 \ldots 12$); W_{ij} is the demand of water of type i per unit area of activity j; and X_j is the total land area used by activity j. (These are the decision variables.) The constraints are as follows.

2.1.1. Area

The general form of the area constraint is:

$$\sum X_{jk} \leq A_k, \tag{2}$$

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

The constraints ensure that the sum of the areas of the crops under each category k will not exceed the area available for that category.

2.1.2. Water

Water constraints are of the following general form:

$$\sum W_{ij} \times X_j \leq W_i, \tag{3}$$

where W_i is the total available amount of water type i.

Such constraints are formulated for the total amount of water, for seasonal amounts of water, for local water sources and for water consumed by certain activities.

3. Applying AGSM to Israeli data

The model was first run on 1994 data for Bet Shean, a district located in the Jordan Valley south of the Lake of Galilee, and then on data for a number of other districts. We used official data for agricultural production (Israel Ministry of Agriculture (IMA), Rural Planning Division and others). Data regarding water were taken from publications of the Water Commission and Mekorot (the national water supply company). Data regarding incomes of crops in all districts were taken from different independent sources (IMA, district planners; Volk, 1993; Israel Farmers Organization). The data were discussed with and approved by the IMA planners of the district.

3.1. Calibration runs

To calibrate the model so that it reflects real conditions, we performed some preliminary runs. In these calibration runs we used actual 1994 figures for the right-hand-side (RHS) values of the constraints for water amounts, total land area and land area of perennial crops (orchards, greenhouse flowers, fishponds), because in the short term these land areas are fixed. The land areas for annual crops (winter grains, industrial crops), however, have more flexibility in the short term. Here we permitted deviations up to 15% from the 1994 data. The prices per m^3 of several types of water in 1994 were: fresh–winter \$0.12; fresh–summer \$0.18; brackish–all seasons \$0.10; recycled–all seasons \$0.12; surface–winter \$0.13; and surface–summer \$0.15.

The outputs of these calibration runs for the optimal land areas, water use and mix of activities were compared with the corresponding actual 1994 values. Significant deviations between the model outputs and actual data were discussed with the district planners, and this usually led to changes in some of the estimated input data (e.g. WRC and water per unit area). When the comparison was satisfactory, we conducted a limited sensitivity analysis, using different water prices and WRCs of crops. The model's responses to these changes were compared with the planner's intuitive predictions, resulting in additional changes in model inputs where required. After these runs the model was ready for systematic runs to study the effect of changing water prices. In these runs the calibration restrictions on the RHS values of the land-area constraints were removed.

As an example, the results of the calibration runs for Bet Shean district showed a satisfactory fit with the 1994 actual mix of activities and the use of land and water, as can be seen from Table 1. In this particular case the model optimal total water use was 7.79% less than actual values. Since the model is an optimizing one, this is not a large discrepancy. This was discussed with the planners in the district who checked the reason for the apparent discrepancy. We also carried out a limited systematic set of experiments using different water prices for fresh and saline water. The results regarding both the direction and magnitude of the changes in production were compared to subjective estimates of the planners and were approved by them.

4. Obtaining demand curves for water

After the calibration showed acceptable results, AGSM was run systematically to evaluate the response of agricultural production to water prices ranging from \$0.10 to 1.00 per m^3. In the systematic runs we used the same water price for all quality-season water types. That is, every water price, except for the calibration run, can be viewed as an average price of the different quality-season water types in the district under consideration. Because in Israel water prices are controlled by governmental authorities and are changed quite frequently, they are hardly predictable. In the future, however, we will use predicted different prices when and where they will be available.

The weighted-average price is calculated by:

$$P_a = \frac{1}{W_t} \sum \sum P_i \times W_{ij} \times X_j, \qquad (4)$$

where W_t is the total optimal amount of all water combinations to be used in the district. The other symbols were defined previously.

