Water productivity: a basic tool for sustainable irrigation

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Abstract

The rapid population, economic and standard of living growth with the global climate changes is increasing the per capita demand on water. This increase in water demand is resulting in less available fresh water supply for agriculture. To sustain irrigated agriculture, better water management is necessary at all levels. Water supply in the Middle East and North Africa region (MENA) is unequally distributed in space and time. This region has among the lowest per capita water supply in the world. On the other hand, the intensive extraction and use of water without proper planning and provisions for the protection of their water resource has led to serious water pollution. Agriculture consumes 70–80% of water in this region. This leads to a fundamental problem for water-short countries that should manage between their renewable water resources and their capacity for food production. Water-short countries do import food commodities, which has imbedded water called "virtual water". The aim of this paper is to present a model with the general objective to maximize water productivity (monitory units per cubic meter of water). The mathematical model resulted in a maximum water productivity of 6.92 $/m^3 with eight crops out of 43 crops grown on site. The remaining 35 crops induced a saving 3,408 m^3/ha, which equals the virtual water. Three sets of scenarios were tested. First a decrease in available water from 100% to 50% showed a decrease in the objective function value from 6.92 to 4.727 $/m^3, second a decrease in on farm crop prices by 10, 20 and 40% caused decreases in the objective function value by 4.8%, 9.66% and 20.29% respectively, while an increase in prices increased the objective function value and third an imposition of certain crops in the project area decreased water productivity.
Keywords: water productivity, virtual water, water use efficiency, crop yield.

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1 Introduction

The rapid population, economic, and standard of living growth with the global climate changes is increasing the per capita demand on water. This increase in water demand (both in domestic and industrial water supply) is resulting in less available fresh water supply for agriculture. So, the area of land irrigated per capita is decreasing. Proper water resources management becomes essential in order to optimally allocate water among domestic, industrial and agricultural domains. Meanwhile, a major issue is still disregarded, this issue being whether there will be enough water for the next generations.

Water supply in the Middle East and North Africa (MENA) region is unequally distributed in space and time, both at regional and international level. The Southern Mediterranean and Middle East sub-regions have among the lowest per capita amount of water supply in the world. It is estimated that 7% of the entire Mediterranean population (28 million persons) lie below the severe scarcity line of 500 m^3/year per capita and another 29% (115 million persons) are below the poverty line of 1000 m^3/year per capita as defined by the United Nations. In certain countries, exploitation indexes of renewable natural fresh water resources have reached and exceeded 100%. In the Mediterranean countries, agriculture consumes 70-80% of water; the remaining is shared between domestic and industrial uses. The Food and Agricultural Organization estimates that an overall expansion of 2.25% per year in irrigation is needed to meet the word food demand; yet expansion in irrigation has slowed down to less than 1% per year [1].

Will humanity face water scarcity? Will the “blue gold” be scarce, expensive and source of conflicts between states? This increase in number of inhabitants will have to share the same amount of water that we use nowadays. There is a major threat that the water available may be inadequate to meet growing food demands particularly in water short countries (Rosegrant et al [2]). Two other threats should be considered. The first one is pollution arising from wastewater, agricultural pesticides, fertilizers, and industrial wastes discharged to rivers and the ground water. In this case, one cubic meter of polluted water renders 8 to 10 m^3 unusable. The other threat that is difficult to quantify, is global warming. It could modify the hydrologic systems of various regions of the world. This leads to a fundamental problem for water-scarce countries that should balance between their renewable water resources and their capacity for food production. Every year, farmers and traders in the MENA move volumes of virtual water equivalent to the flow of the Nile into Egypt, or about 25% of the region’s total available freshwater through the import of food and fibre (Allan [3]).

Virtual water and water productivity combine agronomic and economic concepts, with emphasis on water as a key factor of production. The agronomic component addresses the amount of water used to produce crops, while the economic component involves the opportunity cost of water, which is its value in other uses that may include production of alternative crops. The virtual water perspective is consistent with the concept of integrated water management, in which many aspects of water supply and demand are considered when determining the optimal use of limited water resources (Bouwer [4]). The net productivity or gross margin is the value of crop productivity (MU/ha^{-1} or MU/m^3) minus all applicable production costs. For the purpose of this study, water productivity is defined as monetary units per unit of water (MU/m^3). The current approach for demand management in irrigated agriculture recommended by international organizations and governmental agencies is to adopt 'water-saving' irrigation methods such as localized irrigation. Localized irrigation is not a miracle technology, since excellent as well as, poor results were obtained. Moreover, most farmers and irrigation operators lack the understanding of the soil-plant-water-climatic relationship in order to better operate and manage this new adopted technology (Nimah et al [5]).

