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Dima W. Nazer [a,*], Amaury Tilmant [b], Ziad Mimi [c], Maarten A. Siebel [b], Pieter Van der Zaag [b,e], Huub J. Gijzen [d]

[a] *Palestine Technical College, Al-Arroub, Hebron, West Bank, Palestine*
[b] *UNESCO-IHE Institute for Water Education, Delft, The Netherlands*
[c] *Institute of Environmental and Water Studies, Birzeit University, Ramallah, Palestine*
[d] *UNESCO Jakarta Office, Regional Bureau for Science for Asia and Pacific, Indonesia*
[e] *Water Resources Section, Delft University of Technology, Delft, The Netherlands*

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ABSTRACT

We examine optimal irrigation water allocation on the West Bank using a linear mathematical programming model. Our analysis involves five agricultural zones and five fruit and vegetable crops: tomatoes, cucumbers, eggplant, squash and citrus. We analyze three scenarios: (1) maintaining the existing cropping patterns, (2) maximizing profit under water and land availability constraints, and (3) maximizing profit under water and land availability constraints, while also imposing an additional constraint requiring production of crops for local consumption. The water used for irrigation is reduced by 10% (4% of all agricultural water use) by changing the cropping patterns of the five crops we analyze under land and water availability constraints. The total value added in irrigated agriculture increases by 38%, equivalent to 4% of the entire agricultural sector. Imposing the additional constraint requiring production for local consumption also reduces irrigation water use by 10%, while the increase in value added is only 12% (1% for the entire agricultural sector).

1. Introduction and background

1.1. General

With continuous population and economic growth, water resources have become increasingly scarce in many countries and regions of the world. As the largest water user, food production is directly constrained by water scarcity (Yang et al., 2006). Several authors (Rosegrant et al., 2002; Playan and Mateos, 2006; Yang et al., 2006; Falkenmark, 2007) in discussing the capacity of the earth to produce food for its increasing population, argue that one of the main factors limiting further expansion of food production will be water.

The West Bank, as many areas of the Middle East, is suffering from severe water scarcity. The average water use of Palestinians in the West Bank is 50 m^3/(person year), withdrawn from water resources available in the area. This water is used for domestic, industrial and agricultural purposes. Agriculture accounts for 70% of water use in the West Bank. Hence, improvements in agricultural water management are needed to maximize benefits from the area's scarce water resources (Nazer et al., 2008).

Although water is scarce, there are many ways of using it more efficiently, or making each drop of water more productive (Rosegrant et al., 2002). Falkenmark (2007) suggests three options for capturing the additional water needed to meet the requirements of future food production: (1) increasing water productivity by reducing losses, (2) improving the use of rainfall and expanding rain-fed agriculture, and (3) pursuing virtual water options (Allan, 1997; WWC, 2004; Hoekstra and Hung, 2005; Hoekstra and Chapagain, 2007).

Mathematical programming models are helpful in examining the allocation of scarce resources to satisfy proposed needs or to optimize the value of a given objective function, often subject to constraints. Mathematical programming is well suited for analyzing water use in agriculture. Such models can provide information about optimal cropping patterns in areas with scarce water, by describing quantitatively the trade-offs involving crops and farming practices. Results of optimization analysis can be used by agricultural planners and farmers to evaluate their cropping patterns (Loucks et al., 1981; Haouari and Azaiez, 2001; Mimi, 2001; Hillier and Liebermam, 2005).

Many models have been developed for analyzing irrigation water management from a variety of perspectives. Some models seek to maximize profit by irrigation scheduling and allocation of

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[*] Corresponding author at: P.O. Box 606, Hebron, West Bank, Palestine. Tel.: +97 022251725; fax: +97 022251725.
E-mail addresses: d.nazer@unesco-ihe.org, nazerdima@hotmail.com (D.W. Nazer).

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water among competing crops in a fixed area (Vedula and Mujumdar, 1992; Vedula and Kumar, 1996; Sunantara and Ramirez, 1997). Others maximize profit by changing cropping patterns using area as the decision variable by which water is allocated between competing crops (Loucks et al., 1981; Al-Weshah, 2000; Haouari and Azaiez, 2001). No study has yet applied mathematical optimization analysis to cropping patterns in the West Bank. This gap motivates our study in which we use a linear programming model to examine relationships involving cropping patterns, water use, and net revenue in the West Bank.

