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Multi-Objective Planning Model for Large Scale Irrigation Systems: Method and Application

Murat Kilic · Suer Anac

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Abstract An increase in demand, and droughts in recent years have resulted in the need for tools to allocate limited water between users in different regions in order to achieve economic, social and environmental benefits. Multi-objective planning is an important decision support tool for natural resource management. Planners, decision makers and stakeholders use this approach in the decision-making process. In this research, a multi-objective planning model was developed and applied on the Menemen Left Bank Irrigation System of the Lower Gediz Basin in Turkey. The aims of the model were to increase the benefit from production, to increase the size of the total area irrigated, and to reduce the water losses occurring at network level. The model was applied to an open channel system consisting of 44 tertiary channels receiving water from three secondaries, serving an area of 3,606 ha. The model predicted a 20.63% increase in income, and a 29.26% decrease in the total irrigation water requirements of crops dependent on projected changes in the actual crop pattern of the research area. This decrease caused a reduction of 29.90% in expected water losses over the network as a whole. The operation of the model enabled optimum productivity and income at the system level per unit of land and water resources.

Keywords System optimization · Multi-objective planning · Open channel irrigation system · Multi-crop pattern

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M. Kilic (✉) · S. Anac
Department of Irrigation and Agricultural Structures, Faculty of Agriculture,
Ege University, Bornova/Izmir, Turkey
e-mail: kilic.murat@ege.edu.tr

S. Anac
e-mail: suer.anac@ege.edu.tr

1 Introduction

There is increasing awareness that environmental, economic and social problems, challenges associated with agricultural and rural development and natural resource management are tightly interrelated. This is one of the reasons for the increasing attention to the concept of multi-functional natural resource management and agriculture, though under various labels in different parts of the world, e.g., roles of agriculture and ecosystem services (Laborte et al. 2007).

In developing countries, agriculture continues to be an important economic sector as it makes a significant contribution to national incomes and economic growth (Elnaboulsi 2001). In the past, growth in agriculture emanated mainly from expansion in crop areas and shifts from rainfed to irrigated crop production. However, the potential for continued growth from these sources is diminishing rapidly due to the closing of land frontiers and limits on further development of water resources in many parts of the world (Molden et al. 2001a, b; Hussain et al. 2007). As water scarcity intensifies in many regions of the world, better management of irrigation is becoming an issue of paramount importance. The main problem in planning the management of deficit resources is how to allocate them among multiple users efficiently and equitably by considering the social, economic and political issues, while considering the heterogeneity in soils, crops and climate and the complexity of the water distribution system (Chambers 1988; Gorantiwar et al. 2006; Reddy and Kumar 2008; Liu et al. 2009a). Since the most consumptive use of water resources is for irrigation, the planning process of management strategies for the components mentioned above is very important in irrigated agriculture. Optimization of irrigation systems for existing areas and improvement in water resource allocations by appropriate multi-cropping patterns and irrigation scheduling are the best solutions to reduce water deficits. Skilled management of irrigation should start from planning at the regional level. Crawley and Dandy (1993) developed a monthly planning and operation model for the Adelaide headwork system in South Australia. Linear Goal Programming was used to aid in the identification of optimum operating policies for the system. In a multi-objective linear programming (MOLP) model for land resource allocation in the Tweng-Wen Reservoir watershed, Chang et al. (1995) used economic benefits and water quality as the optimization objectives, whereas the carrying capacities of various land-use programs and the assimilative capacity of the reservoir for several main pollutants were the primary model constraints. Nayak and Panda (2001) used the multi-objective planning technique in solving various problems related to water resource management in the Mahanadi Delta of India. Five objectives were considered in the model. Benefit maximization, production maximization, investment minimization, labor maximization and labor minimization goals were investigated in the study. Efficiency values for deficit water resources were not taken into consideration in the model. A stochastic goal programming model was developed by Al-Zahrani and Ahmad (2004) in order to determine the daily production of desalination plants to meet the requirements of water blending stations for major cities in the Eastern Province of the Kingdom of Saudi Arabia. Devi et al. (2005) presented a linear programming model for optimal water allocations in a large river basin system. They applied the model to the transboundary Subernarekha River in India. Babel et al. (2005) developed a simple interactive integrated water allocation model for assisting the planners and decision makers in the optimal allocation of limited water from a storage reservoir to different user sectors. The two individual objectives included in the model are the maximization of satisfaction and the maximization of net economic benefit by the demand sectors. Weighting technique or simultaneous compromise constraint technique was used to convert the multi-objective decision-making problem into a single linear objective function. Efficiency values for the water conveyance system were not taken into consideration in the model. Khare et al. (2006) analyzed the feasibility of conjunctive use management in the Sapon irrigation command area of Kulon Progo Regency, Yogyakarta province, Indonesia, using a simple economic-engineering optimization model. Agha (2006) presented application of Goal Programming with Integer programming for water quality management in the Gaza Strip. The optimal distance of the mixing reservoir from other underground wells was achieved for optimum mixing of water to maintain World Health Organization standards (250 mg/l for chloride and 50 mg/l for nitrates).

Booker and O'Neill (2006) demonstrated that minimization of losses may influence an optimal operation policy, e.g., a typical drought storage rule (Lund 2006) for a system of reservoirs, might be to store water in one or several reservoirs rather than distributing storage among many reservoirs, in order to minimize overall water losses. Gastelum et al. (2009) carried out an investigation in order to improve water resources management in the Conchos Basin. The storage volumes of five different reservoirs were estimated in the model by the Reservoir Mass Balance Equation. Soil moisture requirements for six common crops were determined by the Soil Moisture Balance Equation. In addition monthly effective precipitation was determined for the district. The efficiency values for the system were not taken into consideration in the model. Montazar et al. (2009) carried out an investigation on conjunctive water use planning in an irrigation command area. An integrated soil-water balance algorithm was used to carry out water allocation planning in deficit agricultural water resources systems based on an economic efficiency criterion. In the study, the annual net benefits were maximized, but multiple objectives were not taken into consideration. An inexact linear programming model for optimal land use management of a surface water source area was developed by Liu et al. (2009b). The model was proposed to balance the economic benefits of land use development and water source protection. The maximum net economic benefit was chosen as the objective of land use management. The total environmental capacity of rivers and the minimum water supply were considered to be key constraints. Groundwater levels in the district were not taken into consideration in the model. Verma et al. (2010) applied the Goal Programming Methodology with its three approaches for the Mahanadi Reservoir Project System in India for optimal monthly operation. Min–Max Goal Programming, Weighted Goal Programming and Preemptive Goal Programming techniques were applied on the system. The system goals and constraints were expressed deterministically. The input data set was kept the same to facilitate a justifiable comparison of Goal programming models. The efficiency values for water conveyance were not taken into consideration in the model.