The theme of an alternative water demand management is to have more "monetary value per drop of water". To achieve this alternative, the virtual water and water productivity concepts are combined as an approach to deal with water scarcity (Moukarzel and Nimah [6]). This new approach does prioritize and arrange in a descending order what food commodities to import and what crops to grow locally. The general objective of this study is to combine and maximize the virtual water and water productivity concepts.

The specific objectives of this study are to (a) Develop a mathematical model to optimize the crops to be produced by maximizing water productivity per unit water i.e. monetary units per unit of water and (b) Estimate the volume of virtual water within the context of national water need and water availability for future strategic planning of water management.

2 Methodology

2.1 Model description

A linear mathematical model is developed to solve the problem of how best to allocate water among different crops to have the best combinations of net revenue per cubic meter of water and quantity of water under conditions of limited water available. In addition the model satisfies the different constraints imposed by the decision manager of the irrigation project. The optimization model developed in this study required input data generated from a set of implicit equations. This input data consist of crop water requirements, crop water demand, and water use efficiency.

2.2 Objective function

The objective function of the model is to maximize the water productivity (MU/m^3) subject to linear constraints such as cost of production constraint, water requirement constraint; and non-negativity constraint. This optimization model is developed in such a way that determines the crops that are most suitably grown locally and their respective quantities. The rest of the crops that are not advised to be grown locally will be imported. The objective function is presented by the formula:

$$MaxZ = \sum_{i=1}^{n} p_i x_i \tag{1}$$

where Z represents the total water productivity ($/m^3), i is the Index of crop type, p_i is local farm-gate price of crop i ($/kg), x_i the quantity of crop i to be grown locally (kg/m^3), and n is the number of crops. The model is subjected to the following constraints:

2.2.1 Water availability constraint

This constraint make the production capacity water needed not exceed water availability in the project area.

$$\sum_{i=1}^{n} w_i x_i \leq 1 \tag{2}$$

where W_i is specific water demand (SWD) (m^3/kg).

2.2.2 Cost of production constraint

Each crop requires a specific cost of production. These costs are disaggregated into cost of water, cost of irrigation system and its maintenance depending on the system used (surface, sprinkler and trickle) as well as other costs including fertilizers and other cultural practices. In order to grow these crops locally, they should not exceed the price of the same crop imported. This constraint is defined mathematically as follows:

$$\sum_{i=1}^{n} (C_{w_i} + C_{ir_i} + C_{p_i}) x_i \leq P_{p_i} \tag{3}$$

where C_{wi} is the cost of one m^3 of water ($/Kg), C_{iri} is the cost of the irrigation system ($/Kg), C_{pi} is the cost of production for crop i including fertilizers ($/Kg), P_{pi} is the price of crop i imported at Beirut port ($/kg).

2.2.3 Non-negativity constraint

It assures the non-negativity of the study decision variable and is formulated as:

$$x_i \geq 0 \tag{4}$$

2.3 Data needed and analysis

The following input data is needed to solve the mathematical model. Crops suitable to be planted in this area, Crop planting and harvesting pattern over the year, Yield of crop i per unit area (Kg/m^2), Crop water requirements per growing month (mm/month), Cost of production of one kilogram of crop i at the farm gate ($), Selling price of one kilogram of crop i at the farm gate in dollars, Cost of different irrigation systems per unit area ($/m^2), cost of 1 m^3 of water ($/m^3), and total available water over the year.

2.4 Water requirement, crop yields and price

The data generated is specific to the South Bekaa region for the 6700 hectares area specified as phase 2 area of the South Bekaa Irrigation Scheme project. Data for this research were extracted from the feasibility study of the project. The crops that were chosen totalled 43 crops. The crops were divided into three subsets: vegetables, fruit trees, and field crops. The different crops, their respective net irrigation requirements, water use efficiency, crop water yields, and farm prices are listed in table 1. Crop water yield is better defined as the quantity in kilograms of crops i produced in one cubic meter of supplementary irrigation as calculated in eqn. (6).

