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ENVIRONMENTAL AND ECONOMIC MULTI-OBJECTIVE MODEL FOR MANAGING IRRIGATION AND DRAIN WATER

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ABSTRACT To maximize total net benefits, farmers often tend to increase the area under cash crops production. Such crops may include water-intensive or salt sensitive crops. Restrictions on available water and drain water disposal conditions in the arid and semi-arid region could limit adoption of high value cropping pattern. Production of huge amounts of saline drainage waters threatens environmental sustainability of downstream water resources. A multi-objective model is presented for simultaneous management of crop yield, irrigation and drain water. The proposed model is an environmental economic model, at irrigation district-scale, that integrates agronomic, irrigation, drainage and economic aspects of irrigated agriculture. Source reduction strategies for irrigation water management are considered because they affect management of drainage water, crop yield and net profits. The recent MOPSO technique was applied to solve the multi-objective problem. Distributed soil-water-atmosphere-plant model (SWAP) was set up for regional simulation of soil salinity, crop yield and drain water. The developed model was applied to Voshmgir irrigation and drainage network in north eastern IRAN. It was found that using a multi-objective model makes feasible a flexible balance between environmental and economic benefits of irrigation and drainage scheme management. The proposed model obtained the optimized irrigation water allocation and cropping area to different crops which resulted in the reduction of drainage salt load to downstream while ensuring the net benefit function in the satisfactory level. The model results showed that variety in the physical and water allocation policy within different parts of irrigation and drainage network have a considerable impact on the cropping area and irrigation water of each crop and thus the net benefits as well as production of drain water for each crop and its salt load.

Keywords: Drain water, Irrigated agriculture, Multi-objective model, Salinity.

INTRODUCTION Large parts of the irrigation area in arid and semi-arid regions have shallow saline ground water that threatens crop productivity and financial sustainability

of irrigated agriculture because of soil salinization and water logging. The soil salinity reflects the salinity of both the irrigation water and the ground water. The conventional approach to control the above problems and prevent crop yield reduction is to install drainage networks. The drains lower the water table depth, thus reducing upward flow, while removing the drainage water needed to leach salts from the root zone. However, disposal of the drainage water is necessary for the drains to operate. The drainage water volume and salinity is relatively high and worrying in these regions. Many disposal options such as evaporation ponds, deep well injection, desalination, drain water reuse and treatment have been investigated, but were found to be either technically, environmentally and or economically unsatisfactory (Hanson and Fulton, 1994). However, regardless of the disposal method ultimately used, reduction of the drainage water through improved irrigation water management and source reduction, will play a major role in dealing with the problems. In this option, it is possible to manage and conserve irrigation water as well as drainage water simultaneously. This issue is very important in arid and semi-arid regions with ever-increasing demands on limited water resources and food production. It must be a systems approach that considers interactions between yield, irrigation and drainage. This approach is an integrated management of irrigation and drainage water. Strategies for source reduction through irrigation water amounts management must consider the effect of the management not only on the drainage water, but also on crop yield, soil salinity and profits. Relations between applied water, crop yield and drainage show complex interactions and relations in environmental and economic purposes of irrigated agriculture. Creating trade offs between environmental and economic objectives of irrigated agriculture is one of the important purposes in irrigation and drainage schemes management. This necessitates the development of a two-objective model, which optimized irrigation water allocation, while aiming at maximum benefits from the irrigation and minimum drainage water salt load. This paper gives details and sample application of the two-objective model, an irrigation district-scale environmental economic model that integrate agronomic, irrigation, drainage and economic aspects of irrigated agriculture.

TWO-OBJECTIVE MODEL FOR INTEGRATED MANAGEMENT OF IRRIGATION AND DRAIN WATER The model was applied at the irrigation scheme-scale. The model basically consists of four components: spatial units' construction for analysis, multi-objective optimization model, simulation model, and multi-objective optimization technique.

