OPTIMAL ALLOCATION OF LIMITED WATER SUPPLY FOR A LARGE-SCALE IRRIGATED AREA — CASE STUDY

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ABSTRACT

A study is conducted on a large-scale pressurized irrigation scheme located in southern Italy. The ultimate goal is identifying optimal allocation of limited available water supplies under the existing cropping pattern scenario and infrastructures. The irrigation scheme was originally designed some 30 years ago to allow extensive agricultural development for the area. Nevertheless, major changes in cropping patterns occurred. As a result, the current operating conditions and irrigation demand patterns are different from the original design. Different levels of limitation in water resources are considered to account for climatic trends. Crop irrigation requirements were preliminarily mapped, under three different climatic conditions. Then the allocations of different levels of limited water supply are analyzed. Economic objectives as well as physical, social and environmental constraints are considered using optimization model. Tariff rules for irrigation water are discussed as related to different water management options. Optimal conjunctive use of surface and groundwater for the different time periods of the irrigation season are also analyzed. Based on the results, practical recommendations about the operation of the existing infrastructures as well as modernization options are provided. Results indicate the importance of data monitoring, data interpretation and the need for quantitative-based models to improve decision-making and the economic sustainability of irrigated agriculture.

INTRODUCTION

A large-scale irrigation scheme located in Southern Italy and managed by a local Water Users Association (WUA) is investigated. The irrigation system serving the study area was originally designed some 30 years ago to allow for extensive agricultural development. Changes in cropping patterns occurred as a result of

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favorable agro-climatic conditions and of market trends; also progresses in farming and irrigation practices were achieved. Consequently, current farmers' irrigation demands are different from those foreseen during the design stage and from the ones existing since the system was first put into service.

On the other hand, different levels of limitation in available water supply for irrigation may occur as a result of climatic trends. The combination of different possible conditions of water demand and supply might require different management strategies in order to allow satisfactory economic returns from farming activities and to maintain a sustainable irrigated agriculture in the area.

OBJECTIVES AND APPROACH

The main purpose of this study is to develop a model for optimal allocation of limited available water supplies to a large-scale agricultural area, under the existing cropping pattern conditions and for the existing irrigation infrastructures. Crop irrigation requirements were mapped under three different climatic conditions, by using a soil-water balance model. This preliminary task involved analysis of historical climatic data series (1959-1994) and the application of a probabilistic approach to identify three scenarios characterized by three different levels of climatic water demand (average, demanding, very-high demanding). Based on this spatially-distributed set of information, allocations of different levels of limited water supply were simulated for each of the three climatic scenarios.

The simulations were conducted on a volumetric basis for the whole irrigation season. Economic objectives as well as physical, social and environmental constraints were considered within the optimization model**.** Yield response to irrigation was estimated by means of the Stewart model (Doorenbos and Kassam, 1979). Finally, optimal conjunctive use of surface and groundwater for the irrigation season was analyzed.

BACKGROUND ON THE STUDY AREA

The analyses were carried out on the areas served by the "Sinistra Bradano" large-scale irrigation system, which is located in the south-eastern part of the Italian peninsula. This system covers a total topographic area of 9,500 ha. The physical boundaries of the study area as well as its location, shape, topographic conditions and extent are reported in Figures 1 and 2.

