

## GIS and Multi-Criteria Evaluation for Integrated Water Resources

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### Abstract

Integrated Water Resources planning and Management is considered a very complex issue. It is usually solved through the multi-sectoral, Interdisciplinary and hierarchal decomposition approaches. In general, integrated management indicates the consideration of water, social, socio-economic, economic and environmental issues. The current study aims at merging the GIS and Multi-Criteria evaluation (MCE) approaches and solves the integrated management of a cultivation area. Thus, an area of about 120.000 thousand acres (250.000 Feddan) has been selected to be simulated through the merging of GIS and MCE for the scale of integrated management. The selected area is located at Northern Nile River Delta area with a coastal zone on the Mediterranean. The GIS has been applied to picture the area with its different sectors that are: social, economic, environment and water. Different randomization cropping pattern distribution scenarios have been proposed. Through the merging of GIS and MCE three scenarios have been run and evaluated on three different levels: farmer, canal catchments area and integrated area. It has been found that this merging is result in a very powerful and robust tool for evaluation of different proposed plans on the integrated levels. The merging of GIS and MCE is really facilitated the decision making process for such type of problems. It is recommended to use such methodology in the integrated management of similar problems.

Additional Keywords: GIS, MCE, Integrated water resources, Water balance.

### Introduction

Water is considered nowadays an important issue due its scarcity especially in the Middle East zone. Also, water now is considered a limiting factor for development in many countries. Usually water is controlled by water resources authorities that are responsible for managing water resources. These authorities have usually the power to control the infrastructures that deals with water discharge along rivers, canals and drains. Also, in many places all over the world the water authorities are responsible to assess penalties in the case of violating the water distribution laws and irrigation rotations. However, from the interdisciplinary point of view, a number of other authorities are also involved in water use. There are Agriculture and Land reclamation, Health, Tourism, Power generation, Transportation, Industry, Housing and New communities. Each of these authorities has different role in dealing with water. For example, the agriculture and land reclamation authority has special responsibilities in the countries that are depending on irrigation rather than rains because agriculture consumes the highest amount of water. For example, in Egypt agricultural sector is responsible for use about 85% of surface water. On the other hand, and due to the globalization several countries have started to change the cropping pattern to the liberal system where the farmer has the right to cultivate whatever he wants. Prior to this liberalization, the cultivation authorities used to decide, depending on the international market prices and national food safety, which crops had to be grown and in which localities. Such planning was undertaken a year in advance. From this exercise, the requested specific volumes of water to be delivered to each canal could be estimated by the water distribution sector at water resources authority. Then, water resources to be allocated for each spatial zone through the irrigation canal network system.

Accordingly, the main problem that faces the water distribution and water resources decision makers nowadays in a country that has a canal network and totally depends on irrigation is how to estimate water volume along the canal network under the condition that there are randomize in the cropping allocation. This will lead to have very high difficulties in assigning water volumes along canals since the water distribution engineer has to know what the current cropping pattern is in each spatial unit which may be either governorate level or agricultural directorate or farm...etc. Thus, the water distribution engineer is using some previous data, may be the last year cropping pattern to assign water for the New Year. Moreover, the issue of integrated water resources management is also raised everywhere, since water now is considered one of the major issues in the sustainable development of any country. Thus, any water resources plan for a certain area must consider the economical, environmental and social issues.

### Case Study for Merging GIS and MCE

#### *Study Area*

In the current study, an area in Northern Egypt is selected to be a case study of merging GIS and MCE under the shed of the integrated water resources management. The study area is located in the NorthEast of the Dakahlia governorate, The area is named by El-Khalalah which has the longitude and latitude between (31° 15' - 31° 30') N and (31° 15' - 31° 30') E. It spreads over 34 km in length and 24 km in width. The population in this area is about 1.5 million capita and it contains 350 village and different land use type.