In addition to the cost of production of the crops, the irrigation system installed, as well as, its operation and maintenance costs and the price of water is considered. Three types of irrigation systems are usually used: surface, sprinkler, and trickle. The total annual costs are: 0.0438, 0.0510 and 0.0544 $\$/m^3$/year for surface, sprinkler and trickle irrigation systems, respectively.

2.5 Solving the model

The mathematical model was solved using the LINDO (Linear Interactive Discrete Optimizer) software after all the parameters were defined. The output data of the model are: crops to be cultivated locally; the crops to be imported, the quantity of each crop to be grown per cubic meter of water, and the maximum water productivity with respect to combination and quantities of crops produced locally.

In order to test the sensitivity of the model, different scenarios were analyzed. The first scenario was tested with respect to the production constraint, i.e. certain crops were imposed to be grown with a specific percentage for each crop, because of strategic planning issues. The second scenario dealt with water scarcity constraint. The third scenario was to test the reactivity of the model to an increase or decrease of the imported crops prices.

3 Results

3.1 Optimization model results

The initial model output is the model results without any applied constraints. The sensitivity of this model to the imposition of: production, water availability, and to the change in price of imported crops constraints will be presented and discussed later.

The initial results indicate that the maximum water productivity is 6.92032 $\$/m^3$ if only eight crops are grown in the project area instead of the 43 crops that are actually being grown. The eight crops are garlic, green beans, onions, radish, spinach, chickpea, lentils and janarek. The remaining 35 crops can be imported, and their cost of importation is less than their cost of production locally. This means that this irrigation project can be sustained and the saved water (virtual water) can be used to expand the irrigated area. Results also showed land use area for each crop. The term land use is defined as the square meters that can be irrigated by one cubic meter of water to achieve the objective function.

Table 1: Yield, net irrigation requirement (NIR), crop-water yield, water use efficiency (WUE) and farm price for different crops grown in Lebanon.

Crop	Yield per m^2	NIR	Crop Water Yield	WUE	Farm Price
	(Kg/m^2)	$m^3/m^2/yr$	m^3/kg	Kg/ m^3	$/Kg
Broad beans	0.892	0.132	0.148	6.778	0.460
Cabbage	2.012	0.138	0.069	14.569	0.230
Carrot	2.203	0.528	0.239	4.176	0.185
Cauliflower	1.312	0.141	0.108	9.292	0.335
Cucumber	1.289	0.276	0.214	4.679	0.403
Eggplant	1.323	0.512	0.387	2.582	0.322
Garlic	0.631	0.020	0.031	32.194	0.511
Green beans	0.646	0.103	0.159	6.290	0.617
Okra	0.810	0.310	0.383	2.611	0.861
Lettuce	2.183	0.145	0.066	15.066	0.233
Melon	1.325	0.400	0.302	3.311	0.382
Peas	0.580	0.113	0.195	5.133	0.645
Potato (early)	2.640	0.232	0.088	11.365	0.239
Radish	1.259	0.047	0.037	26.902	0.257
Spinach	1.511	0.073	0.048	20.841	0.351
Squash	0.978	0.276	0.282	3.550	0.403
Tomato	2.049	0.587	0.287	3.489	0.305
Water melon	1.225	0.299	0.244	4.092	0.245
Alfalfa	2.212	0.297	0.134	7.445	0.250
Barley	0.300	0.134	0.447	2.235	0.280
Chickpea	0.650	0.056	0.086	11.566	0.400
Lentils	0.580	0.066	0.114	8.735	0.400
Lupine	0.670	0.418	0.624	1.602	0.383
Dry pea	0.650	0.418	0.643	1.554	0.533
Vetch	0.750	0.070	0.093	10.760	0.283
Wheat	0.300	0.199	0.663	1.509	0.313
Almond	0.400	0.072	0.179	5.594	0.526
Apple	1.494	0.797	0.534	1.874	0.537
Apricot	0.874	0.275	0.315	3.178	0.693
Cherry	1.190	0.254	0.213	4.685	0.535
Grape	0.825	0.388	0.470	2.128	0.409
Janarek	0.900	0.072	0.079	12.587	0.713
Peach	1.193	0.473	0.396	2.524	0.679
Pear	1.300	0.645	0.496	2.017	0.702
Plum	1.085	0.275	0.253	3.945	0.400
Quince	1.493	0.254	0.170	5.878	0.533
Walnut	0.600	0.672	1.121	0.892	0.267

3.2 Effect of different scenarios

3.2.1 Scenario I

The model was tested to its sensitivity to alternative cropping pattern. The eight crops that were selected in the initial model output were eliminated from the cropping pattern. The model reaction was positive and selected a new array of seven crops. The new selected crops are: four vegetable crops, one field crop, and two fruit crops, with an objective function value equal to 3.319 $/m^3. In both the initial and this scenario, the model selected the least water demanding crops with competitive prices (like cabbage, cauliflower, lettuce and vetch/ winter crops and short season fruit trees like almonds and cherries).