Spatial units' construction for analysis The entire study area with irrigation scheme-scale was divided into sub-areas denoted as Units (U). Each unit was assumed to be homogenous in terms of physical conditions and management limitations. An extensive data base was constructed for the irrigation and drainage scheme studied, including point data such as meteorological and groundwater levels as well as distributed data like soils, drainage system and cropping areas. Physical characteristics mostly defined by soil types, meteorological condition, cropping pattern and areas, drains (type, drains depth, drains distance), irrigation practices and groundwater salinity and level. Management limitation was described by irrigation water availability. Different physical characteristics layers (PCL) and management limitation layer (MLL) resulted in a matrix of unit combinations. By overlaying the PCL and the MLL using a Geographic Information System (GIS), the total area of each unit was obtained. These units are considered to be the building blocks

for the simulation, i.e. the whole irrigation and drainage district is treated as a set of homogenous areas. Within each unit, different irrigation water applications can occur.

Two-objective optimization model By considering the drainage salinity flux and the resultant drain water salt load, the objective function 1 (Eq. 1) for minimizing the total annual drain water salt load from an irrigation network is expressed as:

$$F_1 = \sum_{m=1}^{12} \sum_{mu=1}^{nmu} \sum_{c=1}^{nc} A_{c,mu} DSF_{c,mu,m} \quad (1)$$

Where *nc* is total number of crops grown in the irrigated area of each management unit (*mu*); *nmu* is the total number of management units; $A_{c,mu}$ (*ha*) is cultivated area for crop *c* in management unit of *mu*; $DSF_{c,mu,m}$ is drainage salinity flux (*ton/ha*) for crop *c* in management unit of *mu* and in m^{th} month. Objective function 2 maximizes the total net benefits from irrigation system (Eq. 2). In this function $Y_{c,mu}$ (*ton/ha*) is crop yield for crop *c* in management unit of *mu*; P_c (*Rials/ton*) and C_c (*Rials/ha*) are yield benefit and production cost, respectively, for crop *c*.

$$F_2 = \sum_{mu=1}^{nmu} \sum_{c=1}^{nc} (P_c Y_{c,mu} - C_c) A_{c,mu} \quad (2)$$

Based on simulation results of each simulation units by *SWAP* model which was linked to optimization model, the crop yield (*Y*) and drainage salinity flux (*DSF*) for each crop *c* in management unit of *mu* was obtained and inserted to the objective functions. The multiple objectives (Eqs. 1, 2) of the model were subjected to the crop area constraints, yield constraints, drain water disposal constraints and water availability constraints at reservoir level which are expressed as follows:

Crop area constraints The allocated area was limited by the total available cropping area in the region (Eq. 3) and a constraint which was forced on the wheat cropping area by Local Agriculture Authority to ensure food production (Eq. 4),

$$\sum_{c=1}^{nc} A_{c,mu} \le Atotal_{mu} \quad \text{for} \quad mu = 1, nmu \quad (3)$$

$$AMIN_{total} \le \sum_{mu=1}^{nmu} \sum_{c=1}^{nc} A_{c,mu} \quad (4)$$

$$\sum_{mu=1}^{nmu} A_{c,mu} \le AMIN_c \quad \text{for} \quad c = \text{wheat} \quad (5)$$

where Atotal is the total agricultural areas in the management unit of mu and AMIN is the minimum cropping area of wheat which is defined by the Authority.

Yield constraints The process of growing a crop necessarily involves production costs for seeds, fertilizers, labor, cultivation, etc. Thus the model is required to at least recover the

production cost, by getting some minimum yield per unit area from the crops grown in the command area. Therefore the constraint is expressed as,

$$Y_{c,mu} \geq YMIN_c \qquad \text{for} \quad c = 1, nc \quad ; \quad mu = 1, nmu \tag{6}$$

where YMIN is minimum yield which should be achieved from crop c in management unit mu.

Drain water disposal constraints This constraint deals with disposal of drain water salt load to be made in each month into a water body in order to meet its environmental limitation. Potential disposal capacity (PDC) of water body in each month depends on the water volume and quality of water body and allowable water salinity that meets environmental standards of water quality class (Eq. 7).

$$\sum_{mu=1}^{nmu} \sum_{c=1}^{nc} A_{c,mu} DSF_{c,mu,m} \leq PDC_m \qquad \text{for} \quad m = 1, 12 \tag{7}$$

$$PDC_m = \left[A_{c,mu} D_{c,mu} + Q_m T\right] C_m^{criteria} - \left[Q_m T\right] C_m^{water\ body} \qquad \text{for} \quad m = 1, 12 \tag{8}$$

where PDC is potential disposal capacity in mth month, D is drain water depth for crop c and in mth month in management unit of mu, Q is water flow of water body in mth month, $C_m^{water\ body}$ is salinity of water body in mth month, $C_m^{criteria}$ is allowable salinity of water body in mth month and T is time for converting water discharge to volume.