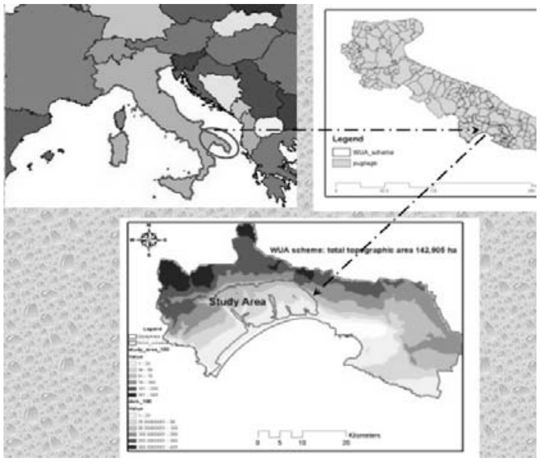


Figure 1. Location and extent of the area of interest

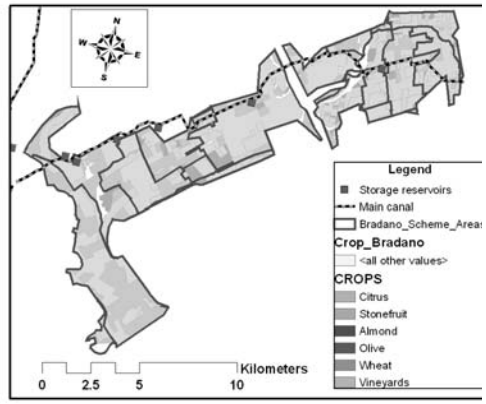


Figure 2. Representation of the "Sinistra Bradano" irrigation scheme

Main irrigated crops are table grapes, citrus, olive and summer vegetables, as shown in Table 1 and from Figure 2. Most of the farms utilize trickle irrigation as predominant method, while in some limited areas sprinkler irrigation is still utilized for citrus and summer vegetables.

Table 1.Existing cropping pattern in the study area.

Crop	Sinistra Bradano (ha)
Table grapes	3753.4
Citrus	2208.3
Vegetables	2184
Olive	431.9
Stone fruit	44
Almond	14.4
Total (ha)	**8636**

Source: *Water Users Association « Stornara e Tara », 2001*

Due to favorable agro-climatic conditions, agriculture in the area is intensive and highly market-oriented. Climate is semi-arid with an average yearly precipitation of about 550 mm, which are poorly distributed along the months. Therefore profitable farming is strongly dependent on irrigation. As a matter of fact, collection of water fees is tightly linked to the quality of irrigation services provided by the WUA. The typical irrigation season lasts from the beginning of April to mid November. The hydraulic scheme is composed of a main canal conveying water from a regional dam to four storage and compensation reservoirs, which serve ten irrigation districts. From each of these reservoirs, district pressurized distribution networks originate for delivering irrigation water to the farms. Figure 2 shows the main features of the irrigation scheme.

Irrigation distribution network is operated by rotation delivery schedule. The usual rotation is based on a 10-day shift. At present, distribution of irrigation water to farms, as reported by many farmers, is too restrictive and not timely matching the actual crop water requirements. As a result of all the above issues, during the last 10 years a large number of water users started developing their "private water sources" by drilling on-farm irrigation wells (nearly 6,000 wells). This led to over-pumping from aquifers. Further environmental concerns are saline intrusion in groundwater and an increasing process of salt build-up in the soils. Therefore, a sound estimation of agricultural water demand is strongly needed as initial step for improving water management in the study area. The final goal of this plan is maximizing the net benefit for the entire irrigated area. This operational plan represents the general objective of the present study.

MODEL FORMULATION

A non-linear programming model was developed to achieve the optimal allocation of available water supply among the different cropped areas. The model was developed based upon data and information. Information on crop water requirements were generated by running a soil-water balance model on each identified simulation unit. Simulation units are areas characterized by the same crop, soil and climatic conditions.

Objective function

The objective function for the developed model is the following:

$$NetBenefit = \sum_{i=1}^{n} \left[\left(Ya_i * MV_i * A_i \right) - \left(PC_i * A_i \right) - (Ia_i * 10 * A_i * C_w) / S_{eff} \right] \qquad (1)$$

where $\boldsymbol{Ya_i}$ is the actual yield of crop $\boldsymbol{i}$ (ton/ha), $\boldsymbol{MV_i}$ is the averaged value on the local market for the crop $\boldsymbol{i}$ (\$/ton), $\boldsymbol{A_i}$ is the area of crop $\boldsymbol{i}$ in hectares, $\boldsymbol{PC_i}$ is the production cost of crop $\boldsymbol{i}$ (\$/ha) excluding the cost of irrigation water, $\boldsymbol{Ia_i}$ is the amount of irrigation water required by crop $\boldsymbol{i}$ to obtain the actual yield (gross irrigation requirement, mm), $\boldsymbol{C_w}$ is the unitary cost of water (\$/m^3) and $\boldsymbol{S_{eff}}$ is the overall efficiency of the irrigation system, assumed to be 80%. In this model the crop water requirements are net amounts. The related gross amounts are considered in the objective function, where the overall irrigation system efficiency is accounted for.