In Table 2, the results for the \$0.146 water price (second row) are those calculated with actual

Table 1
Actual and calculated data for Bet Shean

Activity	Unit	Actual data in 1994	Model results	Difference (%)
Orchards	Dunam	14,698	14,500	−1.4
Winter crops	Dunam	35,551	35,550	0
Industrial crops	Dunam	14,364	14,550	1.5
Total field crops	Dunam	49,915	50,000	0
Total vegetables	Dunam	19,332	19,040	−1.5
Total unirrigated crops	Dunam	11,477	11,500	0
Total cultivated area	Dunam	105,570	105,570	0
Total fresh water	m^3	54,200,000	45,467,600	−16.2
Total recycled water	m^3	2,400,000	2,400,000	0
Total brackish water	m^3	35,917,000	35,917,000	0
Total surface water	m^3	18,533,000	18,533,000	0
Total water	m^3	111,050,000	102,317,600	−7.79

Table 2
Optimal selected values for different average water prices—Bet Shean

Water price (P_a) ($/m^3)	Irrigated area (ha)	Total water use (million m^3)	Water per land (m^3/ha)	Fresh water (million m^3)	Fresh water (%)	Water expenses (million $)	Net income (million $)	Water expenses/net income (%)	Activities leaving the optimal basis as price rises
0.10	8209	97.76	11909	23.41	23.95	5.98	22.85	20.74	
0.146	8209	97.76	11909	23.41	23.95	10.86	17.99	37.64	Calibration run
0.20	5209	89.81	17241	23.41	26.07	14.16	13.33	51.51	Winter crops
0.25	5191	38.53	7422	18.62	48.33	9.63	9.27	50.95	
0.30	4416	34.19	7742	15.11	44.19	10.26	7.40	58.10	Fish ponds
0.35	4396	34.01	7737	15.14	44.52	11.93	5.73	67.55	Maize
0.40	3139	28.81	9178	11.99	41.62	11.52	5.73	66.78	Part of orchards
0.45	1961	17.52	8934	7.08	40.41	7.89	3.01	72.39	Sunflowers
0.50	1954	17.45	8930	6.81	39.03	8.73	2.17	80.09	Part of vegetables
0.55	984	9.50	9654	6.89	72.53	5.22	1.53	77.33	Spices
0.60	869	8.58	9873	6.33	73.78	5.15	1.11	82.27	Potatoes
0.65	394	2.88	7310	1.19	41.32	1.87	0.94	66.55	Vegetables
0.70	394	2.88	7310	1.19	41.32	2.02	0.85	70.38	Orchards
0.75	0	0		0		0	0.00		All irrigated activities

prices for 1994. The results of the systematic increase of the water prices for Bet Shean are presented in Table 2.

The columns of Table 2 are explained by their respective headings except for the last column. That column shows the activities that leave the optimal basis at different prices as water price increases. For example, the fourth row of the table reads as follows: for $P_a = \$0.25$ per m^3, the entire irrigated area is 5191 ha, and the total water demand is 38.53 million m^3, resulting in an average of 7422 m^3 of water per hectare. Fresh water demand is 18.62 million m^3 which is 48.33% of the total amount. Total expenses for water are $9.63 million; and net income is $9.27 million (WRC is, therefore, $9.63 + 9.27 = \$18.90$ million). Water expenses are 50.95% of WRC. The last column indicates that winter crops cannot pay the price of $0.25 per m^3 and leave the optimal basis when prices rise from $0.20 to 0.25 per m^3. The last column (of the third line) indicates that the reduction in the irrigated area (from 8209 to 5209 ha) is due to the fact that winter crops left the optimal basis.