1.2. Study area

The West Bank is situated on the central highlands of Palestine. The area is bordered by the Jordan River and the Dead Sea in the east and the 1948 cease-fire line in the north, west and south. The total area of the West Bank is 5800 km^2 including the area of the Dead Sea that falls within its boundaries (Fig. 1). In 2007 the total Palestinian population living in the West Bank was 2.4 million (PCBS, 2008). Population growth projections based on the 2007 survey are not yet available. Earlier projections based on the 1997 census indicate that the projected population of the West Bank in 2025 will be 4.4 million, assuming that the population growth rate declines from 3.8% to 2% during 1997–2025 (PCBS, 1999).

1.3. Available water resources and water use

The West Bank receives average rainfall of 540 mm/year which is equivalent to a volume of 2970 million m^3/year, of which 77 million m^3 flow as runoff and 7 million m^3 are harvested in rain water harvesting systems. The total evapotranspiration is 2207 million m^3/year and 679 million m^3/year infiltrate into the groundwater aquifers (Nazer et al., 2008). The water issue in the West Bank is complicated, in part due to the political situation, as the aquifers are controlled by Israel.

Fig. 1. West Bank regional location.

The West Bank can be classified as an extremely water scarce area using Falkenmark's (1986) definition of water scarcity (1000 m^3/(cap year)). In 2005 average water consumption in the West Bank was 50 m^3/(cap year) (Nazer et al., 2008). An optimistic scenario regarding future water availability estimates the available water at 80 m^3/(cap year) if Palestinians are provided the existing water withdrawals (123 million m^3/year) plus an extra 75 million m^3/year agreed upon in the Oslo II Agreement (1995). However, per capita water availability might decline to 45 m^3/(cap year) if additional water resources are not made available to the Palestinians (Nazer et al., 2008).

Irrigation currently accounts for 83 million m^3/year, or about 70% of the water withdrawn annually, for the use of Palestinians, from West Bank aquifers. In addition, water stored in the soil is used to cultivate rain-fed crops such as olives, grapes and many others. This water cannot be reallocated for other uses of water without changes in land use.

1.4. Existing situation of the agricultural sector

Most of the fruit and field crops produced on the West Bank are rain-fed, while most of the vegetables are irrigated (Table 1). Olives account for 83% of the area in fruit production, while grapes account for 6.6%. Citrus trees are irrigated, but they account for only 1% of the area in fruit production. Wheat and barley account for 36% and 23% of the area in field crops, respectively. About two-thirds of the area planted in vegetables is irrigated. The primary vegetable crops are tomatoes, cucumbers, eggplant and squash, accounting for 78% of total vegetable production (PCBS, 2006). These crops account for 51% of the area planted in vegetables (Table 2). The total annual vegetable production in the West Bank is 340,000 metric tons. We focus on these primary vegetable crops and citrus, as these crops account for 36% of agricultural water use in the area. Greenhouses are sometimes used to cultivate tomatoes and cucumbers. We assume in our analysis that the area of these greenhouses is fixed.

1.5. Linear programming

A linear programming model is appropriate for solving problems in which the objective function, *Z* which describes the

Table 1
Rain-fed and irrigated areas of fruit trees, field crops and vegetables in the West Bank.

	Fruit trees	Field crops	Vegetables	Total
Rain-fed area (ha)	106,900	43,400	4,000	154,300
Irrigated area (ha)	2,100	1,500	8,600	12,200
Total	109,000	44,900	12,600	166,500

Source: PCBS (2006).

Table 2
Areas cultivated in tomatoes, cucumbers, eggplant and squash, and the total production of each crop, West Bank 2004/2005.

Crop	Area cultivated		Production	
	Area (ha)	Proportion (%)	Quantity (ton)	Proportion (%)
Tomatoes	1,700	13	101,000	30
Cucumbers	1,800	14	89,000	26
Eggplant	900	7	43,000	13
Squash	2,200	17	31,000	9
Other vegetables	6,000	49	76,000	22
Total	12,600	100	340,000	100

Source: PCBS (2006).

quantity to be maximized or minimized, and the constraints which indicate the scarceness of resources, appear as linear functions of the decision variables, x (Loucks et al., 1981; Walsh, 1985; Karamouz et al., 2003).

