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Application of Hydro-Economic Model in Optimal Distribution of Agricultural Water under Drought Conditions (Case Study: Irrigation Networks Downstream of Zayandehrud Dam)

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ABSTRACT

Planning for optimal distribution of Zayandehrud Dam water to six Irrigation Networks (INs) located downstream of this dam was carried out based on a hydro-economic model under water scarcity conditions. The hydro-economic structure was developed through coupling the hydrologic simulation model (MODSIM) and economic optimization modelling approach (Positive Mathematical Programming, PMP). Water distribution priorities to the INs are based on the economic value of water used by crops in the current cropping pattern under different scenarios of normal (base year, 2014-2015) and drought conditions. Results showed that, in addition to the change in the priorities of water distribution throughout the six INs, the existing cropping patterns should also change. The order of water delivery to the six INs starts from Rudasht IN and ends with the Traditional IN. Also, the highest reduction in the area under cultivation in the base year, compared to the optimum cultivation, is related to alfalfa (in Nekoabad and Mahyar-Jarghouyeh INs), clover (in Rudasht and Abshar INs) and forage corn (Borkhar and Traditional INs). Beans cultivated area increases by 14 and 21% for Abshar and Rudasht INs, respectively. Based on the results, the economic value per m^3 of water will rise on the average, if water is allocated on the basis of its shadow prices. Moreover, under drought conditions, the highest and the lowest increase in the economic value of water will take place in the Nekoabad IN (4,660 Rials m^{-3}) and Rudasht IN (3,890 Rials m^{-3}), respectively.

Keywords: Cropping pattern, Economic value of water, MODSIM model, PMP.

INTRODUCTION

In the last few decades, water scarcity has become a significant challenge in many parts of the world. Water resources planners have realized that relying solely on traditional supply management techniques does not fill the gap between supply and demand for water. In arid and semi-arid regions of the world, where annual rainfall is the primary source of water resources in the agricultural sector, the problem is much more severe (Serageldin, 1995). Operational management of the water resources is getting worse due to inefficient supply oriented strategies employed in these regions. (Braga and Lotufo, 2008). Therefore, countries located in arid and semi-arid regions are forced to review and revise their views on water resources management (Gleick and Cooley, 2009).

The multidimensional and interdisciplinary nature of water resources issues and problems (Mousavi *et al.*, 2012) needs a holistic view in the rehabilitation projects. Bitter experiences resulting from the weakness of integration in management and development (Braga and Lotufo, 2008) reveal the importance of replacing

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the supply oriented strategies with demand management alternatives. Planning and decision making in such a complex environment, and also the existence of multiple and conflicting objectives require systematic analysis in the form of integrated management (Serageldin, 1995). Through such an approach, a framework for management of water resources will be developed in such a way that both economic and social consequences of the implementation of policies for water sector and unfavorable environmental costs will be taken into account.

In order to implement the concept of holistic management of water resources in an analytical framework, at different scales of the study area, the decision support systems (Labadie, 1995), as well as several modeling methods, have been used to integrate the economic, social, hydrological, political, and environmental components (Lefkoff and Gorelick, 1990).

The point that has been addressed with sensitivity and carefulness in these types of studies is the choice of adequate decision support tools for analyzing the components of the system in an entirely holistic format. Such tools have been selected in different studies by considering different scales of study, spatial and climatic characteristics, availability of required data, and specific capabilities of the water resources management tools and models. Results and experiences gained from numerous studies indicate that hydro-economic model would be an appropriate model for implementing holistic management of water resources under dry and semiarid climatic conditions. Hydro-economic model represents spatially-distributed water resources systems, infrastructure, management options, and economic values in an integrated manner (Harou *et al.*, 2009). This model is an appropriate tool for policymakers and planners to provide the necessary insights for optimal water use. It is considered as an essential tool for identifying and selecting the most efficient and lasting strategies (Varela-Ortega *et al*., 2011).

The use of hydro-economic model in arid and semi-arid regions of the world dates back to 1960s and 1970s (Harou *et al*., 2009). It was then continued by the studies of Noel and Howitt (1982) on conjunctive uses of water resources for various uses and Vaux and Howitt (1984) on interregional transfer of water. Following the pioneers, Lefkoff and Gorelick (1990) focused on simulation of hydrological conditions considering the effect of climate scenarios on salinity of groundwater, soil quality, and income of farmers. Vedula and Mujumdar (1992) employed the hydro-economic model on reservoir operation for irrigated agriculture. Moreover, optimizing irrigation management for sustainable crop yield (Musharrafieh *et al.*, 1995) and preventing contamination of groundwater while maximizing irrigated crop yield (Peralta *et al*., 1994) are other examples of using hydro-economic model and structure.

In Australia, Rogers *et al.* (1993) used the hydro-economic model to investigate the relationship between changes of water availability and growth of the agricultural sector. Beare *et al.* (1998) studied the value of irrigation water and analyzed the impact of hydrologic changes on it. They studied the relationship between water availability changes and growth of the agricultural sector and its effect on the value of irrigation water. Evers *et al.* (1998) studied and evaluated the changes in the supply of water resources caused by climate change and its impact on crop cultivation patterns in the state of Oklahoma, USA, by combining production growth and hydrology models. In a study by Quinn *et al.* (2001), the SWAP/WADE (State Wide Agricultural Production/Westside Agricultural Drainage Economics) model was used to assess water policies in the agricultural sector of San Joaquin basin. The model is one of the agricultural production models for integration of water and economic models. It was employed for analyzing various effects of climate change in the basin.

Enhancing economic efficiency is a broad concept. It looks for the highest economic value of water use through both physical and managerial measures at the irrigation system and river basin level. An integrated economic-hydrologic river basin model was applied by Cai *et al.* (2003) in the Maipo River Basin in Chile. To achieve this end, a series of modeling scenarios were defined, and policy implications based on changes in physical and economic efficiencies for basin-wide irrigation water management were analyzed.

Cai and Wang (2006) combined hydrological models with multi-input and multi-product economic models [including Positive Mathematical Programming (PMP) modelling approach] in empirical and theoretical subjects. Medellin-Azuara *et al.* (2012) employed a self-calibrating profit-maximizing model of agricultural production based on the SWAP (Soil, Water, Atmosphere and Plant) model. Calibration of this model was performed by employing the PMP approach. The model was applied to the Tulare Basin in California's Southern Central Valley. Results showed that subsidizing efficient irrigation technology might have little effect on total land and water use. This may not promote water conservation without other incentives or regulations. Hashemy Shahdany *et al.* (2017) proposed a new configuration of an economic, operational model. The goal was to provide a realistic water delivery framework that maximizes the net revenue in limited-water periods based on the potential of the existing irrigation districts. When the total demand exceeds the canal inflow, users suffer water shortage in proportion to their ability to maximize their income. Esteve *et al.* (2015) used the hydro-economic model to show the effects of drought in optimal allocation of water resources in agriculture and to evaluate various water allocation policies and management options under different climate scenarios.