Set of Constraints

Area constraints. There are two sets of areal constraints imposed.
The first one concerns the area occupied by each crop included within the cropping pattern. In the preliminary study on crop water requirements, 42 different simulation units were identified and coded on the basis of crop-type,

soil-type and the climatic sub-area they are located in. The total area was imposed as maximum area constraint for each code within the model. The area constraint for each simulation unit is in the form of:

$$\sum_{j=1}^{m} A_{ji} \leq A_i \quad (2)$$

where $\boldsymbol{A_{ji}}$ represents the area of the different plots belonging to the same simulation code $\boldsymbol{i}$.

1. The second type of constraint was included in the model to ensure that the sum of areas relative to different simulation units does not exceed the total cropped area served by the irrigation scheme. This constraint is in the form of:

$$\sum_{i=1}^{n} A_{ci} \leq TA_{serv} \quad (3)$$

where $\boldsymbol{A_{ci}}$ represents the area of the different simulation codes and $\boldsymbol{TA_{serv}}$ is the total area served by the irrigation scheme.

<u>Yield constraint</u>. Water deficits in crops and the resulting water stress on the plant have an effect on crop evapotranspiration and crop yield (Doorembos and Kassam, 1979). The yield reduction depends on the level of water stress through the following relationship:

$$\left(1-\frac{Ya}{Ym}\right) = k_y * \left(1-\frac{ETa}{ETm}\right) \quad (4)$$

where $\boldsymbol{Ya}$ is the actual yield (ton/ha), $\boldsymbol{Ym}$ is the maximum obtainable yield (ton/ha), $\boldsymbol{k_y}$ is the yield response factor (dimensionless), $\boldsymbol{ETa}$ is the actual evapotranspiration (mm) and $\boldsymbol{ETm}$ is the maximum evapotranspiration (mm). Maximum-yield constraints were imposed in the model to make sure that the actual yield of each crop does not exceed the maximum yield obtainable. In this constraint, an overall efficiency of the irrigation system of 80 % was also accounted for. The maximum harvestable yield for the different crops and Yield reduction factors are reported in the Table 2.

Table 2. Seasonal Yield reduction factors and Maximum Yield for different crops

Crop	**K_y**	**Max Yield (Ton/ha)**	**Crop**	**K_y**	**Max Yield (Ton/ha)**
Almond	0.80	2.5	Stone fruit	0.80	25
Citrus	0.90	30	Table grapes	0.85	35
Olive	0.80	20	Vegetables	1.10	40

Water Availability constraint. Two water availability constraints were set in the model:

1) The first one relates to the water supplied by the Water Users Association. A volumetric constraint was imposed in the model to ensure that the total volume resulting from the optimal water allocation among the different areas of the irrigation scheme does not exceed the total water supply available from the WUA for the whole irrigation season.

$$\frac{\sum_{i=1}^{n} CIR_i}{S_{eff}} \leq TW_{wua} \tag{5}$$

where $\boldsymbol{CIR_i}$ is the seasonal irrigation requirement for each crop $\boldsymbol{i}$ [which is given by (ETc-Eff.Rain)], $\boldsymbol{TW_{wua}}$ is the total water available by the Water Users Association.