In this research, a multi-objective planning model was devised and run for the commands of 44 tertiary channels receiving water from Ulucak, Kaklıç and Sasalı Secondaries in the Menemen Left Bank Irrigation Network in the Lower Gediz Basin Irrigation System in Turkey.

2 Description of the Irrigation Area

The Gediz Basin is located within the Aegean Region of western Turkey at latitude 38°04′–39°13′ N, and longitude 26°42′–29°45′ E. The main water source for the Lower Gediz Irrigation System is the Gediz River, which is 275 km in length. The drainage area of the basin is roughly 17,219 km^2. The Gediz Basin is a river deposit basin formed from alluvium transported by the Gediz River and its tributaries (Topraksu 1971, 1974; Girgin et al. 1999; Baran et al. 1999; Kilic 2004).

The Demirköprü Dam was constructed on the Gediz River for irrigation, hydropower and flood control. The water is delivered to the Lower Gediz Irrigation System by means of three regulators constructed on the river: from upstream to downstream, Adala, Ahmetli and Emiralem. For the past decade, there has been a scarcity of water in the Lower Gediz Basin because of the increase in urban and industrial demand (Svendsen et al. 2001). This situation increases competition for water between the sectors. Unplanned production patterns, inadequate system capacity, poor distribution and management of water, large numbers of small and divided plots for cropping, and uncontrolled and inappropriate use of water by the farmers are the major factors giving rise to low efficiency in the Gediz Basin Irrigation System. This situation necessitates more efficient use of deficit resources by agriculture. Therefore, it is necessary to devise multi-dimensional plans for the sustainable use of deficit resources and optimum operation of the system.

3 The Menemen Left Bank Irrigation System

The Menemen Left Bank Irrigation System (MLBIS) is the lower section of the Lower Gediz Basin Irrigation System. The MLBIS receives its water from the Emiralem Regulator. Construction of the regulator and the MLBIS was completed in 1944, and the drainage system for the Menemen Left Bank Irrigation Area was completed in 1992. The National Water Agency (DSI) transferred the operation and maintenance of the MLBIS to the locally controlled Menemen Left Bank Irrigation Association (MLBIA) in 1995 (DSI 1998; Kilic 2004). The MLBIS irrigates a 12 830 ha area by means of six secondary channels, which are the Maltepe, Kesikkoy, Seyrekkoy, Ulucak, Kaklıç and Sasalı Secondaries. The total water stored in the Demirköprü Dam determines the volume and duration of irrigation water supplies to the Gediz Basin System. Inflows to the reservoir are measured and observed regularly by the DSI in Turkey. Apart from this, ground water levels are also observed with periodic measurements by the same association. The DSI decides the amount of irrigation water to be allocated from the reservoir to different irrigation associations at the beginning of the irrigation season for a particular year. It usually rains in winter months in the research area. Thus, the district receives no precipitation from the middle of May to September. Therefore, the land needs irrigation in the period from April to September in accordance with the cropping pattern in the district. The amount of irrigation water allocated by the DSI at the beginning of the irrigation season is used in the network. The main and secondary channels are under upstream control. Water level or flow can be controlled from three points in the system, which are: I—the main regulator at the head of the main channel; II—offtake regulators at the heads of the secondary channels; and III—constant-head orifices at the turnout to each tertiary channel.

The MLBIA is responsible for water delivery from the main channel to the secondary channels. A fixed rotation plan is applied by the MLBIA, which does not change according to the varying conditions of the system. No plan has been developed by the MLBIA for irrigation programming at the tertiary level which considers the plant pattern of the commands, irrigation water requirements of different crops, the soil features of the district, the carrying capacities of the channels, the climate conditions for the district, or the conveyance efficiency of the system. Water delivery to tertiary channels and plots is arranged by Village Irrigation Groups (VIGs) which are responsible to the MLBIA. Farmers report their water requirements to the VIGs 1 or 2 days before the desired irrigation date, and VIGs decide the allocation of water to the plots according to the reports from the farmers. A rotation system is applied in delivering the water. Each rotation zone has a fixed length of irrigation time, and farmers receive water from the channels to their plots according to this fixed rotation plan. However, the farmers, especially in the head of the channels, do not follow this plan, but continue receiving water from the system and decide for themselves whether an adequate amount of water has been received. Therefore, especially in peak irrigation periods and under water scarcity conditions, farmers in the tail end of the network cannot use the system equally and cannot receive an adequate amount of water on schedule. Disagreements between the farmers are handled by the VIGs or the MLBIA. Water charges are collected annually by the MLBIA according to the crop type and size of the area. As in the whole of Turkey, the crop pattern on the Menemen Plain is not planned, and farmers follow the tradition of planting crops with a high water requirement without considering the availability of irrigation water.

4 The Irrigation Area of the Ulucak, Kaklıç and Sasalı Secondaries

This investigation was carried out on the commands of 44 tertiary channels receiving water from Ulucak, Kaklıç and Sasalı Secondaries in the Menemen Left Bank Irrigation System. These secondaries deliver irrigation water to 20, 6, and 18 tertiary channels respectively. The Ulucak and Kaklıç tertiary channels are concrete-lined and have a trapezoidal cross section, while the Sasalı tertiary channels are precast concrete channels with an elliptical cross section. The lengths of the Ulucak, Kaklıç and Sasalı Secondaries are 6.487, 7.778 and 8.62 km respectively. These three secondary channels deliver water to the irrigation districts of Menemen Centre, Koyundere, Ulukent, Gunerli, Tuzcullu, Kaklıç and Sasalı (DSI 2006; Kilic 2007). The layout of the secondary channels, the location of the tertiaries and the irrigation area of the system are shown in Fig. 1.