A general linear programming problem maximizes or minimizes a linear function Z:

$$Z = f(x) = c_1x_1 + c_2x_2 + \cdots + c_nx_n$$

Subject to the constraints

$$\left.\begin{array}{l} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n \leq, =, \geq b_1 \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n \leq, =, \geq b_2 \\ \cdots \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n \leq, \geq, = b_m \end{array}\right\}$$

And the non-negativity constraint

$$x_1 \geq 0, \ldots, x_n \geq 0$$

where x_i are the decision variables, a_{ij} and b_i are constants.

In vector-matrix notation the general problem can be written as follows:

$$Z = CX \tag{1}$$

Subject to constraints

$$AX \leq, =, \geq B \tag{2}$$

$$X \geq 0 \tag{3}$$

where C is an n-component row vector, X is an n-component column vector, A is an $m \times n$ matrix, and B is an m-component column vector.

1.6. Solving the model

We solve empirical versions of our linear model using the "solver" function in Microsoft Excel, which provides helpful summaries of results. In particular, solver provides the optimal solution to the problem (1) to (3), the optimal value of the objective function, z^*, the optimal values of the decision variables, x^* and the shadow prices of constraints (2) and (3). Solver also provides a sensitivity report, which contains information about the decision variables and the constraints. It is important to perform a sensitivity analysis to investigate the effects of changes in parameter values on the optimal solution and to identify parameters for which small changes in values have notable impacts on the optimal solution. Shadow prices, which are also available in the sensitivity report, indicate how much profit is achieved by relaxing a constraint, B, by one unit.

1.7. Water productivity

Water value as defined by Rogers et al. (1998, 2002) consists of two parts: the economic value and the intrinsic value. The economic value consists of: (1) values to users, (2) net benefits from return flows, (3) net benefits from indirect uses and (4) the adjustment for social objectives. Our calculations of water productivity describe only the values of water to users.

Average water productivity in agriculture can be expressed as the amount of agricultural product generated per unit of water. Production is usually expressed in units of crop weight (kg or ton). However, expressing the productivity in monetary units is more convenient when considering several crops (Playan and Mateos, 2006). The overall productivity of water for z zones and x crops can be calculated according to Eq. (4)

$$WP = \sum_{j=1}^{j=z}\sum_{i=1}^{i=x}\frac{PV_{ij}}{WU_{ij}} \tag{4}$$

where WP is the overall water productivity in (\$/m^3), PV_{ij} is the value of product i in zone j (\$), WU_{ij} is water use of crop i in zone j (m^3) (it is based on how much water is applied to the crop).

The marginal value of water for crop irrigation indicates the value of the last unit of water used. This concept has important implications. In times of water shortages, neoclassical economic theory advises supplying the last unit of water to its most productive uses and thereby maximizing the productivity of available water.

2. The linear programming model

We formulate a linear programming model to find the optimal crop patterns in the West Bank, with the goal of reducing water use for irrigation while maximizing net benefits from irrigation. Thus we seek to increase water productivity. The objective function of the model is to maximize total profit under the constraints of land availability, water availability and production demand. The decision variables are the areas cultivated in each crop.

Maximize total profit, TP,

$$TP = \sum_{j=1}^{j=z}\sum_{i=1}^{i=x}P_{ij} * A_{ij} * Y_{ij} - \sum_{j=1}^{j=z}\sum_{i=1}^{i=x}Cc_{ij} * A_{ij} - \sum_{j=1}^{j=z}\sum_{i=1}^{i=x}Wc_j * A_{ij} * Wd_{ij} \tag{5}$$

where TP the total profit achieved from cultivating X crops in Z zones (US\$), P_{ij} the farm gate price of crop i in zone j (\$/1000 kg), A_{ij} the area cultivated by crop i in zone j (ha), decision variable, Y_{ij} the yield of crop i in zone j (kg/ha), Cc_{ij} the variable cultivation cost of crop i in zone j (\$/ha), Wc_j the cost of water in zone j (\$/m^3), and Wd_{ij} the water required to produce crop i in zone j (m^3/ha)