Different applications of the hydro-economic model in water resources management have been mentioned in the literature review of this study. It should be noted that water resources allocation in the mentioned studies has been carried out based on net profit, added value of water, or the opportunity cost. It is worth mentioning that water allocation based on these approaches is applicable when water price is determined by water market. In basins with lack of market mechanisms, the optimal water prices should be ascertained in a reliable economic-oriented approach.

Considering the potentials of the hydro-economic framework in dealing with a wide range of water resources management issues, and also due to lack of a water market in determining the agricultural water prices within the Zayandehrud River Basin (located in Isfahan Province, central Iran), this study employs the framework in upgrading the current agricultural water planning system. Accordingly, a hydro-economic model was developed, calibrated, and employed to renovate the common water allocation throughout the six irrigation networks located in this basin. The existing water allocation in the basin is inefficient, especially in dorught conditions, because an unsustainable condition has occurred.

Annual overexploitation of 460 Million Cubic Meters (MCM) of water from just one of the aquifers within this basin, and 16.4 MCM of annual over-diversion from the surface water in one of the irrigation districts are consequences of lack of any systematic water allocation within the basin (Hashemy *et al.*, 2018). Moreover, the Gavkhuni Swamp, located at the end of the basin, is drying up, mainly due to successive unsustainable water resources management in the water shortage periods over the recent years. Accordingly, it is essential to replace the unreliable agricultural water allocation with a new approach, capable of increasing farmers' incomes and respecting the environmental concerns as well.

Considering the mentioned problems and the concerns of optimal water allocation throughout the agricultural sections in Zayandehrud River Basin, the research questions were formulated as follows: (i) What are the economic values of water in each irrigation district, calculated via the hydro-economic model?, and (ii) How does the new water allocation system change the area under cultivation of each crop in the existing cropping pattern of irrigation districts?

The main contribution of this study is developing and examining the application of a hydro-economic model for allocating agricultural water based on the economic value of water in Zayandehrud River Basin. The basin suffers from lack of a systematic mechanism for agricultural water allocation within the irrigation districts, since no economic orientation (e.g. water market) exists in the current water resources management in this basin. Moreover, optimum cultivation area for the current cropping pattern in each irrigation district is determined. To the best of our knowledge, for the first time, this study aimed to develop a hydro-economic model for agricultural water allocation in the irrigation districts in a basin. The results of this study could be important to Iranian water authorities in upgrading the current inefficient water allocation in other similar basins with the economic-oriented one.

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The objectives of this study were the followings: (1) Develop and employ a hydro-economic model to find out the economic value per cubic meter of water for every crop within the current cropping pattern of each irrigation district, throughout the Zayandehrud River Basin, (2) Determine the optimal price of water based on an economic orientation, and (3) Assign priority of agricultural water allocation within the basin by considering spatial variation of the calculated economic value of water.

MATERIALS AND METHODS

Establishing the Hydro-Economic Model in Zayandehrud Basin

The first step in establishing a hydro-economic model is denoting the target area. Here, the study area includes six Irrigation Networks (INs) supplied by Zayandehrud Dam, Isfahan Province, central Iran. These irrigation networks are as follows (Figure 1):

1) Traditional IN (Zayandehrud Dam to Nekoabad Diversion Dam)

2) Modern network of Mahyar and Jarghouyeh (Intake site: Steel Factory)

3) Modern network of Nekoabad (Left and Right canals; Intake site: Nekoabad Diversion Dam)

4) Modern network of Borkhar (Intake site: End-gate of Left Nekoabad canal)

5) Modern network of Abshar (Left and Right canals; Intake site: Abshar Diversion Dam, Isfahan City)

6) Modern network of North and South Rudasht (Intake site: Rudasht Diversion Dam)

From the perspective of model formulation and solving methods, the holistic hydro-economic modeling is divided into two categories of models: distributed and holistic (integrated) models (Cai, 2008). Each of these methods, having different structure, has its strengths and weaknesses. In the distributed approach, despite the possibility of using holistic simulation and optimization techniques, there is a mutual relationship between economic and hydrological components of the model and only the output data are transmitted from one component to another (Noel and Howitt, 1982). However, in the holistic approach, a single unit covers both the hydrological and economic aspects, which are integrated into a consistent structure. Transfer of information between hydrological, agricultural, and economic components in the distributed models is considered as a technical challenge, while in the holistic models, the model structure needs to be solved as a whole and data transmission is done internally. Since the significance and objectives of a research

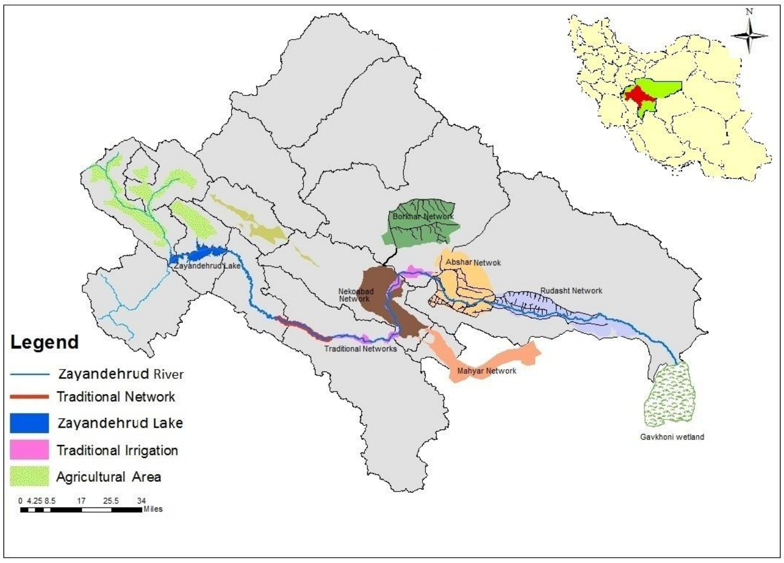

Figure 1. Geographical location of irrigation networks supplied by Zayandehrud Dam.

determine the type of holistic hydro-economic modeling approach (Maneta *et al.*, 2009), a distributed modeling technique can help to achieve the present research's objectives (Figure 2).