In 2005, an area of 3,606 ha was irrigated in the district, and cotton, maize, tomatoes, watermelon, wheat, alfalfa, grapes, apples, sesame, citrus and olives were grown at a ratio of 40.42%, 21.50%, 7.19%, 4.56%, 20.87%, 1.56%, 1.42%, 2.09%, 0.04%, 0.10% and 0.25% respectively (MLBIA Reports 2006). The infiltration capacities of different types of soils in the district were determined by the double-ring infiltrometer technique (Kilic 1997). Texture, bulk density and moisture content of the soils at the level of field capacity and permanent wilting point were determined by analyzing samples taken from the district (Kilic 2004, 2006). The research area

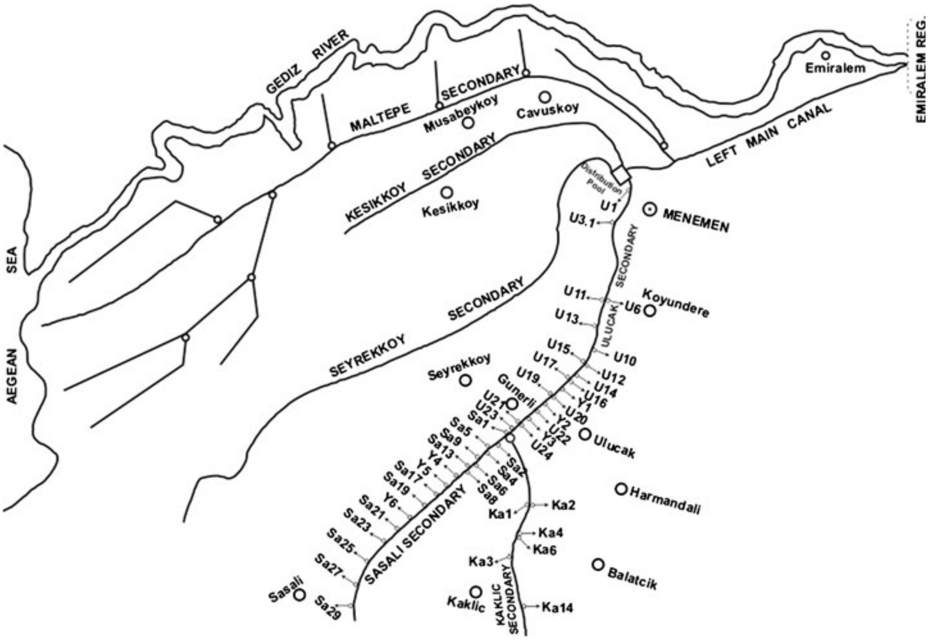

Fig. 1 Layout of the secondary canals, location of the tertiaries, and irrigation area of the system

consists of loam, silty loam, sandy loam and sandy soils. The district has a Mediterranean climate. Rain falls mostly in the winter months, while summers are dry. The effect of the Aegean Sea is felt inland because the mountains run perpendicular to the sea.

5 Method

The aim of this research was to develop a multi-objective planning model for the sustainable use of deficit resources and to apply it on a large scale irrigation system.

In the first stage of the study, channel rotation groups and water delivery zones were established for the network. The maximum carrying capacity of the system's Ulucak, Sasalı and Kaklıç secondaries is not sufficient to supply water to all tertiaries at the same time, and therefore water is delivered to the network a the rotation basis (Kilic 2004, 2007; DSI 2006). The model took account of the maximum carrying capacities of the channels, and thus it enabled the whole system to benefit at the highest possible level. This approach also constitutes one of the main principles of water allocation by the rotation method.

6 Determining the Channel Rotation Groups and Allocation Zones

The rotation system for the irrigation network was devised in two main steps. The first was to determine the channel rotation groups and the second was to determine the borders and sizes of allocation zones in the system.

There is not a linear relationship between the water conveyance efficiency (or loss; % 1 km^{-1}) and the length of the channels. The amount of water lost over a certain length of channel cannot be found by linear proportion or interpolation methods. Therefore, the amount of water conveyed from the unit length of the channel to the following section must be determined by interactive calculation series (Kilic 2008; Kilic and Tuylu 2008). These calculations, used in determining the channel rotation groups at network level, were performed using the formulas given below.

$$QS_{mur} \times (ESC_{mu}/100)^{f} \geq QT\max_{mu(r+1)} \tag{1}$$

$$f = l_{m(r+1)} - l_{mr}$$

$$\left(l_{m(r+1)} - l_{mr}\right) \geq 0 \tag{2}$$

where m = indices of secondary channels from the head to the end of the network; u = indices of segments with different carrying capacities in secondary m from the head to the end; r = indices of tertiary channels from the head of the secondary to the end; QS_{mur} = discharge remaining in the secondary after water is received by tertiary r from segment u of secondary m ($\mathrm{m}^3\ \mathrm{s}^{-1}$); ESC_{mu} = water conveyance efficiency for segment u of secondary m (% 1 km^{-1}); $QTmax_{mu(r+1)}$ = maximum carrying capacity of the consecutive tertiary $(r + 1)$, receiving water from segment u of secondary m ($\mathrm{m}^3\ \mathrm{s}^{-1}$); l_{mr} = the distance from the point where tertiary r receives water to the head of secondary m (km); $l_{m(r+1)}$ = the distance from the point where the consecutive tertiary $(r + 1)$ receives water to the head of secondary m (km); and f = length of a secondary channel segment between the consecutive tertiaries r and $(r + 1)$ receiving water from secondary m (km).

Each tertiary channel validating the conditions indicated in formulas (1) and (2) will be in the same rotation group and can receive water simultaneously from the secondary. On the other hand, if the conditions are not validated by the tertiary, this channel will be in the consecutive rotation zone together with the tertiaries validating the conditions. The channel rotation groups were formed by carrying out the process repetitively for the entire network. Thus, the system is divided into different allocation zones to ensure efficient usage of resources and operation of the network.

In the second step, the size of a definite allocation zone was determined by the borders of the command of the tertiary rotation group delivering water simultaneously to this allocation zone.

$$AR = \sum_{z=1}^{nz_a} AT_{az} \text{ For } a = 1, 2, \ldots na \tag{3}$$

where a = indices of allocation zones in the system (in order from the head of the network to the end); na = total number of allocation zones in the system; z = indices of tertiary channels delivering water simultaneously to allocation zone a (in order from the head to the end of the secondary); nz_a = total number of tertiary channels delivering the water simultaneously to allocation zone a; AT_{az} = size of the area irrigated by tertiary z in allocation zone a (ha); and AR = total size of the irrigated area in allocation zone a (ha).