On the other hand, for strategic planning issues, some crops need to be produced locally. Alfalfa and vetch for example are needed for animal feeding. These crops were imposed to be part of the cropping pattern solution of the model. In the initial model, the maximum water productivity is attained at 17.38 m^2/m^3 of land use Alfalfa and vetch are imposed to be produced on 10% of these 17.38 m^2, divided into 57% (one m^2) for alfalfa and 43% (0.73 m^2) vetch of the 1.73 m^2.area. The results obtained from this imposition were seven crops beside the two imposed crops, and the objective function became 6.306 $/m^3. Also, the same procedure was followed for fruit trees. Ten percent of the allocated land is already planted to apples, apricots and Janarek with the following allocation: 23%: 34.7%: 42.3% of the 1.73 m^2/m^3. The objective function decreased to 4.429 $/m3. By imposing certain crops as outlined before, the objective function or the maximum revenue per unit water decreased by 8.88% when alfalfa and vetch were imposed and by 36 % when fruit trees were imposed.

The above results shows clearly on the effectiveness of the model in choosing a cropping pattern that will yield the best revenue per unit water. Thus, applying this model will help in sustaining the irrigation of agricultural land.

Table 2: Selected crops and water productivity according to different scenarios: I-a removing initial crop; I-b imposing alfalfa and vetch; and I-c imposing fruit trees.

Scenario I-a		Scenario I-b		Scenario I-c	
Crop	Return $/kg	Crop	Return $/kg	Crop	Return $/kg
Cabbage	0.270	Garlic	0.521	Garlic	0.521
Cauliflower	0.084	Onions	0.221	Onions	0.221
Lettuce	0.354	Radish	1.625	Radish	1.625
Peas	0.422	Spinach	0.366	Spinach	0.366
Vetch	0.520	Alfalfa	0.555	Chickpea	0.505
Almond	0.681	Chickpea	0.392	Apples	0.318
Cherry	0.988	Vetch	0.154	Apricot	0.286
		Janarek	2.472	Janarek	0.587
Z ($/m^3) = 3.319		Z ($/m^3) = 6.306		Z ($/m^3) = 4.429	

3.2.2 Scenario II

Five different quantities of available irrigation water volumes were applied to test the sensitivity of the model towards water scarcity. The amount of available water was imposed to decrease from one cubic meter in the initial model to 90%, 80%, 70%, 60% and 50% (fig. 1). The reduction of available water that might be caused by dry years or any other factor is pronounced in the results obtained from the model. The decreases in water productivity are 5.25%, 1.68%, 16.67%, 23.08% and 31.69% for 90%, 80%, 70%, 60% and 50% of available water, respectively. Also, the land use decreased from 17.39 m^2/m^3 to 9.63 m^2/m^3 in the above ranges of available water, which is an approximate decrease of 45% Moreover the cropping pattern did change. The number of selected crops decreased as water scarcity increased.

The decrease in water productivity as related to water shortage was found to be curvilinear and this relation fits the following mathematical equation:

$$Z = -0.0255w^2 - 0.2521w + 7.183 \qquad \left(R^2 = 0.9992\right) \tag{5}$$

where Z is the water productivity ($\$/m^3$), and w is the fraction of available water in decimal.