After choosing the type of hydro-economic modeling approach, which is based on the importance and objectives of the particular study, the next most important and fundamental matter is choosing the type and method of combining different models in the hydro-economic structure. This significant step was taken by considering the importance of integrated water resources management and economic value of water as seen by the policy makers and experts of the water industry (e.g. the 20-year Perspective Document of Iran, general policies of the system, long-term strategies for development of water resources). Due to lack of optimal allocation of water within the six INs of this study, and taking into account the most critical problems and challenges, the type and method of combining different models in the hydrological-economic structure was selected as shown in Figure 2. The critical challenges within the case study include: (1) Vulnerability of performance of INs, because of increasing demand for drinking water and industrial water, (2) Significant difference between economic value of water and water tariffs, (3) Inefficient use of water, and (4) Inappropriate cultivation patterns based on economic perspectives.

In mathematical programming methods of analyzing water resources systems, there are two main types of approaches or techniques (which are not entirely separate): Simulation methods (via hydrologic model), which are descriptive, and optimization methods (employing the economic model), which are prescriptive. Although simulation models simulate the behavior of water resources systems in accordance with a set of rules (real or hypothetical) governing the water allocations and exploitation of hydraulic structures, the main drawback of these methods is their inability to achieve the best alternative for design and exploitation of the system and its components. In contrast, optimization models have the potential to achieve the best design and operation alternative, if they are correctly defined and formulated. However, due to restrictions (including computational costs), employing the optimization methods are under strict

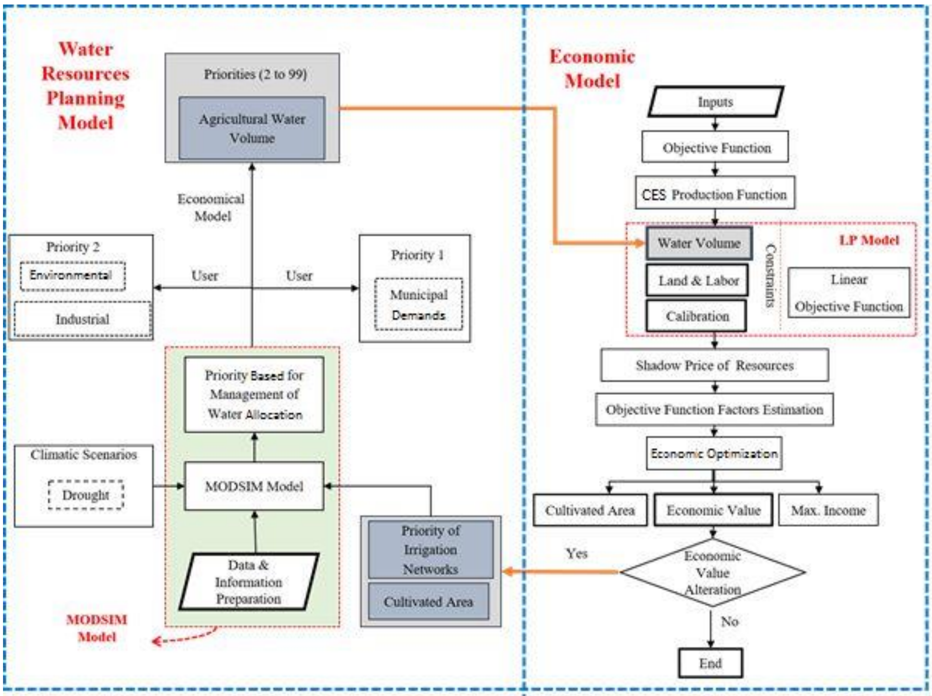

Figure 2. Structure of the developed hydro-economic model.

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computational constraints. Therefore, in systems containing many elements and components, the optimization methods do not have the potential of modeling the real system, taking into account spatial and temporal elements.

Considering these potentials and limitations, the purpose of our integrated modeling was an attempt to integrate the hydrological model with the economic model (as shown in Figure 2). The former is capable of stimulating water allocation from the Zayandehrud Dam. The latter component (PMP approach of the economic model) optimizes distribution of water between the INs based on the average economic value of water for agricultural crops.

The system consists of two main interconnected components: The hydrological model (simulation) and the economic model (optimization). The first part of this modeling is systematic simulation of the natural flow of water entering the Zayandehrud Dam Reservoir, assessing the hydrological effects of agricultural practices and priority-oriented management of supply and demand, which is the bridge between the two models, the existing available cultivated area in the present cropping pattern of the INs, and the volume of water simulated by the hydrologic model. The primary objective of using the economic PMP approach is to represent the existing optimal cultivation pattern of agricultural areas in the six INs to obtain the economic value of water for crops.

Distribution of optimal water to each IN is carried out by the hydro-economic structure (as given in Figure 2). At the beginning and during the implementation of simulation by an economic model, the optimum surface water volume (X_{isw}), optimum cultivated area, and the economic value of water for each crop (X_{iland}) in the existing cropping pattern of each IN, provide the basis for linking this model and the hydrologic model.

By providing the required boundary conditions for implementation of the hydrologic model, simulation of the available water and its delivery and distribution is peformed by the model based on the economic value of water in each IN. By changing the volume of allocated water, as a limitation of the economic model, the optimal cropping pattern and economic value of water in each IN undergoes a change, consequenly, the hydrologic model is run again to test the feasibility of the scenario and evaluate the hydrological effects of the allocated water. Therefore, after running the two models successively, the feedback and retrieval of the information are refined and modified to

achieve optimal use of water. This cycle continues until the convergence between the two models is attained. This convergence occurs when the economic value of water becomes constant between two successive replications and, consequently, the optimal cropping pattern resulting from the economic model does not undergo any changes.

Agricultural Economic Model

Since one of the goals of policymakers and planners, especially in the agricultural sector, is to know the results of implementing different policies and farmers' reaction to them, they look for models that can help them achieve these goals with high confidence. Also, planners believe that simulation of potential reactions of farmers to the implementation of different policies can have an active contribution to making decisions that are more correct. The conventional method to evaluate decisions made by the producers is to create a pattern that reflects the objectives, opportunities, and constraints of the conditions. The PMP is an empirical analysis method that utilizes all available information, irrespective of how scarce they are. This method is particularly important in regional and local policy analyses (Arfini *et al.,* 2003).