7 Description of the Multi-Objective Planning Model

One of the objectives of this model is to increase the 10.904 × 10^6 TL benefit from the production pattern in reality in the research area to the value of 13.085 × 10^6 TL with an increment of 20%. For this purpose, the Goal Programming Method can be used. Deviational variables for this goal are described as shown below.

d_1^+	overachievement of the target profit.
d_1^-	underachievement of the target profit.

Also, the profit over this goal will be accepted in the model. Because of this, the amount of deviation remaining under this goal $\left(d_1^-\right)$ will be minimized in the objective function. This goal constraint is described as shown below;

$$\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{p=1}^{np_{sa}}\sum_{c=1}^{ns_{psa}} NB_{cpsa} \times A_{cpsa} - d_1^+ + d_1^- = GNB \tag{4}$$

where s = indices of different soil groups in the district; ns = number of different soil groups in the district; p = indices of the irrigation programs applied to the crops; np = total number of different irrigation programs applied to the crops; c = indices of crops grown in the district; nc = total number of crop types grown in the district; NB_{cpsa} = benefit obtained from crop c grown in soil type s by applying irrigation program p in allocation zone a (TL ha^{-1}). The benefit function is described as explained by Mannochi and Mecarelli (1994) and Kodal (1996). In order to obtain the optimum results from crop production, it was assumed that all agricultural activities such as fertilizing, soil cultivation etc. were performed as needed by the farmers. Costs in the model included the price of irrigation water, the price of labor and of seed, bought-in fertilizer, and agricultural chemicals. A_{cpsa} = size of the area to be allocated for crop c grown in soil type s, by applying the irrigation program p in allocation zone a (ha). This parameter is the decision variable in the model; GNB = Goal benefit for the entire command (13.085 × 10^6 TL).

Agricultural activities are carried out in a 3,606 ha area in the district according to the production pattern in reality. However, some plots in different allocation zones were not included in the production area, even though they are suitable for agricultural production and irrigation applications. Hence, another goal in the model is to increase the size of the production area in the district. The achievement of this objective is important from three different points of view. The first is an increment of yield and benefit from production depending on the increment in size of the area. The second is the increment of employment in the district. The third one is to obtain the highest benefit from the system by operating the network effectively and irrigating as large an area as possible.

The aim of the model was to include the plots which were out of production in different allocation zones in the production area. Deviational variables for this goal are described as shown below.

d_2^+	overachievement of the size of the production area.
d_2^-	underachievement of the size of the production area.

This goal constraint of the model is described as shown below.

$$\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{p=1}^{np_{sa}}\sum_{c=1}^{ns_{psa}} A_{cpsa} - d_2^+ + d_2^- = TA \tag{5}$$

where TA = size of the area for production (3,606 ha)

Also, the size of the area over the goal will be accepted in the model. Thus, the deviational variable for underachievement of the size of the production area $\left(d_2^-\right)$ will be minimized in the objective function of the model.

The third goal of the model was to reduce the amount of water loss occurring at network level during the irrigation applications. This objective has an importance from the points of view of efficient operation of the network, optimum allocation of irrigation water and sustainable use of deficit resources in the system. The amount of water loss which occurred at network level was nearly 7.091×10^6 m^3 in reality (Kilic and Ozgurel 2005; Kilic 2008; Kilic and Tuylu 2008). In the model, total amount of water loss at network level was aimed to reduce to the value of 5.318×10^6 m^3 with a reduction of 25%. Since the total amount of goal water loss (5.318×10^6 m^3) contains both the negative and positive deviations, the deviational variables for this goal were described as shown below.

d_3^+ overachievement of the target water loss.
d_3^- underachievement of the target water loss.

This goal constraint of the model is described as given below.

$$\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{i=1}^{ni_{sa}}\sum_{p=1}^{np_{isa}}\sum_{c=1}^{nc_{pisa}} dt_{cpisa} \times \left(1 - E_{cpisa}\right) \times A_{cpsa} - d_3^+ + d_3^- = WL \tag{6}$$

where dt_{cpisa} = total irrigation water requirement of crop c grown in soil type s by applying irrigation program p in allocation zone a in rotation period i (mm). Irrigations were applied to the crops when the moisture depletion level in the soil reached 30–45% of the available water between the field capacity and permanent wilting point. Moisture levels in soils were then refilled to field capacity at each irrigation application. These ratios were taken into consideration for the crops in the command according to the yield response to water at different stages of growth. As explained by Doorenbos and Kassam (1979), available moisture depletion level in soil was not allowed to increase over 50% for the crops. E_{cpisa} = irrigation efficiency for crop c grown in soil type s, by applying irrigation program p in allocation zone a in rotation period i (fraction). The well-known software, Cropwat 7.0 (FAO 1992) was used in determining the irrigation water requirements of the crops; WL = Goal water loss at network level (5.318×10^6 m^3).

The positive deviational variable of this goal (d_3^+) will be minimized in the objective function of the model, since the aim is to reduce water loss at network level.

Consequently, while the negative deviations from the target profit (d_1^-) and size of the production area (d_2^-) are minimized, the positive deviation from the goal water loss at network level (d_3^+) is minimized in the multi-objective planning model.

All the goals in the planning model directly affect agricultural production. For example, an increment in size of the production area also provides an increment in yield, benefit and employment in the district. In addition, efficient use of irrigation water (with lower loss) at network level provides not only an increment in both yield and benefit from production, but also affects the sustainable use of deficit resources in the system. Apart from this, increment in profit cannot be achieved without planning the optimum production pattern in the district, and water resources cannot be used effectively. As stated by Verma et al. (2010), the goal programming approach possesses significant advantage owing to the fact that it may be based on physical operating criteria. The system goals and constraints can be expressed deterministically. A constraint must be strictly satisfied, while for a goal it is desired to achieve the solution as close as possible to the specified target.

Since all three goals have a close relationship and interaction with each other in the system, the model was devised by the Multiple Goal Programming technique, and Goals Equally Ranked. As a result, the objective function of the model is formulated as shown below by considering the goals described above.

$$Z_{\min} = d_1^- + d_2^- + d_3^+ \tag{7}$$

where Z_{min} = minimization of the objective function of the planning model.

Other constraint functions of the planning model depending on the system are given below.