Water availability constraints Water availability constraints include the restrictions imposed on reservoir level and farm level resources. Reservoir level constraints deal with the reservoir releases to be made in each month to meet the irrigation demands, subject to reservoir system dynamics. The reservoir water balance is governed by storage continuity equation (Loucks et al. 1981):

$$S_{m+1} = S_m + INF_m - R_m - EV_m - OVF_m \qquad \text{for} \quad m = 1, 12 \tag{9}$$

where INF, EV, S, R and OVF are stream flow, volume of reservoir evaporation, volume of storage, volume of release and overflow from the reservoir in mth month, respectively. To prevent yearly carry-over reservoir storage, it is assumed that the initial reservoir storage in the first month is equal to the reservoir storage at the last month of the year (Eq. 10). Also reservoir storage in any month was restricted by maximum active storage capacity and minimum storage capacity which meets ecological functions of the reservoir and makes suitable its environment for migrated birds (Eq. 11). The model takes into account the effect of evaporation from reservoir in mass balance equation. A linear averaging method was used to calculate the free water surface area for both start and end of each month (Eq. 12).

$$S_1 = S_{12} \tag{10}$$

$$S_{\min} \leq S_m \leq S_{\max} \qquad \text{for} \quad m = 1, 12 \tag{11}$$

$$A_m = \alpha \times S_m + \beta \qquad \text{for} \qquad \text{m} = 1,12 \tag{12}$$

Farm level constraints deal with allocation of water, released from the reservoir, among different competing crops at farm level. The water released from the reservoir supplies conveyance, application and other losses. The water actually available for irrigation at the farm level Q is therefore a fraction of R, given by,

$$Q_m = \eta R_m \tag{13}$$

where η is the conveyance efficiency accounting for all losses from the reservoir head regulator to the farm level. Total water available for irrigation in each month must be lower or equal to the total water actually allocated to all crops in that month (Eq. 14, 15),

$$D_m = \sum_{mu=1}^{nmu} \sum_{c=1}^{nc} I_{c,mu} A_{c,mu} \tag{14}$$

$$D_m \leq Q_m \qquad \text{for} \qquad \text{m} = 1,12 \tag{15}$$

where I is water allocation for different irrigation events of crop c in management unit of mu in mth month. Since cultivated areas in the command area are in the increments of 10 ha consolidated plots, crop area variables were Subsurface adapted into multiples of 10 ha's plots (Eq. 16).

$$A_{c,mu} \in 10 \times Z^+ \quad , \quad I_{c,mu} \in R^+ \tag{16}$$

Simulation model Water-salt balance and crop growth analyses were performed using the SWAP model (Feddes et al., 1978; van Dam et al., 1997; Kroes and van Dam, 2003). SWAP is a physically based agro hydrological model for water, heat, and solute transport in the saturated-unsaturated zone. SWAP includes physically based modules to simulate irrigation practice, lateral drainage of water and solutes and crop growth. The water transport module in SWAP is based on the well-known Richards' equation. A finite-difference solution scheme is used to solve Richards' equation. Crop yields can be computed using the simple crop growth algorithm of Doorenbos and Kassam (1979) or by a using a detailed crop growth simulation module that partitions the carbohydrates produced between the different parts of the plant, as a function of the different phonological stages of the plant. The latter is based on WOFOST 6.0 (Supit et al., 1994). Actual transpiration and evaporation are obtained as a function of the available soil water in the top layer or the root zone for, respectively, evaporation and transpiration. Irrigation can be prescribed at fixed times, scheduled according to different criteria, or by using a combination of both. Drainage is computed by classical drainage equations and multiple drainage system formulation. In the so-called multi-level drainage approach, it is possible that more than one type of drain become active simultaneously. The effect of nutrient deficiency, pests, weeds, and diseases on crop growth and its production have not been implemented in the present 3.0.3 version of SWAP. For this study, SWAP was used in the distributed way in order to analyze water balances on an areal scale. The whole study area was divided in sub-areas denoted as units and each unit was considered to be homogeneous. Examples of this distributed use are given by Bastiaanssen et al. (1996),

Droogers and Kite (1999), Droogers et al. (2000). More details of the SWAP model can be found in the literature (Kroes and van Dam, 2003).