Subject to the constraints

a. Land constraint

$$\sum_{j=1}^{j=z}\sum_{i=1}^{i=x}A_{ij} \leq A_a \tag{6}$$

b. Water constraint

$$\sum_{j=1}^{j=z}\sum_{i=1}^{i=x}Wd_{ij} * A_{ij} \leq W_a \tag{7}$$

c. Local consumption constraint

$$\sum_{j=1}^{j=z}\sum_{i=1}^{i=x}A_{ij}Y_{ij} \geq TD \tag{8}$$

d. Greenhouse area constraint

$$\sum_{j=1}^{j=z}\sum_{i=1}^{i=x}A_{ijgh} = A_{agh} \tag{9}$$

e. Non-negativity constraint

$$\sum_{j=1}^{j=z}\sum_{i=1}^{i=x}A_{ij} \geq 0 \tag{10}$$

where A_a the total available area for agriculture in all zones (ha), W_a the total water allocated for agriculture (m^3), TD the total local demand for the agricultural crops (ton = 1000 kg), A_{agh} the total available area for agriculture in green houses in all zones (ha), A_{ijgh} the area cultivated in greenhouses of crop i in zone j (ha).

We apply the model to five agricultural zones in the West Bank: Jenin, Jericho, Nablus, Tulkarem, and Tubas, and to the primary vegetable crops (tomatoes, cucumbers, eggplant and squash) and citrus. These zones produce 66% of the vegetables in the West Bank and 83% of the citrus. We analyze three scenarios. Scenario 1 maintains the existing cropping patterns and is used as a reference to compare water use and profit with the other two scenarios. The objective function of scenario 2 is to maximize profit under water and land constraints. For scenario 3, the objective function is to maximize profit under the water, land and local consumption constraints. We include also in scenarios 2 and 3 a constraint that restricts the area cultivated by tomatoes and cucumbers in greenhouses, as these activities are more profitable than open crop irrigation, yet the areas occupied by greenhouses are known and cannot be expanded.

2.1. Data collection

We prepared a questionnaire pertaining to the primary irrigated crops in the West Bank and distributed it to 250 farmers in the agricultural zones. We selected a team of specialists to distribute the questionnaires and to help farmers complete them. Members of the team were selected from the different agricultural zones. The questionnaire was tested by distributing 40 copies to farmers. This procedure served also as training for the questionnaire team members. The questionnaire was improved in line with comments from the farmers and the questionnaire team members. The questionnaires were completed by direct interviews with farmers, who were visited on their farms by team members. Lacking information regarding the number of farmers operating in each zone we distributed 50 questionnaires in each zone. We collected the following information:

1. the variable cultivation cost, Cc_{ij},
2. water cost, Wc_j,
3. farm gate price of crops, P_{ij},
4. the water demand, Wd_{ij}, required to produce the different crops in the different zones. Wd_{ij} was based on how much water the farmers apply to the crops.

Information about the area available for agriculture, A_a, in the different zones and the areas already cultivated, A_{ij} existing, and the crop yields, Y_{ij}, were based on PCBS (2006). The yields were assumed fixed and equal to the maximum because the studied crops are highly sensitive to water deficit, such that the yield response factor (K_y) for these crops is greater than one. According to Doorenbos and Kassam (1979) K_y for citrus is 1.1–1.3 and for tomatoes 1.05. Because the K_y values for squash, eggplant, and cucumbers could not be found in the literature, we assumed that $K_y > 1$ which is the value given by Doorenbos and Kassam (1979) for a group of crops that is most similar to these crops. Depending on the yield response factor, in conditions of limited water availability, one can maintain yield and reduce the area, or reduce yield while maintaining the same area. When $K_y > 1$ it is more convenient to maintain yield and reduce the area (please see Box 1).

The water allocated for the different zones, W_a, was taken from a Palestinian Water Authority report (PWA, 2004).

Total variable cost, $Cost_{To}$, was calculated according to Eq. (11):

$$Cost_{To} = Cc_{ij} + Wc_j * Wd_{ij} \tag{11}$$

The profit achieved from crop i in zone j (\$/ha), Pr_{ij}, was calculated according to Eq. (12):

$$Pr_{ij} = P_{ij} * Y_{ij} - Cost_{To} \tag{12}$$

The total local crop demand, TD, was calculated by multiplying the yearly per capita crop demand (PCBS, 2007) by the total population.