8 Constraint Functions

8.1 Land Area Constraint

Total size of the area allocated for each crop in a definite zone cannot be higher than the area of this zone. Formulation of this constraint function is shown below.

$$\sum_{s=1}^{ns_a} \sum_{p=1}^{np_{sa}} \sum_{c=1}^{nc_{psa}} A_{cpsa} \leq AR \quad \text{For } a = 1, 2, ...na \tag{8}$$

where AR = total size of the irrigated area in allocation zone a (ha).

8.2 Suitable Area Constraint

The growing of some crops can be limited depending on the size of the suitable area, or the policies of groups such as local irrigation associations or the National Water Agency. These constraints are formulated as shown below.

$$A_{cpsa} \leq SA_{cpsa} \quad \text{For } a = 1, 2, ...na; \text{ For } s = 1, 2, ...ns; \text{ For } p = 1, 2, ...np; \\ \text{For } c = 1, 2, ...nc \tag{9}$$

where SA_{cpsa} = size of the suitable area for crop c grown in soil type s by applying irrigation program p in allocation zone a (ha).

9 Size of the Area Depending on the Policy

$$\sum_{a=1}^{na} A_{cpsa} \leq AM_{cps} \quad \text{For } s=1,2,\ldots ns;\ \text{For } p=1,2,\ldots np;\ \text{For } c=1,2,\ldots nc \tag{10}$$

$$\sum_{a=1}^{na} A_{cpsa} \geq AN_{cps} \quad \text{For } s=1,2,\ldots ns;\ \text{For } p=1,2,\ldots np;\ \text{For } c=1,2,\ldots nc \tag{11}$$

where AM_{cps} = maximum size of the area for crop c grown in soil type s by applying the irrigation program p in the entire district (ha). AN_{cps} = minimum size of the area for crop c grown in soil type s by applying the irrigation program p in the entire district (ha).

9.1 Channel Carrying Capacity Constraint

The amount of irrigation water delivered to the system during a definite rotation period cannot be higher than the maximum carrying capacity of the channels. This constraint function was formulated as shown below.

$$\sum_{s=1}^{ns_a} \sum_{i=1}^{ni_{sa}} \sum_{p=1}^{np_{isa}} \sum_{c=1}^{nc_{pisa}} A_{cpsa} * dt_{cpisa} \leq 3600 \times \sum_{i=1}^{ni_a} \sum_{k=1}^{nk_{ia}} Q\max_{ia} \times IRT_{ia} \quad \text{For } a=1,2,\ldots na \tag{12}$$

where IRT_{ia} = the length of irrigation time for each allocation zone during a definite rotation period (h).

9.2 Water Resource Capacity Constraint for the Allocation Zones

Total irrigation water requirement of an allocation zone cannot be higher than the water resource capacity of this zone. This constraint is formulated below.

$$\sum_{s=1}^{ns_a} \sum_{i=1}^{ni_{sa}} \sum_{p=1}^{np_{isa}} \sum_{c=1}^{nc_{pisa}} A_{cpsa} \times dt_{cpisa} \leq WRZ_a \qquad \text{For } a=1,2,\ldots na \tag{13}$$

$$WRZ_a = WS_a + GW_a + DW_a \qquad \text{For } a=1,2,\ldots na \tag{14}$$

where WRZ_a = total water resource capacity of allocation zone a (m^3); WS_a = total amount of irrigation water diverted from the reservoir, for delivery to the channels serving allocation zone a (m^3); GW_a = total amount of groundwater allowed by the National Water Agency to be used for irrigation in allocation zone a (m^3); and DW_a = amount of drainage water which can be used for irrigation in allocation zone a (m^3).

9.3 Water Resource Capacity Constraint for the Entire District

Seasonal irrigation water requirement of the crops cannot be higher than the total water resource capacity of the entire district.

$$\sum_{a=1}^{na}\sum_{s=1}^{ns_a}\sum_{i=1}^{ni_{sa}}\sum_{p=1}^{np_{isa}}\sum_{c=1}^{nc_{pisa}} A_{cpsa} \times dt_{cpisa} \leq TWC \tag{15}$$

$$TWC = TWS + TGW + TDW \tag{16}$$

$$TWS = \sum_{a=1}^{na} WS_a \quad TGW = \sum_{a=1}^{na} GW_a \quad TDW = \sum_{a=1}^{na} DW_a \tag{17}$$

where TWC = total water resource capacity available for irrigation in the entire system (m^3). TWS = total amount of irrigation water diverted from the reservoir for delivery to the channels (m^3); TGW = total amount of groundwater allowed by the National Water Agency to be used for irrigation in the entire district (m^3); TDW = total amount of drainage water which can be used for irrigation in the system (m^3).

9.4 Non-Negativity Constraint

It is possible not to allocate any area for a crop in an allocation zone, but it is impossible to allocate a negative size of an area for a crop. Therefore, decision variable and other deviational variables of the model can not take negative values.

$$A_{cpsa}, d_1^+, d_1^-, d_2^+, d_2^-, d_3^+, d_3^- \geq 0 \qquad \text{For } a = 1, 2, ...na \tag{18}$$

The multi-objective planning model was applied on the research area, and it was solved using the WinQSB package (Lawrence and Pastemack 1998).

10 Results and Discussion

10.1 Allocation Zones in the Research Area

Water distribution is carried out by rotation in the system, since the maximum carrying capacity of the Ulucak, Sasalı and Kaklıç secondaries is not sufficient to supply water to all tertiaries at the same time. The best length of rotation period was determined as ten days, as explained by Sagardoy et al. (1982), Kodal et al. (1997) and Kilic and Ozgurel (2005). In this way it was possible to draw up the most suitable plan for the network's existing infrastructure and the crop pattern in the region. Allocation zones provided by the model and the actual zones are shown in Table 1.