Columns 1 and 3 in Table 2 are the water price and the total demand of water, respectively. They are graphically presented in Fig. 1, creating the optimal demand curve (ODC), for total water for Bet Shean. (Note: At this stage of the model we applied only two curves for each district: linear and power [constant elasticity]. Other equation forms, for example log-linear, may sometimes yield the best fitting curve, but application of other types is beyond the scope of the present discussion and will be dealt with in later stages of the study.) In this case the best-fit curve is of a linear form:

$$P_a = m \times Q + n, \qquad (5)$$

where Q and P_a are water quantities and average prices, respectively; and m and n are constants. The estimated coefficients for this case are $m = -0.0058$; $n = 0.6098$; and $R^2 = 0.8686$. As expected, different districts have different demand curves, as in Fig. 2 for Hachula district. The regression coefficients for the demand curves (Eq. (5)) for eight districts in the north of Israel are presented in Table 3.

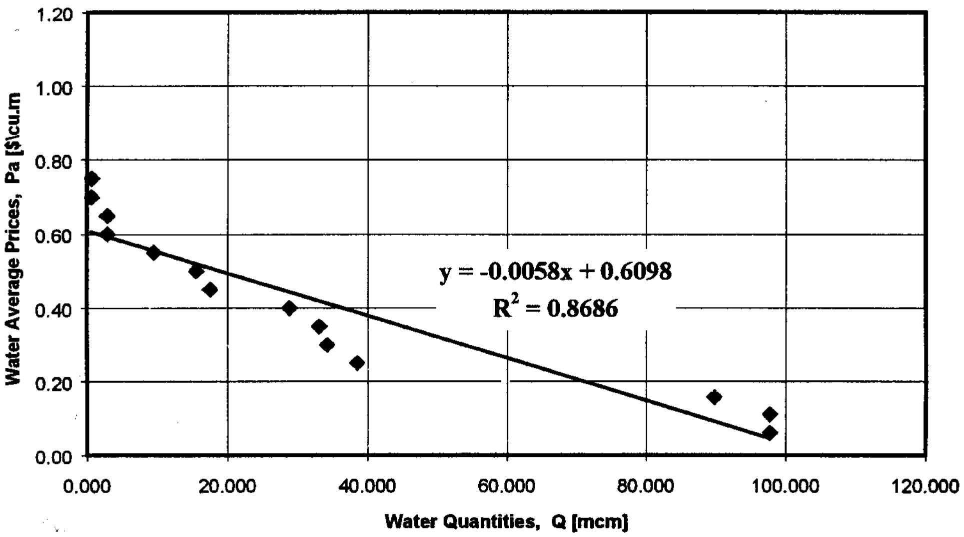

Fig. 1. Bet Shean—optimal water demand curve.

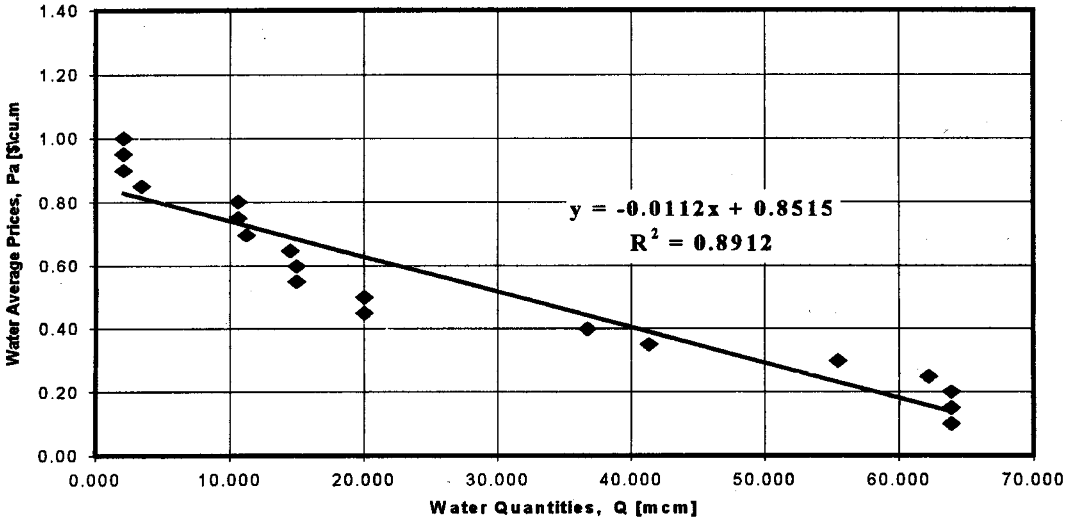

Fig. 2. Hachula—optimal water demand curve.