Box 1. Yield response factor K_y

Yield response factor is a term used to quantify the response of yield to water supply. It relates relative yield decrease ($1 - Y_a/Y_m$) to relative evapotranspiration deficit ($1 - Et_a/Et_c$) according to Eq. (13) (Doorenbos and Kassam, 1979)

$$1 - \frac{Y_a}{Y_m} = K_y\left[1 - \frac{ET_a}{ET_c}\right] \quad (13).$$

where Y_a is actual yield of the crop [kg ha^{-1}], Y_m is maximum (expected) yield in the absence of environmental or water stresses, K_y yield response factor, ET_c potential (maximum) crop evapotranspiration in the absence of environmental or water stresses ($K_c ET_o$), ET_a actual (adjusted) crop evapotranspiration as a result of water stresses.

Application of the yield response factor for planning, design, and operation of irrigation projects allows quantification of water supply and water use in terms of crop yield and total production for the project area. Under conditions of limited water supply the yield decrease for crops with $K_y > 1$ will be greater than the loss of yield for crops with $K_y < 1$. When maximum production for the project area is being aimed at, and the land is not a restricting factor, the available water supply would be towards fully meeting the water requirements for crops with $K_y > 1$. When $K_y > 1$, for maximum production, the irrigated area is based on the available water supply meeting full crop water requirement $ET_a = ET_c$ and $Y_a = Y_m$ over an area irrigated with crop water requirements fully met. When $K_y < 1$, for maximum production, the irrigated area is based on available water supply partially meeting the crop water requirement $ET_a < ET_c$ and $Y_a < Y_m$ but increased area is maintained (Doorenbos and Kassam, 1979).

3. Results

3.1. Water use, productivity and profit

Table 3 presents the area, water use, total profit and water productivity for the three scenarios. In scenario 2 water use is reduced by 10% and the value added in crop production increases by 38%. Water use declines by 10% also in scenario 3, but the increase in value added is only 12%. Water productivity increases by 9% in scenario 2 (from \$3.20 m^{-3} to \$3.50 m^{-3}) and by 6% in scenario 3 (from \$3.20 m^{-3} to \$3.40 m^{-3}).

3.2. Cropping patterns

The most suitable crop in Jenin is eggplant, while eggplant and citrus are suitable in Jericho, and open irrigated squash and citrus are suitable in Nablus (Table 3). In Tulkarem open irrigated squash is the only crop that is appropriate, while tomatoes are recommended for Tubas. There is no need to cultivate cucumbers under open irrigation because the quantity cultivated in greenhouses is sufficient. In scenario 3 extra area is allocated to tomatoes and rain-fed squash in Jenin, while in Jericho the eggplant area is reduced and additional area is needed for tomatoes, squash and citrus. In Tulkarem and Tubas extra area is allocated for citrus, while rain-fed squash is recommended for Tubas. Table 4 presents examples of cropping patterns in Jenin and Jericho.

3.3. Production

In scenario 2 the production of tomatoes and citrus does not satisfy the West Bank demand and is less than the existing production, while the production of eggplant is more than the existing production (Table 5). In scenario 3 the demand is satisfied at the expense of profit.

Table 3
Water use, added value and the water value given by the three scenarios studied.

	Scenario[a]	Scenario 1	Scenario 2	Scenario 3
	Area (ha)	5330	5300	5310
Water use ($10^6\,m^3$)	Total agricultural sector	83	80	80
	Studied crops	30	27	27
	Reduction with respect to studied crops (%)	0	10	10
	Reduction with respect to total (%)	0	4	4
Added value (10^6\$)	Total agricultural sector (PCBS, 2006)	267	277	270
	Studied crops	26	36	29
	Increase with respect to studied crops (%)	0	38	12
	Increase with respect to total (%)	0	4	1
Water value	Value (\$/m^3)	3.2	3.5	3.4
	Percentage increase (%)		9	6

[a] Scenario 1 represents the existing situation, scenario 2 represents maximizing profit under water and land constraints and scenario 3 represents maximizing profit under water, land and local consumption constraints.

Table 4
Existing and proposed area in (ha) cultivated in each crop in the Jenin and Jericho zones under the 3 scenarios.

Zone	Jenin			Jericho		
Crop[a]	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Tomatoes, Op	145	0	625	371	0	365
Tomatoes, Gh	70	70	70	30	30	30
Cucumber, Op	511	0	0	190	0	0
Cucumber, Gh	169	169	169	46	46	46
Eggplants, Op	142	360	0	496	1600	724
Squashes, Op	251	0	0	692	0	322
Squashes, Rf	265	0	703	0	0	0
Citrus, Op	15	0	0	68	216	300
Total	1568	599	1567	1893	1892	1787

Scenario 1 presents the existing situation, scenario 2 presents the maximizing profit under land and water availability constraints and scenario 3 presents maximizing profit under land, water availability and local consumption constraints.