2) The second constraint relates to the total seasonal volume that can be withdrawn from the groundwater. The concept of Safe Yield of aquifer is applied in this water modeling project and ground water is only used for emergency and supplemental irrigation when the water from WUA is not sufficient relative to water demand. The allocated supplemental volumes to deficit cropped areas do not exceed the seasonal Safe Yield of the aquifer. This constraint is given by:

$$\frac{\sum_{i=1}^{n} CIR_{GW\,i}}{Application\ Efficiency} \leq TW_{GW} \tag{6}$$

where $\boldsymbol{CIR_{GWi}}$ are the irrigation deficits for each crop $\boldsymbol{i}$ to be compensated by using groundwater, $\boldsymbol{TW_{GW}}$ is the seasonal Safe Yield from the aquifer and ***Application Efficiency*** is assumed to be 90 %.

Constraint on equity distribution. This was done in order to allocate a 50 % fraction of the total available water supply from WUA on the basis of equity. The selected equity criterion is to deliver to each cropped area an amount of water corresponding to 60 % of the maximum harvestable yield. The other 50% of available water supply from WUA is delivered to those farmers willing to pay increasing unit prices for increasing water volumes.

$$ETci_{(0.60Y)} \geq \left[\left(\frac{Y_{60}}{Y_{max}} \right) - 1 + k_y \right] * \frac{ETc_{max}}{k_y} \tag{7}$$

$$\frac{\sum_{i=1}^{n} ETci_{(0.60Y)}}{Overall\ Efficiency} \leq 0.50 * TW_{wua} \tag{8}$$

where $\boldsymbol{ETci_{(0.60Y)}}$ is the crop evapotranspiration corresponding to 60 % of the maximum yield for each crop ***i***, $\boldsymbol{Y_{max}}$ is the maximum harvestable yield and $\boldsymbol{Y_{60}}$ is 60 % of $\boldsymbol{Y_{max}}$.

Net benefit constraint. The last constraint is related to the net revenue obtained by farmers for each simulation unit. This constraint basically prevents any cropped area getting negative net benefit. This is related to the cost for any unit of water utilized by farmers.

$$NB_i \geq 0 \tag{9}$$

where ***NBi*** is the net benefit for each cropped area ***i***.

Sources of information and data description

As previously pointed out, information relative to crops grown in the area were obtained from different sources. 1) "Stornara e Tara" Water Users Association – Agronomic Division; 2) Istituto Nazionale di Economia Agraria (INEA-RICA), 3) Agricultural Office – Apulia Region, 4) Chamber of Commerce of the Province of Taranto, 5) Private agriculture consultants, 6) Public and private extension service officers, and 7)Web sources

Harvestable Crop Yield. The data in Table 2 represent the 5-year averaged maximum obtainable yield for the different crops normally grown in the area served by the "Sinistra Bradano" large-scale irrigation scheme.

Market value of crop productions. These data represent the last three season average of what was normally paid to farmers in the study area. Crop market values are reported in the following Table 3. As for summer vegetables, the values are the average between the three main crops, namely bell pepper, eggplant and water melon.

Table 3. Local market values of crops grown in the study area

Crop	***Yield (Ton/ha)***	***Price (EU/tons)***	***Price ($/tons)***	***Market Value ($/ha)***
Almond	2.5	945.0	1228.5	3,071
Citrus	30	400.0	520.0	15,600
Olive	20	700.0	910.0	18,200
Stone fruit	25	320.0	416.0	10,400
Table grapes	35	500.0	650.0	22,750
Vegetables	40	287.5	373.7	14,950

** Conversion 1 Euro = 1.30 US Dollars*

Crop production costs. Crop production costs relate to all farming practices necessary to achieve high quality yield as reported in Table 4 and do not include cost related to irrigation.

Table 4. Production costs for crops grown in the study area

Crop	*Total farming cost (EU/ha)*	*Total farming cost ($/ha)*
Almond	1,000	1,300
Citrus	8,000	10,400
Olive	7,000	9,100
Stone fruit	900	1,170
Table grapes	12,500	16,250
Vegetables	4,335	5,633

** Conversion 1 Euro = 1.30 US Dollars*

Cost related to irrigation. In the study area water is currently charged by the managing body (WUA) based on the cropped area served. This basically means that also irrigation represents a fixed cost regardless the water volume actually utilized by farmers.