The growing demand for a model that simulates behavior functions under technical, economic, political, and, recently, environmental conditions has increased the use of PMP, which lacks excessive specialization, validation, and flexibility problems to changes of parameters and can be calibrated. This model has been widely used in applied research and policy analysis (Cai and Wang, 2006). The economic model of the present research was based on the PMP method.

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Objective Function

It is assumed that all farmers involved in the agricultural activities in the six INs, downstream of Zayandehrud Dam, are seeking to maximize their net income or profits in each agricultural year. Therefore, the basis of the analytical model in this research was its objective function, which is as follows:

$$\max net = \sum_i \left[\begin{array}{l} p_i q_i(X_{ih}, P_i) - \sum_h p_h X_{ih} - \\ (\alpha_i X_{iland} + 0.5\psi_i X_{iland}^2) \end{array} \right] \quad (1)$$

The first part in the right-hand side of Equation (1) represents the gross income, *pi* is price of the crop *i*, $qi(X_{ih},P_i)$ is production function, X_{ih} is the matrix (i×h) consisting of crop *i* and agricultural inputs *h* (including land, surface water volume used in irrigation, leased labor, family labor, and purchasable inputs such as fertilizers, pesticides, and so on), and P_i represents the amount of rainfall during the growing season of crop *i*.

The cost per unit of crop *i* is defined in two separate parts in Equation (1). The first part indicates the market price of inputs (p_h) multiplied by their consumption amount (X_{ih}), and the second part, which is in parenthesis, is for the implicit cost of allocated land to each crop, which has parameters α_i and ψ_i, and takes into account the final cost of land for different crops. Due to the allocation of land for a particular crop by the farmer, the remaining land may not have proper quality for other crops' production, which will result in increased production costs for the crop in a nonlinear manner. Since these effects are not directly observable and cannot be measured, ignoring them leads to a problem in decision-making.

Production Function

The production function $q(X_{ih},P_i)$ provides an estimate of the products produced by a set of available inputs and precipitation level for each crop. The functional form used for *q* is the Constant Elasticity of Substitution (CES); but the form of this function is different for rainfed and irrigated crops.

CES Function for Rainfed Crops

$$q_i^r = A_i Precip_i \left(\sum_h b_{ih-1} X_{ih-1}^{\gamma} \right)^{\frac{\varepsilon_i}{\gamma}} \quad (2)$$

Where, the exponent *r* in q_i^r stands for rainfed, A_i is the contribution of environmental parameters, b_{ih} represents the production-function parameters, $\gamma = \frac{\sigma - 1}{\sigma}$, σ is the elasticity of substitution between the inputs, and ε_i is the scaled efficiency. The *h-1* index reflects the concept that all inputs, except surface water, are used in the production of rainfed crops, and $Precip_i$ is the ratio between actual precipitation level P_i^a and expected precipitation level P_i^e.

CES Function for Irrigated Crops

$$q_i^{ir} = A_i \left(\sum_h b_{ih-1} X_{i\,h-1}^{\gamma} + b_w \left(X_{isw} + P_i^a \right)^{\gamma} \right)^{\frac{\varepsilon_i}{\gamma}} \quad (3)$$

Where, the exponent *ir* in q_i^{ir} stands for irrigated, *Ai* represents the contribution of regional, and b_{ih} represents the parameters of the production function for all inputs, except surface water, b_w is the share of surface water (X_{isw}), P_i^a is actual precipitation, γ and ε_i are as defined in Equation (2).

Shadow Price for Non-Market Inputs

For inputs with limited supply, such as family labor force, surface water, and land, the final cost of each unit is derived from the total market price plus their shadow price (λ). Shadow price for any non-market input, or with limited supply, is obtained by Lagrange coefficient. This coefficient is calculated by solving Linear Programming (LP) model, with the objective function of maximizing farmers' profit, and calibration limitations, along with resources constraints, aiming at estimating shadow prices for cultivated crops. Assuming maximization of the efficiency, the model is specified as follows. This pattern, which uses calibration constraints, reproduces the values in the base year:

$$\max_{land} \sum_i p_i \hat{y}_i X_{i\,land} - \sum_i p_h a_{ih} X_{i\,land} \quad (4)$$

Subject to:

$$\begin{cases} \text{Land}: \sum_i X_{i\,land} \le B_{land}, \\ \text{Family labor}: \sum_i a_{i\,fl} X_{i\,land} \le B_{fl}\ , \end{cases} \quad (5)$$

$$\left\{ \textit{Surface Water}: \sum_{\boldsymbol{i}} \boldsymbol{X}_{\boldsymbol{iswm}} \le \boldsymbol{B}_{\boldsymbol{swm}}, \right. \quad (6)$$

$$\left\{ \textit{Surface Water}: \sum_{\boldsymbol{i}} \boldsymbol{X}_{\boldsymbol{iswm}} \le \boldsymbol{B}_{\boldsymbol{swm}}, \right. \quad (7)$$

Model Calibration Constraint

$$X_{iland} \le \hat{X}_{iland} \quad (8)$$

Where, P_i is price of the product i, ŷ is yield per ha of land under crop i (X_{iland}), P_h is cost per unit of input h used in the production of crop i, a_{ih} is inputs used per ha of land $\left(X_{ih} / X_{iland} \right)$, and B_{land} and B_{fl} represent total available land and family labor, respectively. Equation (7) ensures that the total amount of surface water used (X_{iswm}) in a month or year m is less than or equal to the total amount of available surface water (B_{sw_m}) for irrigation of crops in the same month or year. It is calculated by using crop coefficient (K_c), reference crop evapotranspiration (Et_o) for each crop i and the actual rainfall level (P_n^a) per day of the year (n). The shadow prices of limited resources (λ_{land}, $\lambda_{FamilyLabor}$, $\lambda_{SurfaceWater}$) in equations (6) and (7) show an increase in net income of farmers for an extra unit of available land, family labor, and water. In Equation (8), $\hat{X}_{iland}$ is total real *ha* of land allocated to crop i. This constraint preserves the patterns of observed cultivation in the region, and the information is used to estimate shadow prices of non-market resources. The Lagrange coefficient in Equation (8), $\lambda_{i\overline{land}}$, represents the profit that farmers gain by reallocating a unit of land to a high-yielding crop.

It is noteworthy that although shadow prices of limited resources (land, water, and family labor) are not specific to a particular crop and may change from one farmer to another, the Lagrange coefficient is specific for each farmer and crop.