[a] Op stands for open irrigation, Gh for green houses and Rf for rain-fed.

4. Discussion

4.1. Water use, productivity and profit

Water use is reduced by 4% in both scenarios 2 and 3 while profit increases by 4% and 1% respectively. Water productivity increases by 9% in scenario 2 and by 6% in scenario 3. These results compare well with those of Al-Weshah (2000), who studied 14 vegetable crops in the Jordan valley. He found a reduction of water use of 0.8% accompanied by a 5% increase in profit when the objective function was to maximize revenue, and a reduction of water use of 9% with a 2% increase in profit when the objective function was to minimize water use. Water productivity increased by 5% and 9% (Al-Weshah, 2000). The marginal productivity of water varies according to cropping patterns. Marginal water productivity is helpful in determining how to allocate water optimally among crops (Al-Weshah, 2000).

Table 5
Total production of each crop under the three scenarios and the West Bank demand for each crop.

Crop	Scenario 1	Scenario 2	Scenario 3	Demand for the crop (tons)
Production quantity in ton (1000 kg)				
Tomatoes	83,560	76,152	81,000	81,000
Cucumbers	79,733	42,372	42,372	35,000
Eggplant	39,358	100,899	36,182	17,000
Squash	24,734	18,351	20,000	20,000
Citrus	30,062	13,373	37,000	37,000

Scenario 1 presents the existing situation, scenario 2 presents the maximizing profit under land and water availability constraints and scenario 3 presents maximizing profit under land, water availability and local consumption constraints.

4.2. Cropping patterns

In scenarios 2 and 3 the model allocates a considerable area for rain-fed squash in Jenin and Tubas. This suggests it is feasible and profitable to cultivate rain-fed squash in both areas, thereby enhancing rain-fed cropping patterns as a means of reducing water use. Farmers should be motivated to shift from irrigated to rain-fed agriculture. According to PCBS (2006), several crops such as olives, grapes, wheat and some vegetables can be cultivated in the West Bank in rain-fed conditions. rain-fed agriculture is attractive in some areas in terms of costs and environmental impacts, although the yields of rain-fed crops often are smaller than those of irrigated crops (Yang et al., 2006; Falkenmark, 2007). Greater efforts in terms of research investments in agricultural technology should be devoted to developing rain-fed agriculture.

Our results suggest that each agricultural zone should specialize in producing one or two crops of the five crops included in the model to maximize profit on the national scale. One may argue about the farmers' acceptance of such a distribution of crops within districts due to the lack of crop diversity within each district. Farmers have many reasons for rejecting monoculture (planting one single crop over a wide area), including on-farm needs for additional crops and the possibility of crop failure due to disease or insects (Loucks et al., 1981). Some specialists recommend inter-planting crops for pest control and insect confusion. For example, marigolds and sunflowers are a good choice for attracting helpful insects because of their wide open flowers. Herbs such as parsley and thyme have strong fragrances that attract beneficial insects. Constraints ensuring at least some pre-specified crop diversification can be added to the model (Loucks et al., 1981). Crops which are not included in the model can contribute to ensure diversification.

In scenario 2 the area planted in eggplant is increased in Jericho and Jenin, while the area in tomatoes is reduced. This suggests that eggplant should be planted in surplus and could be exported, while tomatoes could be imported to satisfy local needs. One may however argue in favor of self-sufficiency in terms of vegetable production. In scenario 3 a constraint was included to investigate the effect of self-sufficiency on profit. It was found that the profit decreases because some crops must be cultivated to satisfy local demand even though these crops (tomatoes and citrus) are not profitable.

The optimal cropping pattern in scenario 3 is closer to the existing cropping pattern than the profit-maximizing cropping pattern. Some may wonder why farmers are currently not cultivating the profit-maximizing combination of crops suggested in scenario 2. Perhaps farmers are driven by the self-sufficiency principle rather than the opportunity to export profitable crops. Moreover, exporting crops poses the risk of closures of exit terminals, which are controlled by Israelis and could be closed for several days or weeks. Such closures can cause significant loss to farmers and the economy. A good example is what happened in Gaza Strip in June 2007 when Israel prevented farmers from exporting strawberries and flowers to the European Union. This caused an estimated $25 million loss to farmers and the economy (Cohen, 2007).