For the present water modeling project a different tariff rule was considered with the aim of optimizing allocation of limited water supply but also to improve the efficiency of water use at the farm level. For these reasons water is charged on a volumetric basis with increasing rates for increasing volumes withdrawn by farmers. These rates are presented in Table 5. Also, according to the water cost applied to different classes of consumption, the resulting unitary cost for incremental steps of volume was calculated and plotted (graph presented in Figure 3).

In case farmers utilize groundwater for irrigating their crops, the unit cost of water is estimated on average at 0.39 $\$/m^3$ (0.30 EU/m^3).

Table 5. Unit prices for water for the different classes of volumes

Water volume (m^3)	*Unit cost (EU/m^3)*	*Unit cost ($\$/m^3$)*
< 2,000	0.113	0.146
2,000 – 3,000	0.225	0.292
> 3,000	0.30	0.390

** Conversion 1 Euro = 1.30 US Dollars*

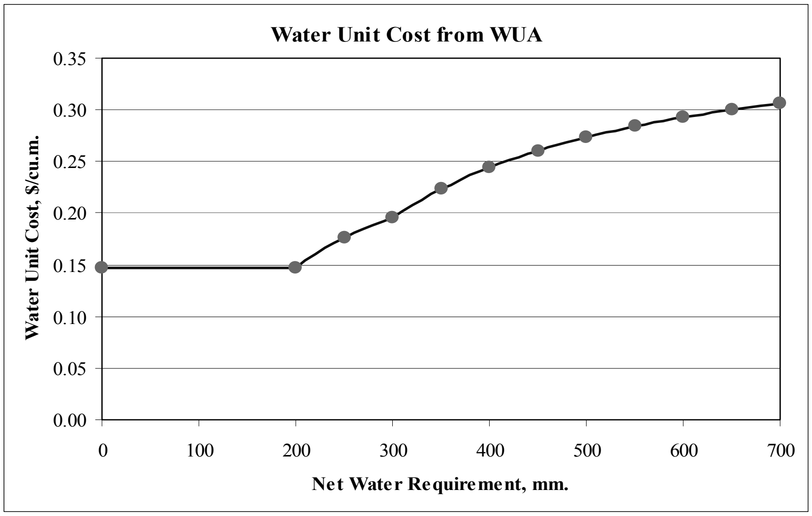
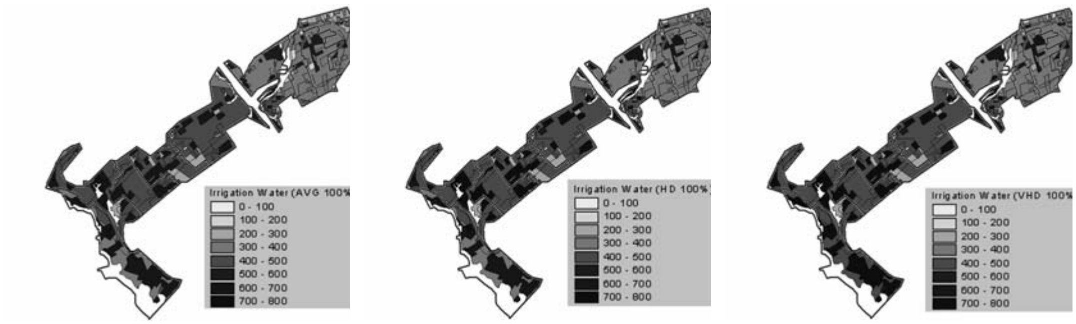


Figure 3. Plot of the unitary cost for the different water volumes withdrawn by farmers

RESULTS AND DISCUSSION

Crop irrigation requirements were calculated and mapped under three different climatic scenarios (average, hi, and very-high demand) corresponding to probability of occurrence of 50 %, 75 % and 95 %. These represent the basic water demand scenarios and are reported in Figures 4.