To use the limitation employed in Equation (6) at monthly time steps, the planting and harvesting dates of each crop i by each farmer, in the six INs of the study area, were collected over 365 days (n) in the 2014-2015 base period. Then, assuming four growth stages for each crop and using the specific crop coefficient (K_c) for each growth stage (Moghaddasi *et al.*, 2010) and reference crop evapotranspiration E_{t0}, optimum evapotranspiration rate was calculated for each crop i at daily intervals ($K_{cin}E_{t0n}$). For those days for which the relation $K_{cin}E_{t0n} > P_n^a$ applied, the difference between $K_{cin}E_{t0n}$ and P_n^a was denoted as Z_{in} ($Z_{in} = K_{cin}E_{t0n} - P_n^a$); otherwise, Z_{in} was taken equal to zero. The annual and monthly sum of Z_{in} is $\sum_{n=1}^{365} Z_{in}$ (n = 1 is first of October) and $\sum_{n=s}^{f} Z_{in}$ (s and f are the first and last day of each month, respectively).

Therefore, using the annual and monthly Z_{in} values, the water demand (Met_{im}) for crop i in month m was calculated as:

$$Met_{im} = \frac{\sum_{n=s}^{f} Z_{in}}{\sum_{n=1}^{365} Z_{in}}. \quad (9)$$

Where, m is 12 months of the year, starting from October. The total amount of applied surface water for crop *i* in month *m* is $X_{iswm} = Met_{im} X_{isw}$. Also, the total amount of surface water sources used for crop *i* is equal to:

$$\sum_i X_{iswm} = \sum_i Met_{im} * a_{isw} * X_{iland} \quad (10)$$

Where, a_{isw} is annual amount of surface water sources used per *ha* of land $\left(X_{isw} / X_{iland}\right)$. Equations (6), (7), (8) and (10) are considered as the set of constraints of the linear optimization problem.

Estimation of Production-Function Parameters

At this stage, using the shadow prices of the limited and unlimited resources and the calibration limitation obtained from the previous step, the parameters of production functions were estimated.

In this study, the analytical approach and optimal economic conditions were used to compute the parameters of production functions (Equations 2 and 3). The optimum economic conditions were obtained by equating marginal product and marginal cost of each unit input. The optimal conditions for using unlimited and limited inputs were obtained by equating the cost of each unit of inputs with their shadow prices ($\lambda_{land}, \lambda_{FamilyLabor}, \lambda_{SurfaceWater}$). For land input, in addition to the market price and its shadow value, the shadow price of calibration limitation was also added to them. In other words, for optimal allocation of land for crop *i*, it is necessary that final cost of a unit of land be equated with the total market price, the shadow value (λ_{Land}) of each unit, and the Lagrange coefficient of calibration limitation ($\lambda_{i\overline{land}}$). In other words, the optimal conditions for using each input are defined as follows:

$$p_i \frac{\partial q_i}{\partial X_{iu}} = p_u$$, for unconstrained inputs;

$$p_i \frac{\partial q_i}{\partial X_{i\,fl}} = \lambda_{fl}$$, for irrigation and non-irrigation family labor;

$$p_i \frac{\partial q_i}{\partial X_{i\,land}} = p_{land} + \lambda_{land} + \lambda_{i\overline{land}}$$, for land;

$$p_i \frac{\partial q_i}{\partial X_{i\,sw}} = p_{sw} + \lambda_{sw}$$, for surface water. (11)

Where, *u* represents unconstrained inputs (X_i). Through the algebraic solution of the above equations, parameters of the production functions were obtained. By putting these parameters in Equation (1), the objective function of the problem (price and amount of inputs, and price of the crops) was calculated.

Optimization of the Economic Model

When Zayandehrud Basin is subject to constraints of resources and water-availability, to obtain the optimal set of inputs that maximize the net income, the following estimated CES production function ($\hat{q}$ given in Equation 3) is used:

$$\max_X net \; \sum_i [p_i \hat{q}_i^r (X_{ih}, P_i) + p_i \hat{q}_i^{ir} (X_{ih}, P_i) - \sum_i p_h X_{ih} - (\hat{\alpha}_i X_{iland} + \hat{\psi}_i X_{iland}^2)] \quad (12)$$

Land: $$\sum_i X_{i\,land} \le B_{land} \quad (13)$$

Family Labor: $$\sum_i X_{i\,fl} \le B_{fl} \quad (14)$$

Surface Water: $$\sum_i X_{iswm} \le B_{swm} \quad (15)$$

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Hydrological Model

According to the structure presented in Figure 2, the water resources model of the integrated hydro-economic structure is the MODSIM model, which is a climate-driven water resources model that systematically simulates the natural flow of water and its uses, as well as infrastructure management for balancing water supply and demand within the model. This model, which is designed to allocate water based on an appropriate equilibrium, consists of a linear programming algorithm that minimizes water shortages for a variety of uses by considering some constraints. These constraints are related to water demands of different uses as well as supplies from various sources.

In the present research, to achieve the objectives, the MODSIM model was used for water allocation in the six INs (located downstream of Zayandehrud Dam), under drought conditions, as shown in Figure 3.

RESULTS AND DISCUSSIONS

Economic Model (PMP)

Utilization of the developed hydro-economic model of the present research begins with its economic model in each IN. By implementing