Decision makers should compromise between profit making via exporting and self-sufficiency, perhaps by promoting the import of water intensive, low valued crops, while promoting also the production and export of high valued crops. This approach would resemble the proposal of Hoekstra and Hung (2005), Hoekstra and Chapagain (2007), and Qadir et al. (2007) who suggest that virtual water trade, through food trade, is an option for addressing water scarcity in arid countries.

Several arid countries such as Jordan have formulated policies to enable water saving by reducing export of water intensive products, notably crops. The remaining virtual water export is largely related to crops that yield relatively high income per cubic meter of water consumed (WWC, 2004). Al-Weshah (2000) argues that although virtual water trade is a means of water saving in water scarce countries, it poses the risk of creating job loss in the agricultural sector. Planners and policy makers should consider projects to shift activities in the same area. Al-Weshah (2000) adds that many voices in the countries sharing the Jordan River are calling for better water resources management in the agriculture sector. The calls of experts from Jordan and Israel suggest that importing some agricultural products may be more rational than producing them locally in terms of their water use. Food staples are commonly available at cheaper prices compared to the cost of producing them domestically for many water-poor nations.

4.3. Sensitivity analysis

In scenario 2, the shadow price of crop area is highest in Jericho, at $7370 ha^{-1} (Table 6). Thus by increasing the area in Jericho by one unit (1 ha) profit will increase by $7370. For Tulkarem and Jenin, no additional profit is expected by increasing the area by the same amount, as the shadow prices are zero (Table 6). If decision makers wish to increase aggregate profit, more land should be allocated for agriculture in Jericho, followed by Tubas, because these areas have the highest shadow prices.

The highest shadow price in relation to the water constraint in scenario 2 is $1.60 m^{-3} in Jenin, followed by Tulkarem ($1.46 m^{-3}). Hence increasing water availability in Jenin and Tulkarem by one unit of water will increase profit by $1.60 and $1.46 respectively (Table 6). In Jericho, Nablus and Tubas the shadow prices are low, suggesting that increasing the availability of water in these areas is not a wise decision if the objective is to increase aggregate profit. The negative shadow prices pertaining to tomatoes, squash and citrus products in scenario 3 suggest that by increasing the production of these crops by one unit (1 ton) profit will decline by the amount indicated by the pertinent shadow prices. Therefore, it is more profitable to import these products rather than producing them domestically (Table 6).

Table 6
Shadow prices for water, land and production in scenarios 2 and 3.

Constraint	Scenarios 2		Scenarios 3	
	Final value	Shadow price	Final value	Shadow price
Area constraint	(ha)	($/ha)	(ha)	($/ha)
Jenin	599	0	1568	960
Jericho	1893	7370	1787	0
Nablus	469	2780	469	5110
Tulkarem	529	0	538	0
Tubas	846	3290	846	6190
Water constraint	(m^3)	($/m^3)	(m^3)	($/m^3)
Jenin	3,900,000	1.6	3,900,000	4.5
Jericho	12,000,000	0.03	12,000,000	1.5
Nablus	3,800,000	0.13	3,800,000	1.0
Tulkarem	4,100,000	1.46	4,100,000	3.9
Tubas	3,500,000	0.07	3,500,000	0.9
Local consumption constraint			(tons)	($/ton)
Citrus			37,000	−485
Squash			20,000	−193
Eggplant			36,182	0
Cucumber			42,372	0
Tomatoes			81,000	−170

Shadow prices associated with water balance constraints are important to decision makers because they provide the marginal value of water related to the value in use, which can be helpful in determining the areas where the value of water is high and the ranges of water demand within which this value is valid.

5. Conclusions

Changing the cropping patterns in the West Bank can reduce agricultural water use by 4%. Moreover, water savings can be achieved while also increasing aggregate profit by as much as 38%. Water productivity and the value added per unit of water also can be increased.

Expanding rain-fed agriculture is an effective method for addressing water scarcity while substantially reducing national agricultural water consumption.

6. Recommendation

The model provides a tool that can be used by decision makers to determine the optimal mix of crops in the West Bank, with the goal of ensuring maximum profit on a national level. The model can be modified according to changes in the allocation of water, land and other parameters. Also the model can be expanded to include other crops and the level of aggregation can be modified to analyze production opportunities at district or regional levels.

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