As for water supply, six different scenarios were simulated starting from full satisfaction of crop water requirements (100 %) up to the most critical situation considered, which corresponds to a water availability of only 50 % of the total water demand. For these, magnitude of deficits was computed. On these water deficit scenarios, a second run of the model was conducted in order to find the optimal allocation of ground water. The model was in fact developed in such a way to give priority of use to water from the WUA. Only when the available water supply from WUA is not sufficient to adequately serve the whole area a supplemental use of groundwater is allowed and for volumes corresponding to the quantified existing water deficit. This approach resulted in computation of the combined net benefit and in developing a sort of seasonal plan of conjunctive use of surface and groundwater resources for the whole scheme.



Average demand High-demand Very-high demand

Figure 4. Map of crop water requirements

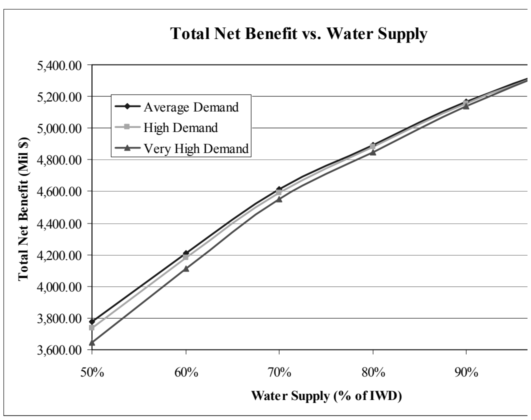


Figure 5. The net benefit for the whole area versus the available water supply from WUA

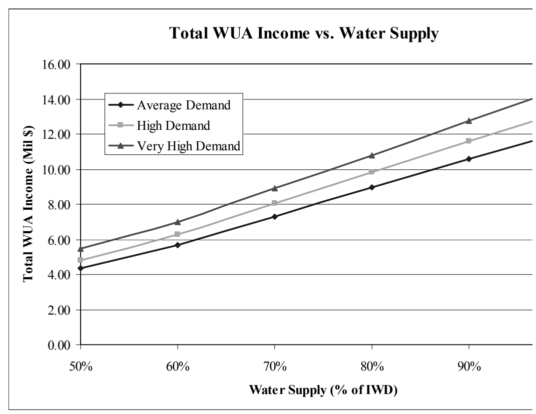


Figure 6. The WUA income for different levels of available water supply from WUA

Figures 5, 6 and 7 report the situation resulting from the first set of model runs. These relate to the optimal allocation of water from WUA. Graphs reported in Figures 8, 9 and 10 represent results from the second set of model runs, which concern the optimal allocation of groundwater over the identified deficit areas. From Figure 5 it can be noticed that the net benefit is rapidly increasing as the water availability increases. Also, the highest increasing rate of net benefit is occurring under the very-high demanding climatic scenario, thus showing that water has a strong effect both on crop yield and on irrigation cost and that this effect has an increasing intensity for increasing water demand conditions. The plot in Figure 6 shows the variation of WUA's income resulting from the water distribution service (sale of irrigation water at increasing unitary prices). Also in this case, the WUA's income increases with increasing levels of water availability. Water is more urgently needed under very-high demanding conditions to avoid any deficit period for crops, which can result in severe yield reduction. For this reason, under very-high demanding conditions farmers are more willing to pay for additional amounts of water in order to avoid any yield loss risk. This can be inferred from the graph, as the rate of income increase varies as the climatic demand scenario becomes more demanding. Similar trends can be observed from the third graph reported in Figure 7, where the actual crop evapotranspiration is plotted versus different levels of water availability. In this case as long as water availability increases also crop evapotranspiration increases by a rate that is different for the three climatic scenarios