#### *Irrigation System in the Area*

The irrigation network is considered relatively dense along the area, it contains different trapezoidal canals of different bed width ranged from main canals with a width more than 25 m in width, bifurcated into smaller canals ranged from 10 to 25m width and these canals are branched into small canals ranged from 5 to 10m width. On the other hand, the drains in this area ranged from 5 to 25 m in width. The area remain is classified to perennial lake or ponds and marshes or under reclaimed. Figure (1) presents the canal network and Drainage network of the area.

#### *Cropping Pattern*

The main feature responding to cropping system in this area is agricultural plants. However this area is divided to old cultivated land, reclaimed land and non-cultivated land. The main crops in this area in summer are rice, maize, cotton and vegetables. On the other hand winter crops are wheat, barley, berseem, etc. This information were obtained based on 1999 cropping pattern system (CAPMAS, 1998).

#### *Social System in the Area*

The area under investigation is mainly inhabitant by farmers. The farmer is either has his own land where he works in it or works in different farms by daily or monthly salary. Men and women are usually works in cultivating lands. There are different statistics that relates the labour requirements for each crop at different stages (CAPMAS, 1998) and (EAYB, 1986,1992,1995).

#### *Health Hazard Issues*

Water borne diseases are very common in the farmers communities. Usually Shcitomaizes is very common in Egypt due to the infected waterways. Also, the use of pesticides and fertilizers is highly suspected to the health hazard issue. Accordingly, data regarding the crop requirements from the Nitrogen- Phosphorus and Potassium Fertilizers are collected (EAYB, 1986, 1992, 1995) and (CAPMAS, 1998). Also, pesticides such as fungicide, herbicide-and insecticide are collected (EAYB, 1986, 1992, 1995) and (CAPMAS, 1998). These types of data are collected for type of crops that are cultivated in the area under study.

#### *Economic Issues*

Information regarding farm gate price, crop cultivation cost, net return, return,...etc are collected for the different crops in the area and their related economic issues (EAYB, 1986,1992,1995).

## **GIS Application**

#### *Basic GIS Information*

The information obtained for this study was from topographically maps of 1: 50,000 scales that cover the study area. Moreover, two field trips were done in order to have a better idea of the region of interest.

#### **Problem Simulation**

The following steps are followed to simulate the Problem:

- The area has been classified into parcels, which ranged from 3 to 305 feddan according to the farmer families whom owned these areas. The cropping pattern is following the agricultural administration as a basic scenario for the whole area.
- The area served by each irrigation canal has been determined from the area served irrigation maps and defined through GIS.
- To create more scenarios that simulate the free cropping pattern system a random distribution approach is assigned for each parcel. Accordingly, each run a new random cropping pattern allocation for each parcel is proposed. The crops are limited to those described in Table (1). Figure (6-a and 6-b) presents winter crops and summer crops in one of these scenarios.
- The databases, for different attributes, related to crops with the spatial data along the area of the study using GIS are merged and different required calculations are done in this stage.

## **Proposed Scenarios**

Different scenarios using the random distribution approach for the different parcels in the area to allocate crops has been proposed and presented in Table (2). Table (3) summarizes the percentage of each crop for winter season while Table (4) summarizes the crop percentage for each crop in summer season.

## **Analysis of Results from GIS Application**

### *Water Related Output Results*

#### *Canal Water Discharge*

Through the GIS technique water requirement of each canal in the distributed system is determined. The monthly-required inflow of each major and minor canal is determined. Figures (9-a and 9-b) show the required discharge for major and minor canals in winter and summer respectively. This discharge has been directly calculated through the GIS technique. It can be presented in map format, table or graph. This is considered one of the major advantages for using the GIS in water distribution system. Discharge can also be calculated along the whole canal length following the water distribution at different frames. The discharge is calculated by the mass balance approach.