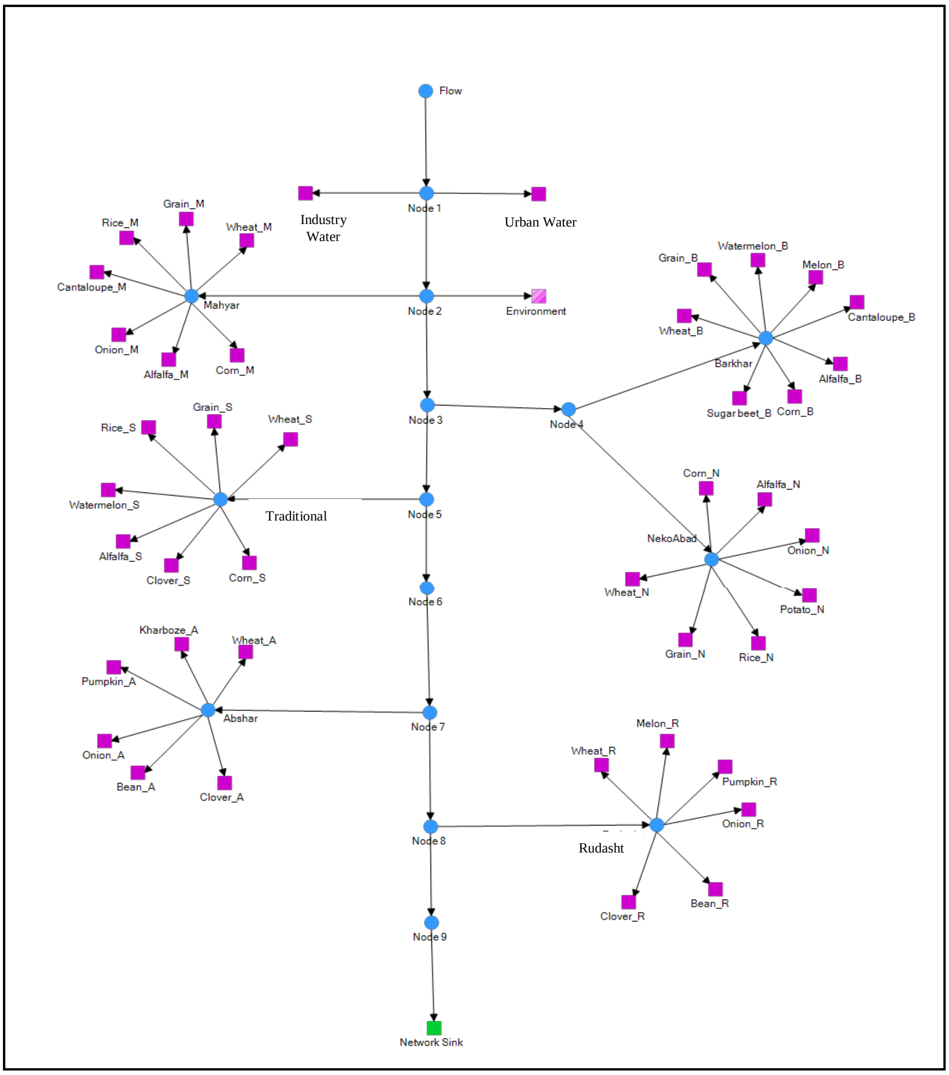

Figure 3. Schematic of the developed model for water allocation of Zayandehrud Dam in the irrigation networks using MODSIM software.

the economic model, the necessary boundary conditions are provided for simulation of the hydrologic model. For this purpose, first, cultivation pattern of each IN (Table 1) was calculated by the PMP approach. This was done using the data and information of the existing agricultural economics of each IN, including the data and information (e.g., land cost, fertilizer, pesticide, water, machinery and labor per unit of each crop in the cultivation pattern) provided by the questionnaire (which was distributed among farmers and stakeholders in each agricultural area), and also the information collected from the relevant organizations and institutions (price of inputs, unit price of crops, crop yield, volume of irrigation water, and volume of water delivered to each IN).

The economic value of each cubic meter of water consumed by the crops in the existing cropping pattern of each IN and the average economic value of each cubic meter of water supplied for them were obtained by the economic model (Table 2). According to this table, Nekoabad and Rudasht INs have the highest and the lowest average economic value, respectively, in the six INs. According to the data in Table 2 and Figure 4, the order of water delivery to the six irrigation networks has been determined by the hydro-economic model. The obtained weighted-average economic value of water for the current conditions is given in Table 2. Figure 4 shows the final priorities of water distribution based on the convergence step of the hydro-economic model. Comparing the calculated weighted-average economic values of Table 2 and Figure 4 reveals the growth of economic values after applying the hydro-economic framework. Table 3 shows the calculated weighted average of the economic water value before and after the optimization of economic value, respectively. Based on this order, Borkhar IN has the first priority and

Table 1. Crops, cultivated area, and volume of delivered water under the baseline conditions in the six irrigation networks.

	Network	Mahyar	Borkhar	Traditional	Nekoabad	Abshar	Rudasht
	Volume of delivered water (MCM) [a]	103.8	894	137	223	200	190.3
	Total cultivated area (ha)	6258*	10981	4569	13316	13258	14315
Existing cultivated area per crop in the cropping pattern (ha)	Wheat	1229	3667	1230	3667	9240	9096
	Barely	1927	2756	1927	2756	–	–
	Rice	285	–	285	1306	-	–
	Potato	–	–	–	1961	–	–
	Onion	55	–	-	1027	1027	2274
	Alfalfa	313	645	55	1898	–	–
	Forage corn	562	2716	562	701	–	–
	Melon	1690	544	–	-	277	273
	Pumpkin	–	–	–	–	462	455
	Beans	–	–	–	–	1925	1895
	Clover	–	–	313	–	327	322
	Grain sorghum	–	–	–	–	–	–
	Watermelon	–	238	197	–	–	–
	Cantaloupe	197	238	-	–	–	–
	Sugar beet	–	177	–	–	–	–

[a] MCM= Million Cubic Meters. Reference: Research findings. * The difference between total cultivated area and sum of the areas for all crops is allocated to orchards or other unmentioned crops.

Table 2. Economic value of water for different crops under the base conditions in the six irrigation networks.

Network		Traditional	Mahyar	Rudasht	Borkhar	Abshar	Nekoabad
Weighted average water value		3140	3370	3002	3407	3249	3438
Water value of the crops (Rials m^{-3})	Wheat	3065	3251	2729	3293	3226	3303
	Barely	3213	3315	-	3417	-	3432
	Rice	3483	3653	-	-	-	3605
	Potato	-	-	-	-	-	3592
	Onion	-	3593	3631	-	3301	3603
	Alfalfa	3245	3321	-	3381	-	3310
	Forage corn	-	3629	-	3661	-	3534
	Melon	-	-	2668	2892	1835	-
	Pumpkin	-	-	3553	-	3550	-
	beans	-	-	3563	-	3586	-
	Clover	1993	-	2446	-	2479	-
	Grain sorghum	-	-	-	3485	-	-
	Watermelon	3079	-	-	-	-	-
	Cantaloupe	-	3511	-	3366	-	-
	Sugar beet	-	-	-	3365	-	-

Reference: Research findings.