4.1. *Elasticity of water demand (Table 3)*

The water demand elasticity coefficients (El) are calculated by:

$$\mathrm{El} = \partial Q/Q : \partial P_a/P_a, \qquad (6)$$

where Q and P_a are the water quantities and average prices, respectively.

El coefficients at $P_a = \$0.20$ per m^3 for the various districts, calculated using Eq. (6), are presented in Table 3.

It should be noted that these elasticities cannot be readily compared with elasticity estimates for water demand by particular groups of crops (e.g. Eckstein and Fishelson, 1994). This is because the elasticity estimates above reflect the effects of water prices on competition among crops for

Table 3
Regression coefficients of optimum water demand curves and water demand elasticity of eight Israeli districts

District	Coefficient m^a	Coefficient n^a	R^2	Elasticity (at $P_a = \$0.20$)
Bet Shean	−0.0058	0.6098	0.8686	0.488
Gilboa	−0.0288	0.8600	0.8313	0.303
Golan	−0.1390	0.9109	0.8018	0.332
Hachula	−0.0112	0.8515	0.8912	0.289
Kinnerot	−0.0161	0.8611	0.9412	0.303
Maale Hagalil	−0.0932	0.9427	0.8524	0.269
Merom Hagalil	−0.0366	1.2735	0.8847	0.186
Yizrael Valley	−0.0153	1.0102	0.9044	0.247
Eight districts	−0.0021	1.0117	0.9535	0.246

[a] m and n as in Eq. (5).

limited land. They are, therefore, affected by the entry into and exit from the optimal basis of particular crops. Having said this, however, the elasticity estimates of Table 3 seem quite reasonable.[2]

Examination of the ODCs for the various districts shows the following:

1. Generally, the generated demand curves have a reasonably regular appearance. The exceptions (e.g. Maale Hagalil) are for districts with relatively limited agriculture or with a dominant crop, as can be seen in Fig. 3. (See later for further explanations of the jumps in the curves.) In several cases (as in Figs. 2 and 3), the demand curve becomes vertical at the RHS. This reflects the fact that, in those districts, at low enough water prices all the available land area is being used, the optimal mix of activities remains the same and, therefore, the water demand does not increase as prices drop further. In effect, water demand has an upper limit imposed by other constraints (here: land).
2. In many cases the ODC becomes vertical at the left-hand side (Figs. 1–3). This reflects the fact that at the higher end of the price range used, irrigated crops become unprofitable except for very high-value crops, usually of limited area, that stay in the optimal basis over the range of prices examined.

So far we have discussed the total demand for water. It would also be possible to produce demand curves for specific water types, but these would naturally depend on the prices assumed for the other water types. (As mentioned previously, such an analysis has not been done yet.) We can, however, gain some insight into the behavior of the demand for fresh (ground) water by examining Table 2. The results show the following:

1. fresh water, as a component of the water mix, is used more as prices rise (24% fresh water at $P_a = \$0.10$ and 74% at $P_a = \$0.60$); and
2. both the total amount of fresh water demanded and the average water demand per land unit remain roughly constant for water prices between \$0.45 and 0.60 per m^3 (at approximately 6.3–7 million m^3 and 9000 m^3 per ha, respectively.)