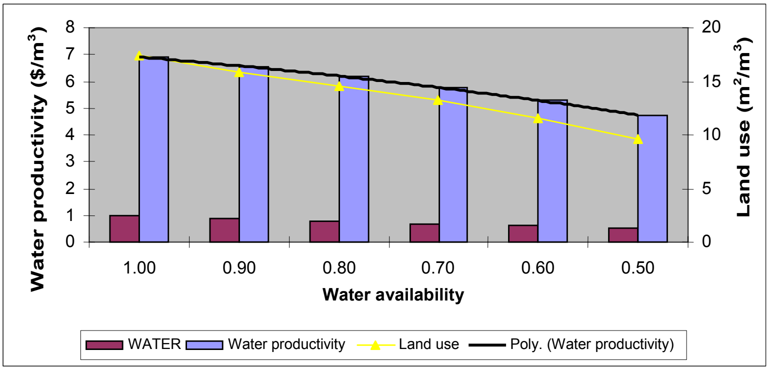

Figure 1: Changes in water productivity and land use as affected by irrigation water scarcity.

3.2.3 Scenario III

The import prices might be subject to increases because of increases in transportation costs due to increases in energy costs or other factors. In other cases, these prices might decrease due to competition because of globalization. Different sets of changes were considered. The import prices were subjected to decreases and increases from the initial model prices respectively by 10%, 20% and 40%. When price decrease was imposed in the model, the number of selected crops to be grown locally was increased and the water productivity did decrease by 4.8%, 9.66% and 20.29% respectively for decreases of 10%, 20% and 40% respectively. While an increase in import price was imposed the number of selected crops by the model decreased but the water productivity increased from 7.253$/m^3 at 10% import price increase to 8.166 $/m^3 at 40% increase. The trend in water productivity changes due to price increase or decrease is shown in fig. 2.

On the other hand the land use per cubic meter of water decreased from 17.388 m^2/m^3 to 13.813 as the import prices of crops decreased to 40%; and reversed with increases in the import prices from initial prices. The land use was increased from 17.388 to 18.873 m^2/m^3. The water productivity-import price relationship is defined in the mathematical equation below.

$$Z = -0.0089p^2 - 0.3311p + 8.4 \qquad (R^2 = 0.9831) \tag{6}$$

where Z is the water productivity ($/m^3), and p is the percentage change in import prices.

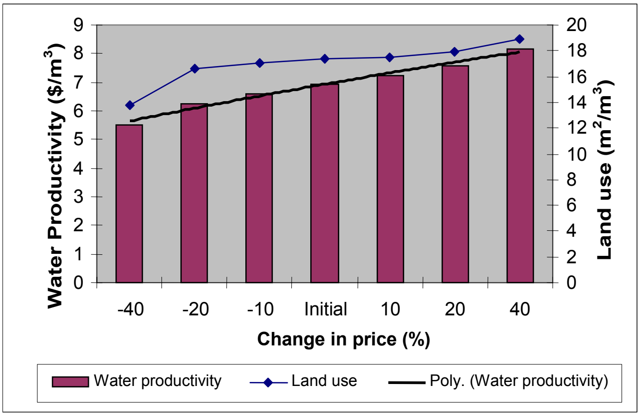

Figure 2: Changes in land use and water productivity with changes in import prices of crops.

4 Discussion

The model developed generated the maximum water productivity and selected the crops to be grown in a certain irrigated project according to the input data and assumptions previously mentioned. When high water demanding cops were imposed like alfalfa, apples, apricots, the model reacted but the water productivity decreased as presented in the results above. On the other hand, when the price of imported crops was deflated, the model reacted by choosing more crops but the water productivity decreased as well as the land used per cubic meter.

Thus, by importing the 35 crops, the net water saving will be 3408 m^3/ha. Therefore, in the 6700 hectares project area 22.8 million cubic meters could be saved and thus imported as virtual water, these findings are in general agreement with what reported [7, 8].

The results obtained in this study are not the ultimate solution for managing the use of water resources. But, they can help in strategic planning for saving water resources. It can help formulating long term agricultural plans in specific water scarce projects based on importing high water consuming crops with least price competitiveness, thus sustaining irrigated area. Since, population growth is continuing in the coming years, there will certainly be challenges in providing water for food security.

5 Conclusion

The formulated model links water productivity and virtual water and did optimize the water productivity or net return per unit of water i.e. "more revenue per drop" based on set constraints. It is certain that if the data on water requirements, yield, cropping pattern, and prices are changed, the value of water will change. The reliability of the model output depends on the reliability of the input data, which can be updated easily. The strength of the study is that by applying linear programming, it was possible to quantify the link between water scarcity or limited water availability, virtual water and sustainable irrigation.

This model can be applied to similar cases with the proper input data. Also it can simulate strategic planning for allocating the scarce water available in an irrigation scheme to keep it sustainable.

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