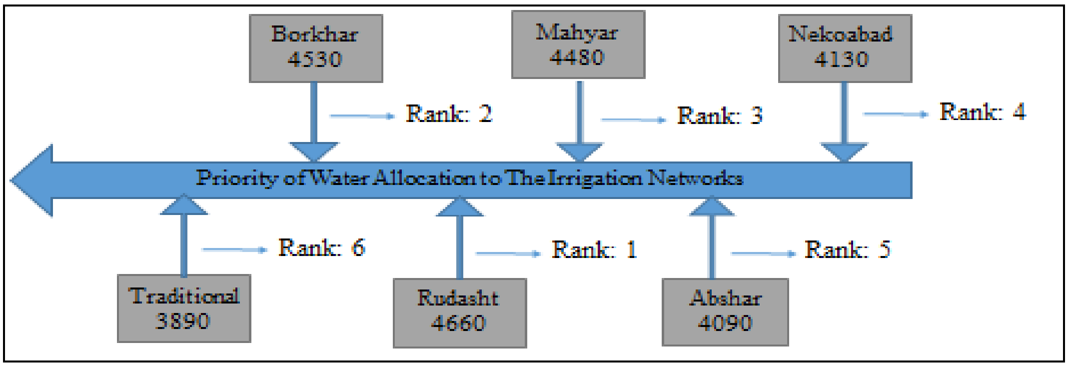

Figure 4. Priority of supplying water for the six irrigation networks, based on the convergence between the economic model and water resources model. Values in the boxes refer to the value of water (Rials m^{-3}).

Rudasht and Traditional INs are the last networks to get the water. Results also indicate that in the case of water scarcity, the economic value of water in the eastern networks of the basin has higher potential. The change in the cropping pattern resulting from the application of the integrated hydro-economic model under drought scenario is presented in Table 4. According to Table 4, the highest reduction in cultivated land under drought conditions (42%) is for clover in Rudasht IN.

According to Table 4, compared to the optimal cropping pattern, the greatest reduction in cultivation area in the base year, obtained from the hydro-economic model, is related to clover production in Rudasht IN. Since the objective function of the hydro-economic model is maximizing the net income of the farmers, factors such as high water demand, low prices,

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Table 3. Weighted average economic value of water before and after employing the hydro-economic model.

Network		Traditional	Mahyar	Rudasht	Borkhar	Abshar	Nekoabad
Weighted average economic value of water	Current agricultural conditions	3140	3370	3002	3407	3249	3438
	Employing the hydro-economic approach	3890	4480	4660	4530	4090	4130

Table 4. Changes in area under cultivation of different crops after applying drought scenario in the hydro-economic model. [a]

Network		Obtained cultivated area for drought conditions versus the base conditions (%)					
		Nekoabad network	Abshar network	Borkhar network	Rudasht network	Mahyar network	Traditional Network
Changes in area under cultivation	Wheat	-19	-14	-15	-33	-11	-17
	Barley	-	-	3	-	8	4
	Rice	-4	-	-	-	-5	-1
	Potato	-12	-	-	-	-	-
	Onion	-2	-3	-	-1	-8	-
	Alfalfa	-34	-	-	-	-28	-26
	Forage corn	-12	-	-23	-	-18	-33
	Melon	-	-2	-3	-5	-	-
	Pumpkin	-	-4	-	-2	-	-
	Bean	-	14	-	21	-	-
	Clover	-	-33	-	-42	-	-21
	Grain Sorghum	-	-	-12	-	-	-11
	Watermelon	-	-	-4	-	-7	-
	Sugar beet	-	-	-18	-	-	-

[a] Reference: Research findings.

increased production costs, time, and location conditions of the crop production, and farmers' previous experiences in agricultural practices contributed to the reduction of the cultivated area for some crops.

Hydrological Model (MODSIM)

MODSIM model was used for systematic simulation of the natural inflow of water to Zayandehrud Reservoir, volume of water available in the reservoir, and delivery and distribution of water to each IN, based on the economic value of water in the year 2014-2015, under drought conditions.

For this purpose, the MODSIM model was designed for the existing water sources (Zayandehrud Reservoir as the sole source of supply) and the uses (drinking, environmental, industrial, and agricultural) for the drought scenario.

In this model, the priority of needs determines how to allocate water to different uses. In this

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research, to plan, deliver, and optimize water distribution to the INs, due to the existence of only one source of supply (Zayandehrud Dam), priority of the supply source was considered equal to one. The priority of drinking, environmental, and industrial needs was considered as 1, 2, and 2, respectively.

Each crop in the cropping pattern of the six INs of Zayandehrud Basin was considered as an independent requirement in the application of the model. Therefore, in order to deliver and distribute optimal water to each specific crop, the priority of delivery and distribution of the irrigation networks was based on the average weight (10-99) of the economic value of crops in their cropping pattern, estimated by the economic model in the previous section (Table 1).

Also, the available and regulated volume of water in the base year was allocated to different uses, based on the priority of the abovementioned requirements. To do so, the drinking, environmental, and industrial water needs were addressed in the order of priority. Once these needs were satisfied under drought conditions, with the priority of their allocation being externally determined by the legislation of the Iran's water resources, the remaining water (share of the agricultural sector) was allocated to INs, based on the economic value of the crops in the existing cropping pattern.

Since allocation of water according to the above conditions by MODSIM model changed the available volume of water for PMP modelling method in the INs and was considered as a scenario for the model, the results of this scenario altered the existing cropping pattern of INs and changed the economic value of the crops.

In the present study, implementation of economic and hydrological models in the hydro-economic model has been repeatedly updated and improved, but not all the intermediate results are presented here.

To analyze drought scenario by the water resources model, the current account of the system of Zayandehrud Basin was implemented as the base model. Thus, the modeling and implementation stages of the model were used in the base conditions. In addition, to simulate the volume of available water under drought conditions and plan optimal allocation of water to agricultural uses, the inflow to Zayandehrud Reservoir in a dry year (2007-2008) was entered into the MODSIM model as drought discharge. After running the above model, results of the first integration of water resources model with the economic model are presented in Figure 5, which shows that the priority of water delivery starts from Nekoabad IN and ends with Rudasht IN. These results show that if water is the scarce input, the economic value of water in eastern INs

Table 5. Changes in net revenues due to upgrading the existing water allocation.