#### *Water Sufficiency*

The water shortage has been determined through the GIS technique by calculating the demand of each parcel. The accumulation of water from each parcel inside the catchment area of each canal will result in the volume of water needed to be delivered through each canal. Accordingly, the input information of delivered water in each canal in the system is gained from the proper authorities. A comparison is done between the calculated water by the previous described method and that of the volume of water delivered by the governmental authorities. A map that describes the shortage, balance, or excess water at each catchment is resulted from the GIS technique. Figure (13) presents one of these maps. It can be easily shown the area where water shortage occurs and excess water occurs. Thus, this system is very applicable in determining the water balance of any cultivated area so that volume of water distributed in the channels can be modified until the balance in the area can be occurred.

### *Socio-Economic Output Results*

The labour during May and September during summer, January and April during winter season, noticed that there is difference between the two months in each season because of the needs of different crops at different times. Moreover, more studies could be done by studying the labour travelling, immigration from different villages ...etc. Economic results are also presented such as crop net income, crop production cost, and return per Feddan and farm gate price of the different areas. As an analysis of some results one can show the spatial variation of these two items along the different zones. The high cost areas are located in the northern area, while the net income has the highest value in the southern and western zones. The crop yield is also considered in the current study, the level of Berseem production along the area of study, it shown varieties due to change in salinity. On the other hand, the wheat production was located and concentrated with the highest level in the southern area. The crop yield is related to the soil salinity map.

### *Environmental Output Results*

From the environmental point of view, the agro-chemicals used in the area under investigation have been determined in a qualitative scale. These are fungicide, herbicide and insecticide. It is obvious that, the high quantity from pesticides located in the northern zone and more related with crops, while the winter vegetable used largest amount from pesticide. Related to fertilizer use, it has been indicated that the high quantity is concentrated on the northern zone where the reclaimed land are existing. Three different types of pesticides are commonly used in this area which are nitrogen, phosphorus, and potassium.

## **Multi-Criteria Evaluation**

### *Multi-criteria Evaluation: Basics and Methods*

The basic mathematical approach for the Multi-Criteria evaluation depends on a filling an evaluation matrix for all the possible alternatives and evaluation criteria. Next to this matrix there are the different proposed preferences or weights for each criterion. Through the different methods of solving such matrix, results are appeared in what defined as the appraisal scores. The conclusion may therefore be the selection of alternate with better score.

There are several arithmetic techniques for Multi-Criteria evaluation techniques and many researchers have classified the Multi-Criteria methods in different ways. The most common one is the Quantitative-Qualitative classification given by (Nachtnebel, 1991). Hobbs et al., 1992 have designed an experiment to evaluate different multi-criteria methods such as Goal Programming, ELECTRE I, Additive Value Functions, Multiplicative Utility

Functions, and three techniques for choosing criteria weights. The authors concluded that experienced planners generally prefer simpler, more transparent methods.

#### *Compromise Programming method*

This method is a distance-based technique. That distance based techniques are designed to identify non-dominated solutions that are closest to an ideal solution by some distance measure. An ideal solution, in general, can be defined as the vector  $f^* = (f_1^*, f_2^*, \dots, f_N^*)$  where  $f_i^*$  are the solutions to the problem stated as Optimum  $f_i(x)$ ,  $i = 1, 2, \dots, N$ . In a discrete setting such as the case problem Under consideration, the ideal solution is defined as the vector of best values selected from the payoff matrix. The vector of worst values represents the minimum objective function values denoted as  $f_i^{**}$ . These values are valuable in determining the degree of closeness of an alternative to the ideal solution. One of the most commonly used measure of closeness is a family of  $L_p$  metrics that could be expressed as:

$$L_p = \left[ \sum_{i=1}^N W_i^p \left[ \left| \frac{f_i^* - f_i(x)}{f_i^* - f_i^{**}} \right|^p \right]^{\frac{1}{p}} \right]$$

Where  $f_i^{**} = \min f_i(x)$ ;  $i = 1, 2, \dots, N$  is the minimum objective function in terms of criterion  $i$ ,  $W_i$ 's is the criterion weight, and  $p$  is the balancing factor and is usually taken equal to 2.

As a last step in this technique, upon determination of the distance of each alternative from the ideal solution in the preceding procedure, the alternative with the minimum distance is selected as the compromise solution.