As Table 1 shows, five separate allocation zones were formed in the research area according to the model solution. These zones were determined on the basis of the

Table 1 Allocation zones according to the model results and actual zones, canal rotation groups, and total size of irrigated areas

Allocation zones from the model solution			Allocation zones in reality		
Allocation zone	Canal rotation groups	Size of the area (ha)	Allocation zone	Canal rotation groups	Size of the area (ha)
AZ I	U1, U3.1, U6, U11, U13, U10, U12, U15, U14, U16, U17, Y1, U19, U20, Y2, U22, Y3, U21, U24, U23, Ka1, Ka2, Ka3, Ka4, Ka6, Ka14, Sa1, Sa2, Sa5, Sa4	1,888.159	AZ I	U1, U3.1, U6, U11, U13, U10, U12, U15, U14, U16, U17, Y1, U19, U20, Y2, U22, Y3, U21, U24, U23, Ka1, Ka2, Ka3, Sa, Sa2, Sa5, Sa4	1,502.48
AZ II	Sa9, Sa6, Sa13	575.843	AZ II	Sa9, Sa6, Sa13, Sa8, Y4, Y5, Sa17, Sa19	1,275.97
AZ III	Sa8, Y4, Y5, Sa17	507.574	AZ III	Y6, Sa21, Sa23, Sa25, Sa27, Sa29, Ka4, Ka6, Ka14	827.55
AZ IV	Sa19, Y6, Sa21	222.345			
AZ V	Sa23, Sa25, Sa27, Sa29	423.772			

system operating at maximum capacity. In this way, the whole network was utilized at the highest possible level. All tertiaries serving each zone were taking water from the system at maximum capacity.

On the other hand, there are three different zones in the actual water allocation program. The tertiary channels in zones AZII and AZIII, supplied by Sasalı Secondary, work at an average of 42.1% and 31.3% lower capacity respectively. The reason for this is that the maximum carrying capacity of the Sasalı Secondary is less than the total capacities of the tertiary channels which it supplies. In other words, this secondary channel is trying to supply too many tertiary channels at above its own capacity (Kilic 2004, 2007; DSI 2006). For this reason, the tertiaries supplied by this secondary can never obtain water at maximum capacity. This prevents the system from being utilized at its highest possible level.

10.2 Channel Capacities and the Size of the Irrigated Area

The maximum water-carrying capacity of Ulucak Secondary is 6.710 $m^3\ s^{-1}$ at the head of the channel. This capacity falls to 3.300 $m^3\ s^{-1}$ at the entrance of the Sasalı Secondary in the second distribution pool, located at the end of the Ulucak Secondary (Fig. 1) (DSI 2006). Water-carrying capacity of the tail end segment of the Sasalı Secondary is 0.691 $m^3\ s^{-1}$. The maximum carrying capacity of the last segment of Sasalı Secondary is 9.710 times lower than the capacity of the Ulucak Secondary. These values indicate that there is an 871.06% capacity difference between the head and the tail end of the system (DSI 2006). On the other hand, the size of the cropped area in AZ I, AZ II and AZ III is 1,502.48, 1,275.97 and 827.55 ha respectively, according to the actual rotation plan (MLBIA Reports 2006). The size of the cropped area in AZI is nearly 1.82 times higher than the cropped area in AZIII. In this situation, even though there is an adequate amount of water in the system, serious problems occur in the conveyance and allocation of the water at the tail end of the network because of the inadequate carrying capacity of the secondary segments. This situation usually occurs in the tertiary commands receiving water from the tail end of the Sasalı Secondary. Because of the unplanned production pattern in the district and the larger area than can be irrigated, significant levels of yield and benefit losses occur in the system.

In face of inadequate water carrying capacity in the channels, farmers use the groundwater as an alternative. However, the cost of groundwater is higher than channel water because of the price, and the use of motorized pump units to supply water to the plots. In addition, the National Water Agency, which controls and regulates the use of groundwater in Turkey, does not always permit groundwater to be used for irrigation, as it is used industrially and domestically besides its use in agricultural irrigation. This is another restricting factor on the use of the groundwater by farmers. This is that water from the open channel irrigation system is priced in TL ha^{-1} and is paid for as a single payment for the whole season. This is more attractive to producers and is cheaper than the use of groundwater. For this reason producers prefer to use water from the irrigation channel system.

On the other hand, the district is divided according to the results from the model solution into five different allocation zones for optimum irrigation conditions. The size of the irrigated area in AZ I, AZ II, AZ III, AZ IV and AZ V is 1,888.159, 575.843, 507.574, 222.345 and 423.772 ha respectively. These were determined interactively as explained in the method part for the optimum operation conditions in the system.

10.3 Production Pattern

Actual crop pattern and that given by the model, based on the allocation zones given by the model, are shown in Table 2.

As Table 2 shows, the model solution plans for production in a total area of 3,617.7 ha, an increase of about 11.7 ha. This increase occurs in zones AZ I and AZ V. This area, despite being suitable for agricultural production, is in actuality not cultivated, but in the model, production is planned on these areas also.

In the research area, cotton, maize, tomatoes, watermelons, wheat, alfalfa, grapes, apples, sesame, citrus and olives were actually being grown in ratios of 40.42%, 21.50%, 7.19%, 4.56%, 20.87%, 1.56%, 1.42%, 2.09%, 0.04%, 0.10% and 0.25% respectively on 3,606 ha of land (MLBIA Reports 2006); the model solution indicated that cotton, maize, tomatoes, watermelons, wheat, alfalfa, grapes and olives were to be grown in ratios of 14.70%, 12.60%, 11.20%, 6.20%, 43.15%, 1.11%, 4.10% and 6.94% respectively on a total of 3,617.7 ha. The results showed the crop pattern derived from the model and the actual one to be significantly different. In addition to this, it may be thought that along with the costs of growing crops, climate change and the effects of global warming, which have been noticeable in the past few years, also play a role.

Apart from this, producers form crop patterns according to tradition and their own preferences. This has a great adverse effect on the efficient management of these

Table 2 Current product pattern in allocation zones and that given by the model

Crop	AZ I		AZ II		AZ III		AZ IV		AZ V	
	Actual pattern (ha)	Model solution (ha)	Actual pattern (ha)	Model solution (ha)	Actual pattern (ha)	Model solution (ha)	Actual pattern (ha)	Model solution (ha)	Actual pattern (ha)	Model solution (ha)
Cotton	622.570	435.398	318.400	96.402	276.790	0.000	113.300	0.000	126.660	0.000
Maize	575.770	455.830	74.948	0.000	43.200	0.000	44.000	0.000	37.260	0.000
Tomatoes	257.000	264.741	0.000	0.000	0.640	0.000	0.000	0.000	1.600	140.439
Watermelons	32.640	224.300	84.380	0.000	39.830	0.000	0.000	0.000	7.580	0.000
Wheat	153.810	507.890	134.732	319.154	154.510	325.856	72.850	124.981	236.560	283.333
Alfalfa	56.040	0.000	0.000	6.712	0.000	33.288	0.000	0.000	0.290	0.000
Grapes	44.830	0.000	0.000	0.000	6.260	148.430	0.000	0.000	0.000	0.000
Apples	73.840	0.000	0.000	0.000	1.700	0.000	0.000	0.000	0.000	0.000
Sesame	1.290	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Citrus	3.620	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Olives	9.100	0.000	0.000	153.575	0.000	0.000	0.000	97.364	0.000	0.000
Total area (ha)	1,830.510	1,888.159	612.460	575.843	522.930	507.574	230.150	222.345	409.950	423.772

systems. In addition, there is a great loss of productivity and benefit because of the great age of systems like the one under study here.