Particle Swarm Optimization (PSO) Algorithm and Multi-objective PSO Particle swarm optimization (PSO) is a population-based, self-adaptive optimization algorithm prompted by observation of simplified animal social behaviors. This technique is becoming more popular due to its simplicity of implementation and ability to quickly converge to a reasonably good solution (Shi and Eberhart 1998). In the PSO algorithm, multiple candidate solutions coexist and simultaneously collaborate. Each solution called a particle, flies in the problem search space looking for the optimal position to land. PSO algorithm combines local search method with global search methods, attempting to balance exploration and exploitation. A particle status on the search space is characterized by its position and velocity, which are updated by following equations (Shi and Eberhart 1998):

$$X_i = X_i + V_i \tag{16}$$

$$V_i = \omega V_i + C_1\, rand()\,(pbest_i - X_i) + C_2\, rand()\,(gbest - X_i) \tag{17}$$

where V_i and X_i represent the velocity and position vectors of particle i, respectively. $pbest_i$ is the best position vector which particle i has found, whereas $gbest$ denotes the corresponding best position found by the whole swarm. Cognitive coefficient C_1 and social coefficient C_2 are constants known as acceleration coefficients; ω is an inertia factor on the basis of Eq. 3 and $rand()$ is generated by uniformly distributed random numbers in the range [0, 1]. In Eq. 3, $\omega_{\max}$ and $\omega_{\min}$ are the maximum and minimum value of inertia factor, respectively and $iter_{\max}$ is defined as the maximum number of iterations for running the model.

$$\omega = \omega_{\max} - \frac{(\omega_{\max} - \omega_{\min}) \times n}{iter_{\max}} \tag{18}$$

To manage any change in the particle velocities, the relevant upper and lower limits are defined as follows:

$$V_{\min} \le V_i \le V_{\max} \tag{19}$$

The movement toward optimal points in multi-objective PSO (MOPSO) is different from that of single-objective PSO (SOPSO). The vector evaluated PSO (VEPSO) is a MOPSO algorithm which was developed by concepts of the vector evaluated genetic algorithm (VEGA). In this algorithm, each objective has been connected to one swarm. In SOPSO, each particle moves in decision space by Pbest and Gbest. In MOPSO, each particle uses its best position as the Pbest and best particle of previous swarm as the Gbest. So, the first swarm uses of last Gbest of last swarm. All particles are moved into the external archive in per iteration. Non-dominated solutions will be stored and others will be removed. So,

the external archive size is dynamic and non-dominated solutions can be reported in per iteration. So, the final archive's members are identified as pareto-front.

MODEL APPLICATION The application time which irrigation decision need to be taken is considered on the basis of local farmers for each crop. The water year begins on October 23 and ends by October 15 of next calendar year. A time interval of one month is adopted for reservoir operation, irrigation allocation decisions and drain water disposal. In a year, there are two principal cropping season: first season (October-May) and second season (June-October). Under this command area, a total of five major crops, two in first season, two in second season and one two-seasonal crop, are considered. In second season, the rainfall is scarce and so the crops mostly depend on the reservoir water. However in first season for part of the time the crops were benefited by rainfall. For model application, the inputs to the model include monthly inflows into the reservoir, daily rainfall and the reference evapotranspiration values, crops parameters, soil data and drainage parameters. The developed model is evaluated for average hydrologic scenario. The scenario is average hydrologic conditions with 1.0* INFave and 1.0*RAINave, where INFave is average monthly inflows into the reservoir and RAINave is average monthly rainfalls in the command area. Average value of inflows from 26 years' data and rainfall from 40 years' data are computed. By overlaying the physical and management layers using GIS, 3 units and the total area for each of them was obtained (Table 1).