#### **Evaluation Criteria**

In this study the selected criteria are chosen to satisfy the Multi-Criteria basis. The evaluation has been decided to be done on three major levels that varied from the farm level, canal catchment level and whole area level. This is in order to simulate the real needs of different decision maker levels. Farmer will evaluate his decision based on social and economic aspects. However, the mid level decision maker usually evaluate his decisions based on the water issues, some minor environmental issues, social issues. Getting to the higher decision levels the decision-maker will evaluate based on environmental, water, economic and social levels. Thus, the current study aims at introducing the evaluation of the different scenarios from different prospective. Table 5 shows basic evaluations criteria that were selected in the current study.

#### **Scenarios Evaluation**

##### *A- Field Level*

Under this level, applied MCE analyses for three different fields that were selected in three different soil salinity levels. Field A with high salinity, field B in average salinity area and field C in low soil salinity area. A sample of the output is presented in Table 6 for the different fields. It must be concluded that this evaluation was done giving equal weight for the different criteria.

##### *B- Canal Catchment Level*

In this stage the MCE has been applied assuming that decision-maker preference has different orientations. First, all of the criteria are giving the same weight, and then the evaluation is done giving the environmental issue the highest weight. Also, the evaluation was done two times more by giving the highest weight to the social aspects and water aspects respectively. The results are shown in Table 7.

It can be shown that the scenario ranking changes by the changing the bias level. For example, the Status Quo scenario was ranked the third when giving equal weight to all of the criteria. However, changing the bias to the environmental, water and Socio-economic criteria the same scenario gained the first rank. This can be considered a very important issue when evaluating the scenarios since the giving weight to any criteria is highly affected the ranking results. Different results are obtained from different catchment areas.

##### *C- Whole Area level*

Table (8) is presented that, biased on equal weight scenario 1 was recorded the best one along the area but based on environmental, socioeconomic and water aspects, the best scenario was the scenarios 3. What means that it is the best one using fertilizers and pesticides. Moreover, has been a good income and return where low percent of shortage and low water quantity requirement.

#### **Conclusions**

From the current study the following can be concluded:

- A methodology for integration the environment, social and economic aspects in order to help the decision maker to evaluate water resources plans under the condition of free cropping pattern has been developed.

- The amalgamation of GIS and environmental, social and economic aspects shows a powerful tool for studying and analyzing several issues in water resources management.
- The MultiCriteria evaluation technique shows a significant powerfulness is evaluating complex and diverted scenarios based on randomize distribution of crops at a certain area.
- Mutlicriteria evaluation provides the decision maker with very powerful information for ranking the different scenarios which lead to facilitate the decision procedures.

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## LIST OF TABLES

**Table (1) The main crops existing in the area under investigating during different seasons**

CropID	Winter season	CropID	Summer season
C1	Berseem	C7	Maize
C2	Wheat	C8	Sorghum
C3	Barley	C9	Rice
C4	Suger beet	C10	Cotton
C5	Legumes	C11	Vegetables
C6	Vegetables	C12	Fruits

**Table (2) proposed cropping pattern in each scenario**

Scenarios ID	Winter	Summer
Sc1	C1+C4	C2+C5
Sc2	C2+C3+C5	C3+C6+C2
Sc3	C6+C4+C1	C4+C5+C3

**Table (3) The percentage of each crop in Winter Scenarios**

Crops	Status Quo	Scenario1	Scenario 2	Scenario 3
Berseem	17%	30%	4%	20%
Wheat	33%	4%	30%	5%
Barley	12%	5%	25%	3%
Sugerbeet	4%	30%	3%	32%
Legumes	2%	10%	28%	8%
Vegetables	5%	5%	3%	30%

**Table (4) The percentage of each crop in Summer Scenarios**

Crops	Status Quo	Scenario1	Scenario 2	Scenario 3
Maize	7%	30%	7%	4%
Sorghum	2%	10%	31%	5%
Rice	1%	8%	27%	18%
Cotton	30%	6%	4%	25%
Vegetables	7%	30%	5%	30%