These phenomena can be explained by the fact that the most profitable activities in Bet Shean (as is generally true elsewhere in Israel) are vegetables, orchards and flowers. Of these, vegetables and orchards must be irrigated with fresh water due to

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[2] At the suggestion of a referee, we produced a number of runs in an attempt to examine the cross-elasticities of demands for different water qualities. The results were not very informative. Due at least in part to the linear nature of the model, it takes large changes in relative prices to alter the optimal pattern of crops and thus alter the pattern of water qualities used. This makes the calculation of cross-elasticities difficult as they tend to go from zero to very large numbers as the price ratios involved change, and the switch occurs only after substantial movements in the ratios.

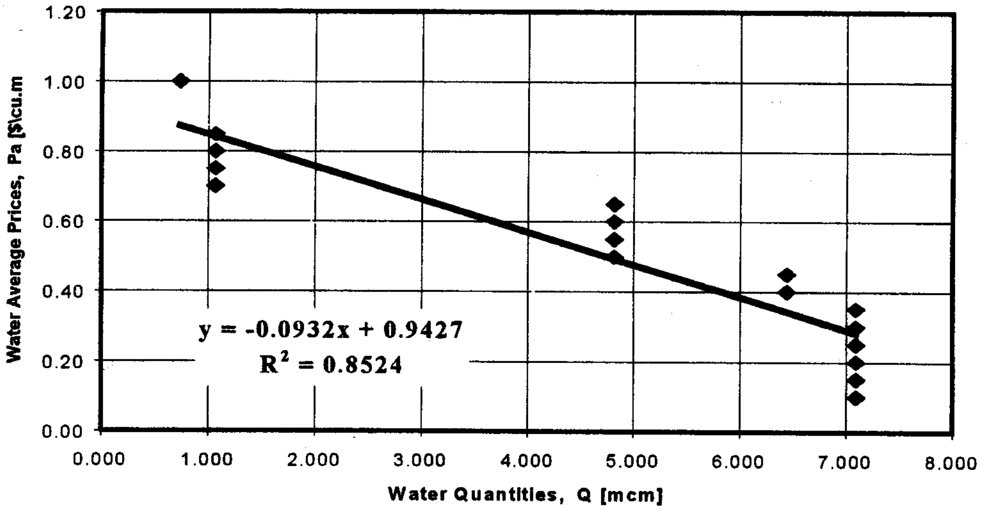

Fig. 3. Maale Hagalil—optimal water demand curve.

health regulations. When water prices increase, the net incomes of all activities decrease until less profitable activities generate losses and leave the optimal basis. As a result, the amount of irrigated land shrinks (from 8209 ha at $P_a = \$0.10$ to just 869 ha at $P_a = \$0.60$); and only the fresh water-using, highly profitable activities, remain. As a result, the total amount of water used is reduced with the reduction of the irrigated land, but at the same time, the share of the fresh water component increases because most of the remaining crops are to be irrigated by fresh water.

4.2. Jumps (discontinuities) in the curves

The appearance of jumps in the curves can result from two sources: (1) an artifact resulting from aggregation (as in Fig. 4); and (2) a real situation resulting from limited number of activities in the district (as in Fig. 3).

4.2.1. Artifact

Consider Fig. 4 for Bet Shean. The curve appears discontinuous when water prices increase from \$0.45 to 0.60 per m^3 while fresh water quantities remain stable at $Q = 7$ million m^3. This apparent discontinuity is due to a high water-related contribution crop that remains in the optimal solution for water prices smaller than \$0.60 per m^3. The fact that all plots of land using a particular activity are assumed to be identical, means that when water prices increase, other things being equal, the model assumes that there is a single 'critical' price, P_{cj}, at which the net income of a particular activity j suddenly becomes zero on all plots:

$$N_j = \mathrm{WRC}_j - W_{aj} \times P_{cj} = 0. \tag{7}$$

Since the P_{cj} for flowers, vegetables and orchards are all higher than \$0.60, these crops remain in the optimal basis when price rises to \$0.60. At $P_a = \$0.65$, however, orchards leave the basis, cultivated land decreases to 394 ha, and fresh water demand is sharply reduced from 6.33 to 2.88 million m^3 (for flowers). In reality, however, this reduction will be gradual because not all plots are identical and, therefore, the activity will gradually leave the basis, smoothing the demand curve. (A method for smoothing such discontinuities is presented in the Appendix).