Table 1- Management units defined as the combination of physical characteristics and management limitation

unit	Units area (ha)	Soil ID	Drainage ID	Groundwater ID	Meteorology ID	Water allocation ID	Drain water disposal ID
1	9400	1	2	2	1	1	1
2	9000	2	1	1	1	1	1
3	5600	1	3	2	1	2	1

RESULTS AND DISCUSSION The MOPSO algorithm is applied to the multi-objective model to arrive at suitable irrigation water allocation and cropping area to different crops and reservoir operation policies for the average hydrologic condition. The model was run with learning factors of 2, particle size of 50, $\omega_{\max}$ and $\omega_{\min}$ of 0.9 and 0.4, respectively and maximum number of generations of 10000. Generally for any multi-objective optimization problem, there will be no single solution which can be said to be optimal. But there exist a number of multiple noninferior or Pareto optimal solutions. Therefore, an ideal multi-objective optimization procedure basically will have two steps: finding multiple tradeoff optimal solutions with a wide range of values for objectives and choosing one of the obtained solutions using higher level information. The optimization has been carried out over a one year time horizon. The population based MOPSO algorithm generates a wide variety of alternatives in the form of Pareto optimal solutions in a single run. This can help the decision maker in plotting the transformation curve between the objectives and to arrive at a suitable policy for implementation. For each alternative solution, the model gives detailed results. These include decisions both at reservoir level and at farm level. The decisions at reservoir level include reservoir

releases, storages, overflow for each month of time period. At farm level they include the cropping area and irrigation water to be allocated to each crop, soil salinity, actual transpiration for each crop, drain water and disposal salt load by each crop. The operating policy corresponding to noninferior solution is called a satisfactory operating policy and it can be discriminated from the optimal operating policy of the single objective optimization. Selecting the final compromising solution require the decision makers analysis and interpretation. In this study, compromise programming approach (Deb, 2001) is adopted for final decision making. The method of compromise programming picks a solution which is minimally from a given reference point. From the generated solutions, distance metric $d(f,z)$ and a reference point z have to be fixed for this purpose. Then the Tchebycheff metric is computed by

$$d(f,z) = \max_{m=1}^{M} \frac{\left(\left| f_m(x) - z_m \right|\right)}{\max_{x \& S}\left(f_m(x) - z_m\right)} \tag{20}$$

where S is the entire search space; z_m is reference solution for objective function m. The reference point comprises of the individual best objective function values $z = \left(f_1^*, f_2^*, ..., f_M^*\right)^T$. Since this solution is nonexistent, the decision maker is interested in choosing a feasible solution, which is closest to this reference solution. So, the solution which has smaller metric value is the desired one. For the average hydrologic conditions, the multi objective model provided a wide set of well distributed Pareto optimal solutions, as shown in Fig. 1. This figure shows the trade-off results between total net benefits and total drain water salt load. The model was resulted in a wide variety of solutions with a maximum drain water salt load of 256668.8 (ton/year) resulting in total net benefits of 219834 Million Rials, and for a minimum drain water salt load of 112148.38 (ton/year), the total net benefits is 97739 Million Rials. After analyzing different alternatives using the Tchebycheff metric, the decision maker can decide to prefer the compromise solution shown by the square box in Fig. 1. On choosing this point with the total net benefits, f_1= 199394.2 Million Rials and f_2= 151614.1 (ton/year), the model readily gives the corresponding decisions at farm and reservoir level for implementation. For this solution, Table 2 gives the corresponding details of crop area (ha), net benefit, NBC (10^3 Million Rials/year) and drain water salt load, DSLC (10^3 ton/year) for each crop for both the seasons. The interaction between different crops and the three management units in order to satisfying both objective of total net benefit and total drain water salt load can be seen. Figure 2 shows the corresponding reservoir releases and storage trajectory for each month. It can be noticed that the reservoir is able to reach its full capacity during the first season, thus ensuring more water availability for second season crops and cotton.