10.4 Production Pattern of Allocation Zones in Reality

The system was divided into three different allocation zones according to the rotation program applied in reality in the district (Table 1). According to the actual rotation plan, 1,502.48 ha area was cropped in AZ I, and cotton, maize, tomato, watermelon, wheat, alfalfa, grape, apple, sesame, citrus and olive were grown at a ratio of 33.40%, 29.50%, 15.10%, 2.00%, 8.50%, 2.80%, 3.00%, 4.80%, 0.10%, 0.20% and 0.60% respectively. The size of the cropped area is 1,275.97 ha in AZ II in reality. Cotton, maize, tomato, watermelon, wheat, grape and apple were grown at a ratio of 51.50%, 11.50%, 0.10%, 9.70%, 26.60%, 0.50% and 0.10% respectively. AZ III is in the tail end of the system, and an 827.55 ha area was cropped in reality. Cotton, maize, tomato, watermelon, wheat, alfalfa and apples were grown at a ratio of 36.00%, 22.60%, 3.90%, 1.20%, 34.40%, 1.80% and 0.10% respectively (MLBIA Reports 2006).

Although the irrigation water requirements of cotton, maize and tomatoes are higher than those of other crops, they were grown at a ratio of 33.40%, 29.50% and 15.10% respectively in AZ I according to the actual plant pattern. On the other hand, wheat was grown at a ratio of 8.50% in spite of its lower irrigation water requirement. This caused an increment in irrigation water requirement in AZ I dependent on the actual plant pattern.

Apart from this, while cotton and maize were grown at a ratio of 51.5% and 11.5% respectively in AZ II, wheat was grown at a ratio of 26.6%. These ratios are not conducive to optimum allocation and the usage of deficit resources. In AZ III, while cotton, maize and tomatoes were grown at a ratio of 36%, 22.6% and 3.9% respectively, wheat was grown at a ratio of 34.4%. The cropping rate of wheat in AZ III is higher than AZ I and AZ II. This is a precaution against water scarcity in the middle and at the tail end of the system. However, the production pattern in the district is not conducive to optimum conditions.

In addition, AZ II and AZ III consist mostly of loam and silt-loam soil groups (Kilic 2004, 2007). Therefore, moisture depletion levels take similar values in different plots in the same period. This necessitates irrigation applications in many plots simultaneously. The secondary channel capacities are not adequate in delivering the water on time to the plots in AZII and AZIII because in the rotation plan applied in reality, channel carrying capacities, the plant patterns of different zones, the size of the irrigated area and the soil types for each zone are not taken into account. The channel rotation program has been applied in the entire district without change for many years.

The model solution, on the other hand, takes into account interactively the soil type of each allocation zone, channel carrying capacities, irrigation efficiency values, the layout of the channels on the command, the irrigation water requirements of the crops grown in different allocation zones, price of the crops, labor cost, yield of crops for the actual conditions and yield-response factor in planning the production pattern for each allocation zone and irrigation periods. As a result, a well-balanced production pattern is obtained for the entire system according to the model solution.

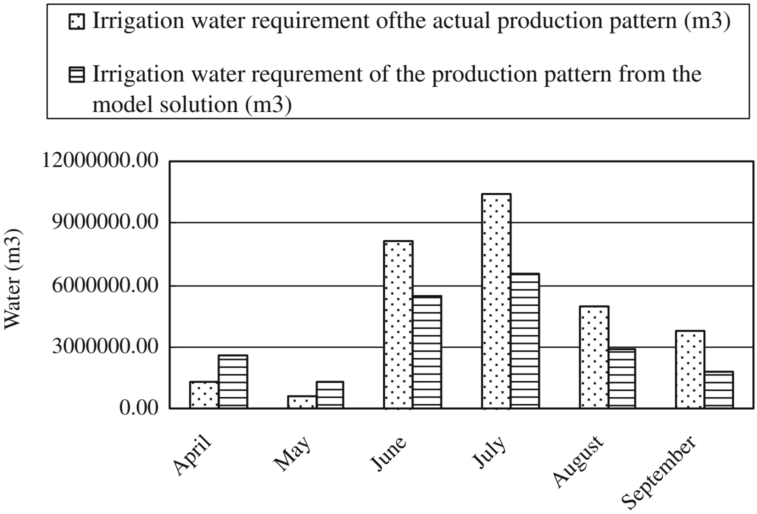

Fig. 2 Total monthly irrigation water demands of the crop pattern derived from the model solution, and that of the actual crop pattern, by volume

10.5 Irrigation Water Demands

Figure 2 presents graphically the total monthly irrigation water demands of crops by volume from the model solution, together with the irrigation water demands of the actual crop pattern.

As can be seen from Fig. 2, the total amount of irrigation water required in the research area during the growing stages of the crops shows a 29.26% decrease. The increase indicated by the model in the area of crops such as wheat, olives and grapes, whose water needs are relatively low, results in a decrease in the irrigation water required by the system as a whole. In contrast, the fact that a higher proportion of cotton and maize is actually grown—crops which require larger amounts of irrigation water—results in a higher demand for irrigation water in the area.

10.6 Water Loss

Water losses expected for the irrigation water demand of the actual crop pattern for each allocation zone in the study area, and that occurring according to the model solution, are shown in Fig. 3.

As it is seen in Fig. 3, amount of water loss from the model solution in AZ I, AZ II, AZ III, AZ IV and AZ V is lower than the water loss expected from the irrigation of the actual crop pattern with the ratio of 21.21%, 37.53%, 46.70%, 39.13% and 27.79% respectively. Over the season, water losses according to the model show a reduction of approximately 29.90% against the losses currently expected in the system. Changes in the crop pattern in allocation zones and a reduction in the demand for irrigation water are responsible for this.