Fruits	4%	5%	25%	7%
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**Table (5) Major and sub-evaluation criteria**

Major Criteria	Sub-Criteria
Water	Water Requirements-Water Shortage
Environment	Amount of Fertilizers used (Nitrogen, Phosphors, and Potassium) Amount of Pesticides Used ( Fungicide, Herbicide, and Insecticide)
Social	Labor- Net Income of the farmer- Return
Economic	Whole area Return-Cost- Crop Yield

**Table ( 6 ) MultiCriteria Evaluation analysis Field Level - Summer Scenario**

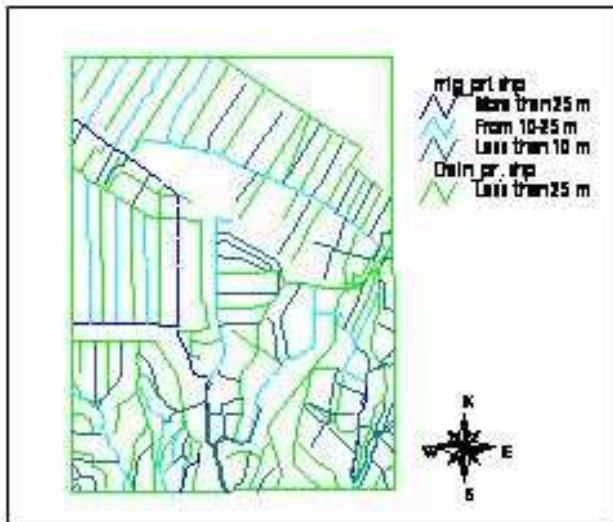
Scenario	A	B	C
Status Quo	1	1	2
Scenario 1	3	2	1
Scenario 2	4	3	3
Scenario 3	2	4	4

**Table (7) Example of Multi-Criteria Analysis results for Catchments Area Summer Scenario: Table shows Rank of different scenario 1= the highest score , 4= the lowest score**

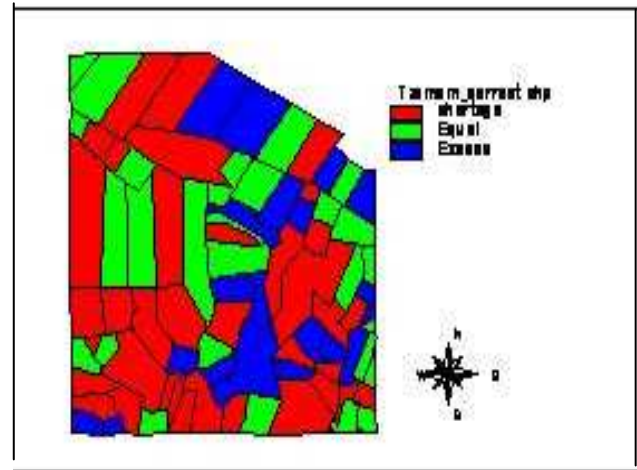
Scenario	Evaluation Criteria			
	Equal Weight	Environmental	Socio-Economic	Water
StatusQuo	3	1	1	1
Scenario 1	1	3	3	3
Scenario 2	2	2	2	2
Scenario 3	4	4	4	4

**Table (8) Example of Multi-Criteria Analysis results for Whole Area -Summer Scenario: 1= the highest score, 4= the lowest score**

Scenario	Evaluation Criteria			
	Equal Weight	Environmental	Socio-Economic	Water
StatusQuo	3	3	3	3
Scenario 1	1	4	4	4
Scenario 2	4	2	2	2
Scenario 3	2	1	1	1