	Irrigation Network					
	Rudasht	Mahyar	Traditional	Borkhar	Abshar	Nekoabad
Net revenue-Existing conditions (10E7 Rials)	1982210.7	487595.2	767562.3	3387735.6	1496790.4	2052684.75
Net revenue–New water allocation (10E7 Rials)	2162408.8	514309.1	792301.8	3572367	1698009.7	2142918.5

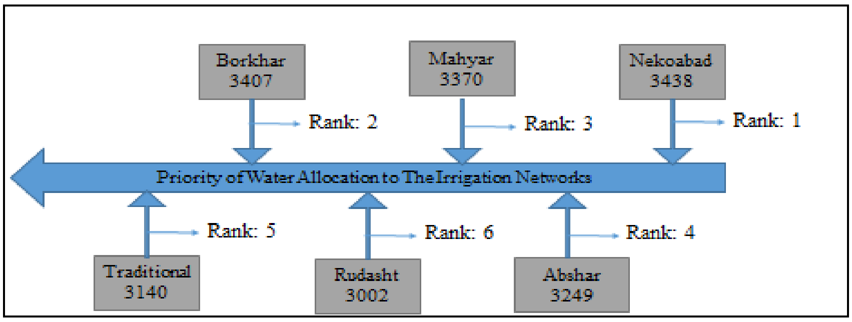

Figure 5. Priority of water allocation in the first connection between economic model and water resources model. Values in the boxes refer to the value of water (Rials m^{-3}).

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is more than other networks in this basin.

Due to upgrading the existing water allocation, net revenues were changed within the irrigation districts (Table 5). Effect of employing the Hydro-economic model on average economic value of water in the six irrigation networks showed that the highest and the lowest economic values of water under the current agricultural conditions were improved after employing the Hydro-economic model.

The objective function of the hydro-economic model is maximizing the net income of the farmers, factors such as high water requirements, low prices, and high production costs of a crop lead to decreasing the influence of employing these models..

CONCLUSIONS

In this study, a hydro-economic model was dveloped to provide a systematic agricultural water allocation to six irrigation networks (Nekoabad, Mahyar, Borkhar, Abshar, Rudash, and Traditional), located in Zayandehrud River Basin. The main reason for this study was lack of proper mechanisms for water allocation within the basin. The existing water allocation approach is just based on personal judgement and expriences of the operators. The economic model was coupled with water resources allocation model (MODSIM) to determine the priorities based on economic perspectives. The developed hybrid model considers the economic perspectives throughout the basin, since economic value of water is assigned as the basis of agricultural water allocation. In addition to allocating the water on the basis of economic value of water, the optimal cropping pattern under the existing conditions of the six INs was determined under drought conditions. Moreover, potential reaction of the farmers (changing of the cultivated area) working across the study area was tested against the drought conditions to figure out its effect on the cropping pattern within the cultivated areas. In this respect, a combination of MODSIM model and PMP approach within the hydro-economic structure was developed in the current study. Results of the study provide a reliable, systematic, and realistic agricultural water allocation in the Zayandehrud River Basin, considering economic perspectives. Simulation results of the existing operational conditions (Table 1) reveal that area under cultivation could be the main reason for differences in water allocation between the districts. The main drawback of this allocation system is personal judgment, being vulnerable to unreasonable decisions and the pressures (from different sources) for changing the distribution patterns. Moreover, the traditional system has failed in water-deficit periods, which frequently occurs in Zayandehrud River Basin. Comparing the results of employing the hydro-economic model in normal and drought scenarios (Figures 4 and 5) reveals the reasonable differences in the calculated economic values of water for each district. Remarkable changes happened in priorities of agricultural water allocation between the districts. The priority of Rudasht district dropped from the first (in normal scenario) to the last (in drought scenario). Similarly, the first priority was assigned to Nekoabad Irrigation District under drought conditions; while this irrigation district held the fourth priority in normal scenario.

Due to upgrading the existing water allocation, net revenues were changed within the Irrigation Networks. Effect of employing the Hydro-economic model on average economic value of water in the six irrigation netwroks showed that the highest and the lowest economic values of water (3,438 and 3,002 Rials m^{-3}, respectively) under the current agricultural conditions were improved to 4,660 and 3,890 Rials m^{-3} after employing the Hydro-economic model.

One of the primary goals of using the hydro-economic model in this research was water allocation based on its economic value in the absence of water market in the study area. However, this objective can only be reached by assuming that the cost of inputs and price of the crops' yield is constant in a year. Therefore, future studies could be directed to investigating the use of Zayandehrud Dam's rule curves and dynamic market of inputs and crop prices in the hydro-economic model to allocate water to different crops in the six INs.

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کاربرد مدل هیدرواکونومیک در توزیع بهینه آب کشاورزی تحت تأثیر شرایط خشکسالی (مطالعه موردی: شبکه‌های آبیاری پایین‌دست سد زاینده‌رود)

د. رجبی، س. ف. موسوی و ع. روزبهانی

چکیده

برنامه‌ریزی توزیع آب سد زاینده‌رود به شش شبکه آبیاری واقع در پائین‌دست این سد بر اساس یک رهیافت هیدرواکونومیک در شرایط کمبود آب انجام شده است. ساختار هیدرواکونومیک از طریق تلفیق مدل شبیه‌سازی هیدرولوژیک (MODSIM) و مدل بهینه‌سازی اقتصادی (برنامه‌ریزی مثبت ریاضی، PMP) به‌دست آمده است. اولویت‌های توزیع آب به شبکه‌های آبیاری براساس ارزش اقتصادی آب مصرفی گیاهان در الگوی کشت فعلی تحت سناریوهای نرمال (سال پایه ۹۴-۱۳۹۳) و شرایط خشکسالی تعیین شده است. نتایج نشان داد که علاوه بر تغییر در اولویت‌های توزیع آب در داخل شش شبکه آبیاری، الگوهای کشت فعلی نیز باید تغییر کنند. ترتیب تحویل آّب به شش شبکه آبیاری از شبکه رودشت شروع و به شبکه آبیاری سنتی ختم می‌شود. همچنین، بیشترین کاهش سطح زیر کشت در سال پایه، در مقایسه با کشت بهینه، مربوط به یونجه (در شبکه‌های آبیاری نکوآباد و مهیار- جرقویه)، شبدر (در شبکه‌های آبیاری رودشت و آبشار) و ذرت علوفه‌ای (شبکه‌های آبیاری بُرخوار و سنتی) می‌شود. افزایش سطح زیر کشت حبوبات در شبکه‌های آبیاری آبشار و رودشت به‌ترتیب ۱۴ و ۲۱ درصد خواهد بود. با توجه به نتایج، اگر آب بر اساس قیمت‌های سایه‌ای آن تخصیص یابد، ارزش اقتصادی هر متر مکعب آب به طور متوسط افزایش خواهد یافت. بعلاوه، بیشترین و کمترین افزایش در ارزش اقتصادی آب در شرایط خشکسالی به ترتیب در شبکه آبیاری نکوآباد (۴۶۶۰ ریال بر متر مکعب) و شبکه آبیاری رودشت (۳۸۹۰ ریال بر متر مکعب) اتفاق خواهد افتاد.

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