4.2.2. Real jumps

Fig. 3 demonstrates the second reason for jumps in the demand curve, namely, the presence of only a limited number of activities in the district. (In Maale Hagalil there are three main crops. In this case the jumps are larger than can be explained by

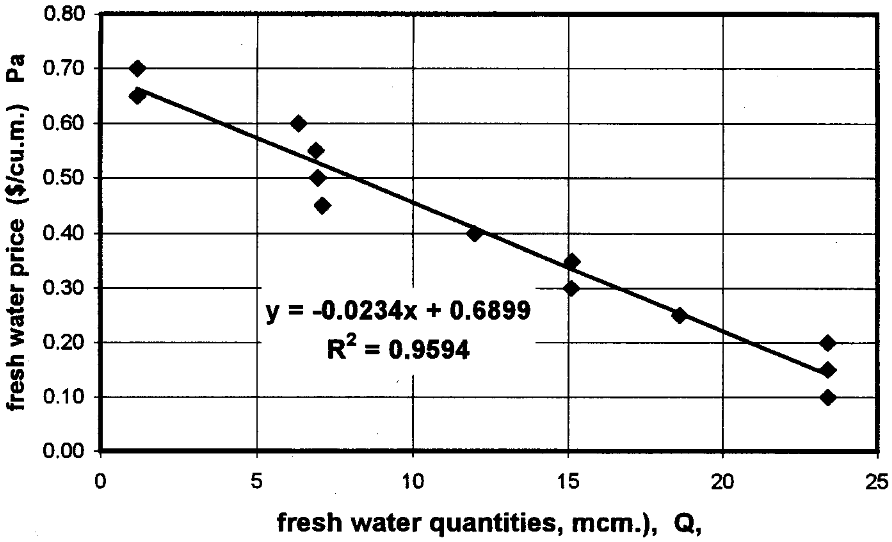

Fig. 4. Bet Shean—demand for fresh water.

statistical distributions of the WRCs and, apparently, reflect a real situation.)

Before leaving this discussion, we must note a phenomenon of social importance, namely, the shrinkage of irrigated land at high water prices. In Bet Shean, for example, winter crops cannot pay for any type of water at a price higher than $0.20. When prices of all water types increase to $0.35, fishponds become unprofitable, and field crops (maize) will not be grown. Because winter crops, fishponds and maize currently occupy approximately 50% of the irrigated area in the district, this means that a large area will not be irrigated at such a price. A partial alternative consists of the growing of unirrigated winter crops. However, this alternative is both limited and risky. It is limited to rainy districts and to winter crops only, and does not provide an alternative to fishponds and field crops such as maize. Furthermore, it is risky in years of partial or full droughts leaving the fields brown instead of green.

This inability of much of agriculture to pay high water prices may have undesirable social impacts. For example, shrinking agriculture and economic losses to farmers may lead farmers to leave the district for the more industrialized, more populated, center of the country. Such a phenomenon would impose difficulties in many countries, but may be particularly severe for Israel where agricultural settlements, especially in districts along its borders (like Bet Shean) have historically been very important for security reasons, and where agriculture is of great ideological importance.

5. Conclusions

Our main goal in AGSM was to develop a decision support tool for planning agricultural production on district and national levels under various water quantities, qualities and prices. We have applied the model to various districts and have reached the following conclusions:

1. The model provides a means of analysing agricultural activities in regard to water. It creates a quantitative basis for analysing seasonal responses of agricultural production to changes in water amounts, qualities and prices. At this point in time, however, AGSM is a short-term steady-state model.
2. The ODCs allow one to quantitatively study the demand for water at various prices, based on the optimal mix of activities for every water price. ODCs can be produced by

AGSM for all districts and for all types of water. The current ODCs are limited to only one price for all water types (except for the calibration point) and to total and fresh water amounts.