Fig(2) Canal and Drainage Networks



Fig(13) Water Shortage map

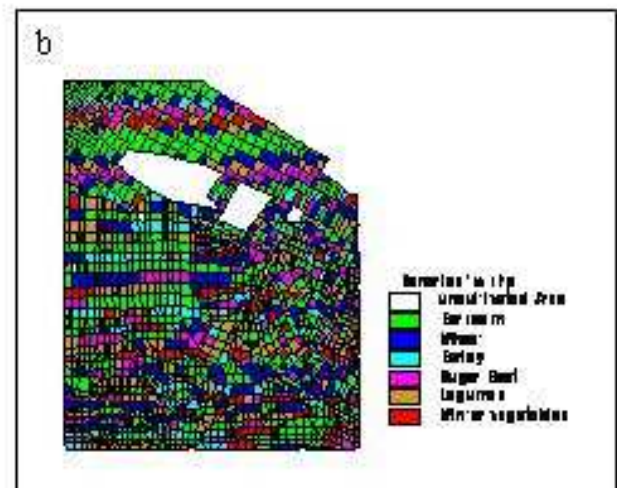
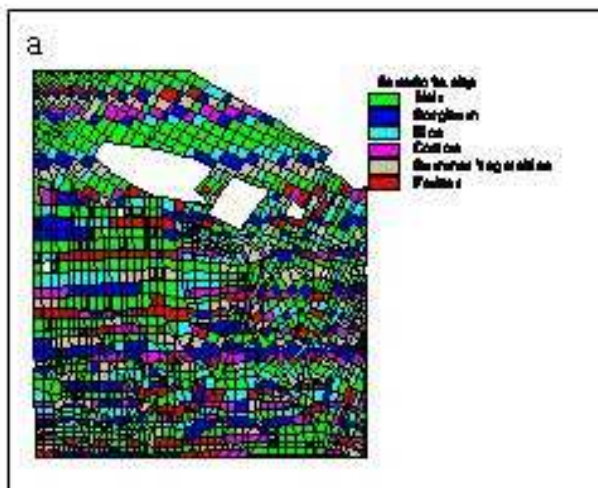
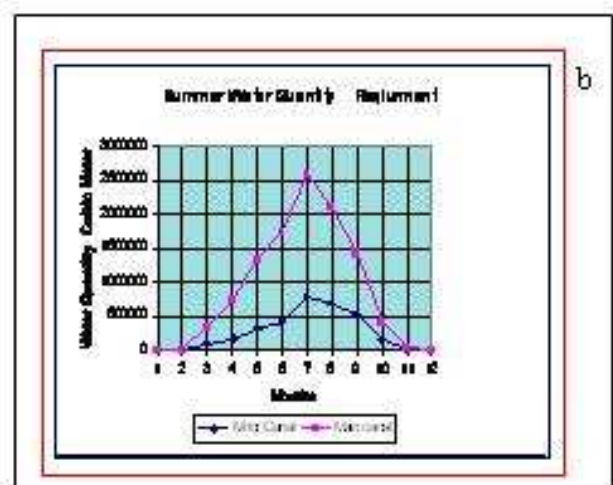
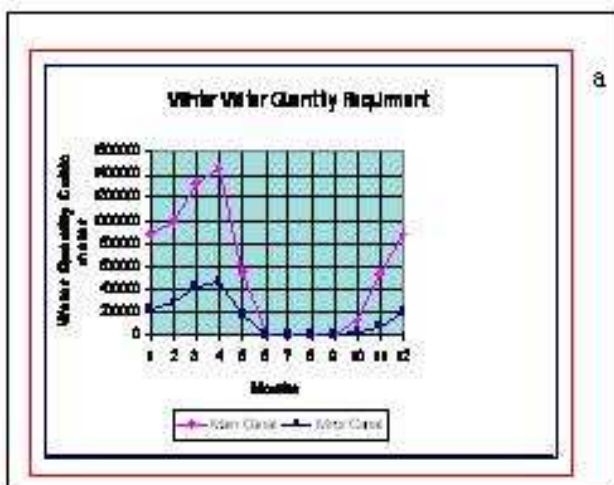


Fig (6-a and 6-b) A, B Summer and Winter Crops pattern of Scenario 1



Fig(9-a and 9-b) Discharge Major and Minor Canal in Winter and Summer