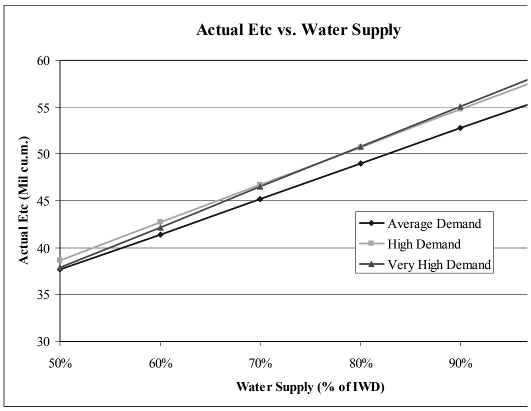


Figure 7. The actual crop evapotranspiration for different levels of water supply WUA

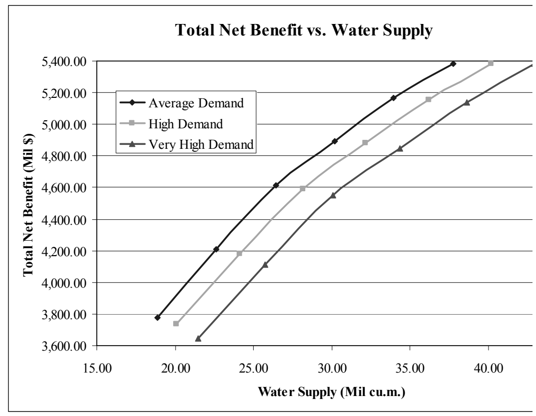


Figure 8. The net benefit versus the available water supply from groundwater

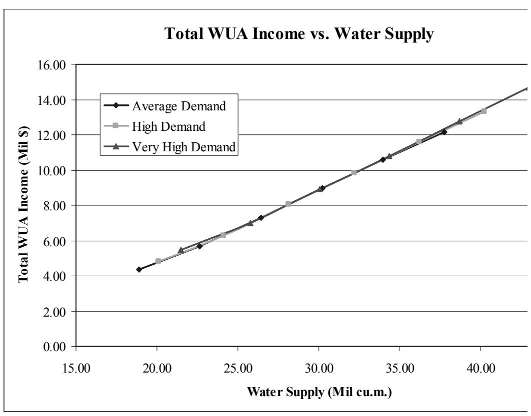


Figure 9. The WUA income for different levels of available water supply from groundwater

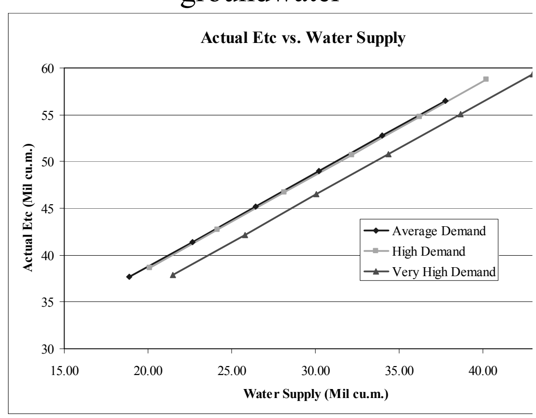


Figure 10. Actual crop evapotranspiration for different levels of water supply from groundwater

In the second set of graphs, net benefit, WUA's income and actual ETc are plotted versus water availability from groundwater aquifers. Similar trends relative to the first set of graphs can be noticed, thus showing that the model is working properly and well representing the simulated conditions.

The optimal solutions found by the model for water allocation were displayed in the GIS environment. In the following sets of figures results from the Very-High Demand scenario are presented. From these, the location of deficits likely occurring under the most critical climatic scenario can be noticed. These deficit areas are also the main targets for allocation of supplemental water to be withdrawn from aquifer.