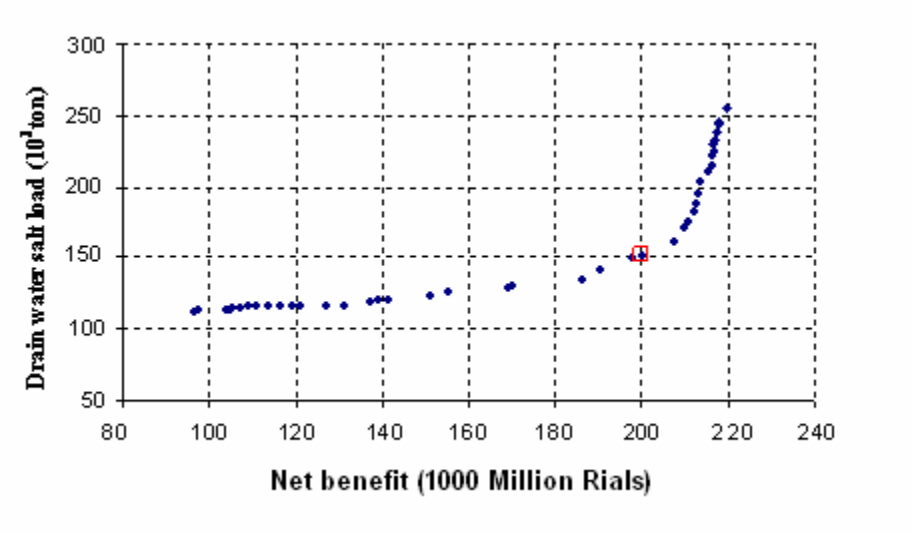

Figure. 1- Results of the multi objective model between total drain water salt load and total net benefits

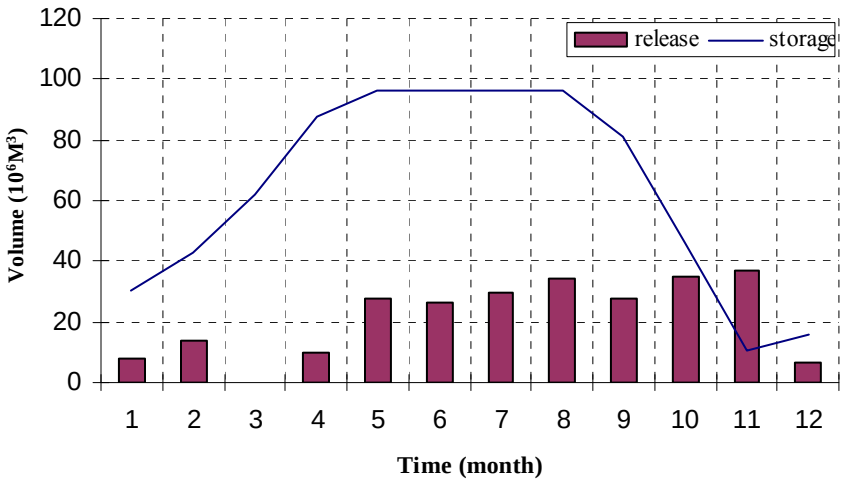

Figure. 2. The obtained reservoir level decisions corresponding to the preferred Pareto-optimal solution

For illustration purpose, the farm level decisions of crop water allocations corresponding to the preferred Pareto-optimal solution for all crops for each month are shown in Fig. 3.

Table 2- Results of the selected best compromised Pareto optimal solution

	A_C (ha)				NB_C (10^3 Million Rials/year)				DSL_C (10^3 ton/year)			
Season/crop	U1	U2	U3	total	U1	U2	U3	total	U1	U2	U3	Total
First season												
Wheat	1970	3030	1470	6470	21.504	39.441	20.129	82.074	17.897	22.259	17.487	57.644
Barley	1760	1590	530	3880	14.118	13.987	5.718	33.823	13.789	9.506	4.418	27.714
Second season												
Grain maize	110	820	740	1670	0.162	4.411	4.083	9.656	0.972	4.134	7.169	12.275
Fodder maize	550	920	430	1900	2.630	4.309	5.541	9.48	2.100	3.990	2.614	8.704
Two seasonal												
Cotton	1100	1510	1250	3860	16.950	27.294	22.117	69.361	12.493	13.577	19.209	45.280
Total	5490	7870	4420	17780	52.364	86.442	50.588	**199.394**	55.251	63.466	60.897	**151.614**