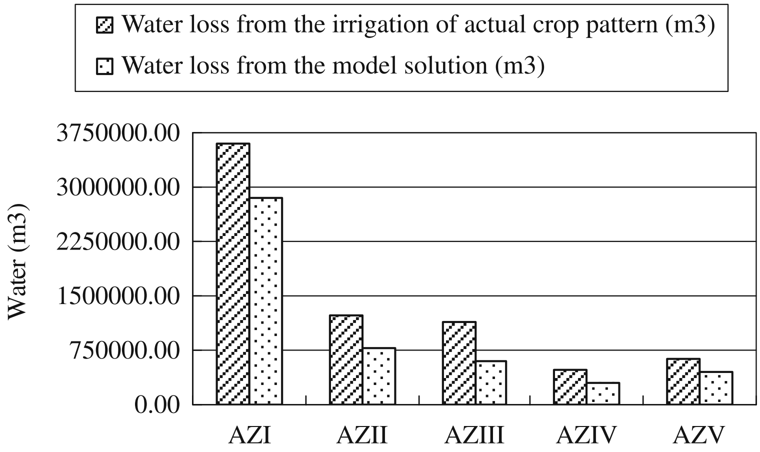

Fig. 3 Expected water losses in irrigating the actual crop pattern, and the crop pattern derived from the model, in the allocation zones

10.7 Economic Benefit

In order to obtain the optimum results from crop production, it was assumed that all agricultural activities such as fertilizing, soil cultivation etc. were performed as needed by the farmers.

In Turkey, water is priced in TL ha^{-1} not TL m^{-3} with a single payment for the whole irrigation season. Thus the number of irrigations and the amount of water used in irrigation applications is not important in pricing the water. Costs in the model included the price of irrigation water, the price of labor and of seed, bought-in fertilizer, and agricultural chemicals.

The expected net income of the crop pattern on the 3,606 ha actually under cultivation was 10.904×10^6 TL (3,023.85 TL ha^{-1}). In the model solution however, the projected crop pattern on 3,617.7 ha was to generate a net income of 13.153×10^6 TL (3,635.74 TL ha^{-1}). These data show that an increase of 20.63% in revenue is achieved according to the model solution.

11 Conclusions

In this research, a multi-objective planning model was developed and applied on the Menemen Left Bank Irrigation System of the Lower Gediz Basin in Turkey. The aims of the model were to maximize the benefit from production, to maximize the size of the total area irrigated, and to minimize water losses occurring at network level.

The model provided a 11.7 ha increase in land under production, giving a total of 3,617.7 ha. This increase was in zones AZI and AZV. A 29.26% reduction in total irrigation water requirements was achieved in the research area in the period of the growing stages of the crops. The crop pattern in the model solution showed a significant difference from the actual crop pattern in the allocation zones, and this directly reduced irrigation water requirements. Expected total water losses in the system as a whole were also reduced by around 29.90%. The change in water demand related to crop pattern caused a reduction in water loss in the system as a whole. The expected net revenue of the crop pattern on the 3,606 ha actually under cultivation was 10.904×10^6 TL (3,023.85 TL ha^{-1}). In the model solution however, the projected crop pattern on 3,617.7 ha was to generate a net revenue of 13.153×10^6 TL (3,635.74 TL ha^{-1}). These data show that an increase of 20.63% in net revenue is achieved according to the model solution.

Results from running the multi-objective planning model show that revenue can be secured at an optimum level and maximum efficiency per unit of land and water.

Notation

The following symbols are used in the multi-objective planning model:

a	indices of the allocation zones in the system (in order from the head of the network to the end).
A_{cpsa}	size of the area to be allocated for crop c grown in soil type s, by applying the irrigation program p in allocation zone a (ha). This parameter is the decision variable in the model.
AM_{cps}	maximum size of the area for crop c grown in soil type s by applying the irrigation program p in the entire district (ha).
AN_{cps}	minimum size of the area for crop c grown in soil type s by applying the irrigation program p in the entire district (ha).
AR	total size of the irrigated area in allocation zone a (ha).
c	indices of crops grown in the district.
dt_{cpisa}	total irrigation water requirement of crop c grown in soil type s by applying irrigation program p in allocation zone a in rotation period i (mm).
DW_a	amount of drainage water which can be used for irrigation in allocation zone a (m^3).
E_{cpisa}	irrigation efficiency for crop c grown in soil type s, by applying irrigation program p in allocation zone a in rotation period i (fraction).
GNB	Goal benefit for the entire command ($13.085 * 10^6$ TL).
GW_a	total amount of groundwater allowed by the National Water Agency to be used for irrigation in allocation zone a (m^3).
i	indices of rotation periods (in order from the beginning of the irrigation season to the end).
IRT_{ia}	length of irrigation time for allocation zone a in rotation period i (hours).
k	indices of tertiary channels delivering water simultaneously to allocation zone a in rotation period i (in order from the head of the secondary to the end).
na	the total number of allocation zones in the system.
NB_{cpsa}	benefit obtained from crop c grown in soil type s by applying irrigation program p in allocation zone a (TL ha^{-1}).
nc	total number of crop types grown in the district.
ni	total number of rotation periods during the entire irrigation season.
nk_{ia}	the number of tertiary channels delivering water simultaneously to allocation zone a in rotation period i.
np	total number of different irrigation programs applied to the crops.

ns	number of different soil groups in the district.
p	indices of the irrigation programs applied to the crops.
$Qmax_{ia}$	sum of the maximum water carrying capacities of the tertiary channels delivering water simultaneously to allocation zone a in rotation period i (m^3 s^{-1}).
s	indices of different soil groups in the district.
SA_{cpsa}	size of the suitable area for crop c grown in soil type s by applying irrigation program p in allocation zone a (ha).
TA	Size of the area for production (3,606 ha).
TDW	total amount of drainage water which can be used for irrigation in the system (m^3).
TGW	total amount of groundwater allowed by the National Water Agency to be used for irrigation in the entire district (m^3).
TWC	total water resource capacity available for irrigation in the entire system (m^3).
TWS	total amount of irrigation water diverted from the reservoir for delivery to the channels (m^3).
WL	Goal water loss at network level (5.318×10^6 m^3).
WRZ_a	total water resource capacity of allocation zone a (m^3).
WS_a	total amount of irrigation water diverted from the reservoir, for delivery to the channels serving allocation zone a (m^3).
Z_{min}	minimization of the objective function of the planning model.

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