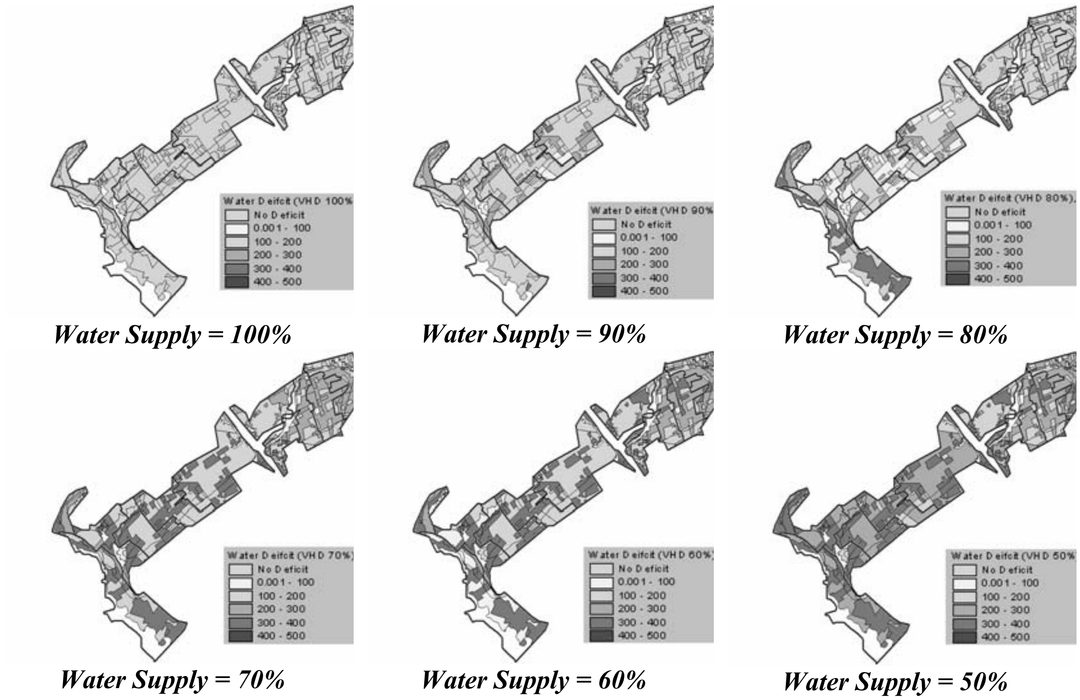


Figure 11. Optimal allocation of water from WUA and resulting deficit areas for the Very-High Demand scenario

CONCLUSION AND RECOMMENDATIONS

The presented model was developed on the site-specific conditions occurring in the study area. Therefore, it can represent the actual situation in irrigated agriculture and also reveal some room for improving water management and economical results both for the WUA and for farmers. To some extent, the model can be useful to understand several issues involved in water management at the large-scale level. The model can also be helpful to district water managers for the following purposes:

a) Evaluating the economical effects of different water management strategies
b) Developing operational plans on a seasonal basis for the irrigation distribution network
c) Developing a plan for conjunctive use of surface and groundwater enabling the economical and environmental sustainability of irrigated agriculture
d) Improving the net benefit for the whole irrigated area and increasing the income of the WUA as related to the irrigation services provided

In order to implement such a model in reality, the water distribution system should be operated on-demand. In this case, in fact, a bottom-up operation will result as farmers would decide when and how much water to take from the distribution network without informing the system managers. Only when the system is operated on-demand, the soil-water balance approach can be applied for quantifying the time-distributed and spatially distributed crop water requirements. The on-demand delivery schedule will also enable to achieve a better efficiency of water use at on-farm level.

As a pre-requisite for this type of operation, an adequate tariff rule based on volumes actually withdrawn by farmers, preferably with increasing rates for increasing volumes should be enforced.

Also, the on-farm delivery points should be equipped with flow meters in order to account for any single withdrawals.

Furthermore, a good communication level should exist between the water management agency and farmers in order to update them frequently about the level of water supply available for the forthcoming time-periods. Finally, good control and supervision over the hydraulic structures and over the aquifer should be implemented in order to enforce the developed plan for conjunctive use of surface and groundwater.

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