3. The ODCs appear to be in agreement with previous estimates of elasticity of water demand. They also replicate actual water usage at historical prices reasonably closely.
4. The model provides a quantitative tool for analysing water policies on a national level, especially where national authorities control water.
5. Many of the ODCs exhibit discontinuities. Such discontinuities can result from two main sources: (1) they can be artifacts resulting from aggregation; in this case, the discontinuities can be ignored or smoothed; and (2) they can reflect the presence of only very few irrigated agricultural activities; when ODCs of several districts are aggregated, the discontinuities tend to disappear.
6. From our experience in applying AGSM, we think that the calibration of the model is an important stage. By comparing the model solution for a specific case with actual data, one is able to examine the formulation of the model to better reflect prevailing conditions of a district and to increase confidence in the model as a decision-support tool.
7. As shown for the North of Israel, AGSM can also be applied to agricultural systems on a scale wider than just for a single district (several districts or nationwide) by aggregating relevant districts into one unit.

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Appendix. Smoothing demand curves

As discussed in the text, discontinuities in the curves can be due to the assumption that all plots of an activity are the same. In this respect, a smoother curve may better reflect real conditions.

The following method for smoothing curves has been developed. We present this method in terms of its application to Bet Shean.

Usually, each activity in a district involves many plots. Each of these plots is operated under different conditions resulting in a different WRC. Because of the large number of plots in a district it makes sense to assume that the WRC_j is normally distributed. Referring to Eq. (7), $\mathrm{WRC}_j = W_{aj} \times P_{cj}$, and since W_{aj} is a predetermined constant, the critical price P_{cj} is also normally distributed with mean, μ, and standard deviation σ.

Since the range $\mu \pm 2\sigma$ includes more than 95% of the values of the distribution we assume that the range of discontinuity in Fig. 4 (between $P_a = \$0.45$ and 0.60) equals $\mu + 2\sigma$, where $\mu = (0.45 + 0.60)/2$. We divide that range into four equal segments, each of which is of length $\sigma = (0.60 - 0.45)/4$, where $P_a = \$0.45 = \mu - 2\sigma$ and $P_a = \$0.60 = \mu + 2\sigma$. According to the normal distribution, approximately 16, 50 and 84% of the plots will generate zero net income $\mathrm{NI}_j = 0$ at the critical prices $P_{cj} = \mu - \sigma = \$0.4875$, $\mu = \$0.5250$ and $\mu + \sigma = 0.5625$, respectively. For each of these new critical prices we can estimate the demand for water by the remaining plots. The results are as follows:

The new Q–P points will be: for $P_a = \mu - \sigma = \$0.4875$, $Q = 7.08 - 0.16 \times (7.08 - 1.19) = 6.14$ million m^3; for the mean price $P_a = \$0.525, Q = 7.08 - 0.50 \times 5.89 = 4.14$ million

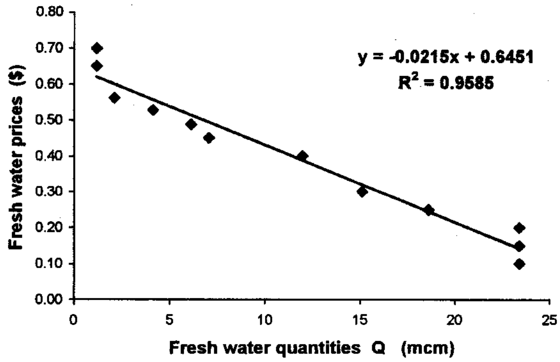

Fig. A1. Smoothed fresh water optimal curve for Bet Shean.

m^3; and for $P_a = \$0.5625$, $Q = 7.08 - 0.84 \times 7.08 = 2.13$ million m^3. The 'smoothed' fresh water optimal curve is presented in Fig. A1.

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