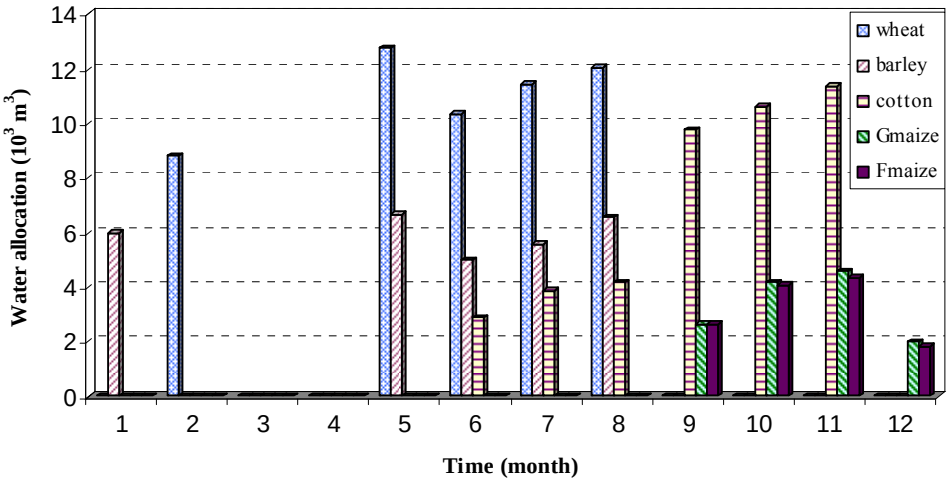

Figure. 3. The obtained farm level decisions corresponding to the preferred Pareto-optimal solution

CONCLUSIONS These results demonstrate that the alternative solutions/policies obtained from the multi-objective model provide good flexibility to the irrigation and drainage network manager or authority and can help in making a suitable decisions for different priorities accorded under the irrigation and drainage system. By effectively exploring the complex search space of large number of decision variables and constrains, the model captured well the nonlinear trade-off curve for the two defined objectives. The application also proved that the MOPSO algorithm is an efficient multi-objective optimization algorithm in providing a wide spread of Pareto-optimal solutions by simultaneously evolving irrigation water allocation, cropping area, reservoir operation, and drain water disposal and salinity. The results also showed that variety in the physical and water allocation policy within different parts of irrigation and drainage network have a considerable impact on the cropping area and irrigation water of each crop and thus the net benefits as well as production of drain water for each crop and its salt load.

REFERENCES

Kroes J.G, van Dam J.C (Eds.) (2003) Reference Manual SWAP version 3.0.3. Alterra Green World Research, Alterra report 773. Wageningen university and research center, Wageningen, The Netherlands, 211 p. ISSN: 1566-7197.

Supit I, Hooyer A.A, Van Diepen C.A (Eds.) (1994) System Description of the WOFOST6.0 Crop Simulation Model Implemented in GGMS, vol. 1: Theory and Algorithms. EUR publication 15956, Agricultural series, Luxembourg, 146 pp.

Doorenbos J, Kassam A.H, (1979) Yield response to water. FAO Irrigation and Drainage Paper 33. FAO, Rome, Italy.

Feddes R.A, Kowalik P.J, Zaradny H (1978) Simulation of Field Water Use and Crop Yield. Simulation Monographs. Pudo Wageningen, The Netherlands, 189 pp.

van Dam J.C, Huygen J, Wesseling J.G, Feddes R.A, Kabat P, van Walsum P.E.V, Groenendijk P, Van Diepen C.A (1997). Theory of SWAP version 2.0. Simulation of water flow, solute transport and plant growth in the soil-water-Atmosphere-Plant environment. Report 71, sub department of Water Resource, Wageningen University, Technical document 45, Alterra Green World Research, Wageningen, The Netherlands, 167 pp.

Droogers P, Kite G (1999) Water productivity from integrated basin modeling. Irrig and Drain Eng. 13():275-290

Droogers P, Bastiaanssen W.G.M, Beyazgul M, Kayam Y, Kite G.W, Murray-Rust H (2000) Distributed agro-hydrological modeling of an irrigation system in western Turkey. Agri Water Manage 43() 183-202.

Bastiaanssen W.G.M, Singh R, Kumar S, Schakel J.K, Jhorar R.K (1996a) Analysis and recommendations for integrated on-farm water management in Haryana, India: a model approach. Report 118, Winand Staring Center, Wageningen, Netherlands.

Hanson, B., Fulton, A., 1994. Methods and economics of drainage reduction through improved irrigation. J. Irri and Drain. Eng. Vol. 120, No. 2, March/April.

Shi, Y., and Eberhart, R. (1998). "A modified particle swarm optimizer." Evolutionary Computation Proceedings, IEEE World Congress on Computational Intelligence, 69–73.

Deb, K (2001). Multi-objective optimization using evolutionary algorithms. Wiley, Chichester.