Introducing an economic agricultural water distribution in a hyper-arid region: a case study in Iran

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ABSTRACT

Operational management of agricultural water based on an economic perspective was investigated as a sustainable approach in water shortage periods. Accordingly, an automatic water distribution system was coupled with the Positive Mathematical Programming economic model for a sustainable agricultural water operation in the Roodasht irrigation network, Iran. Operational management was carried out based on the economic value of water in each irrigated unit. According to the results, the existing operating system was able to supply 71 and 22% of farmers' water requirements under normal and water shortage conditions, respectively. However, employing the proposed automated operational-economic approach reduced water consumption by 14.3%, while maintaining the cultivation area by 11% and increasing farmers' net profit to 840,000 USD under water scarcity. The economic operation can reduce water losses, implement economic strategies in those districts without water marketing mechanisms, and provide sustainable management of limited water resources in hyper-arid regions.

Key words | automation, irrigation district, socioeconomic, sustainable water management, water conservation

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HIGHLIGHTS

- An operating system is proposed for districts with a lack of a market mechanism.
- Surface water distribution is conducted based on the economic value of water.
- The water conservation objective is fulfilled by employing an automatic control system.
- An automatic operating system is developed to fulfill the economic objectives.

ABBREVIATION

RNB	Roodasht Northern Branch
MPC	Model predictive controller
PMP	Positive Mathematical Programming
ICSS	Irrigation Conveyance System Simulation
S-V	Saint-Venant equation
RMSE	Root-mean-square error
CRM	Coefficient of residual mass
ID	Integrator-delay model
NCO	Normal Condition Operation scenario
IFU	Inflow Fluctuations of Upstream scenario
COMR	Current Operational Method of Roodasht
AOE	Automated Operation-Economic alternative
TOE	Traditional Operation-Economic alternative
AOF	Automated Operation-Fair alternative
TOF	Traditional Operation-Fair alternative

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INTRODUCTION

The agriculture sector includes a significant portion of entrepreneurship, a substantial income source, and the means of support for poor rural households. People whose lives depend on agricultural activities make up about 40% of the world's global population. In most agricultural societies, farmers' livelihood has received considerable attention from the government to ensure food security (Nourzadeh *et al.* 2013). Simultaneously, the reduction of available water resources due to climate changes, population growth, and malfunction of water distribution infrastructure in the agricultural sector has drawn attention to optimal management and operation of existing water resources (Monem & Hashemy 2011). The development of cost-effective water distribution policies under water scarcity conditions has been a matter of interest to water managers and researchers. In this respect, the objective is to maximize farmers' net profit under unbalanced water supply and demand conditions by distributing and delivering more water to high-value economic areas (Ren *et al.* 2016).

Most hydro-economy studies focus on large-scale issues (such as large basins); meanwhile, the literature on reducing irrigation losses mainly concentrates on small-scale farms. Accordingly, this study aims at filling the research gap (water delivery and distribution between suppliers and consumers) in integrated water resources management by providing effective management solutions for the economical operation of water delivery and distribution networks (Sheikhipour *et al.* 2018; Eini *et al.* 2019). The present study suggests a single operational-economic strategy under water scarcity conditions to connect macro- (basin) and micro- (farm) management of water resources in a surface irrigation network. Thus, this study aims to apply an operational-economic framework over the distribution of water among offtakes based on the weighted average of water's economic value for agricultural products under water scarcity conditions. For this purpose, integral parts of the model, including the operational model (hydrodynamic simulation) and the economic model (farming activities), are considered, respectively, to examine water distribution alternatives by which water conveyance along the canal fulfills the offtake demands and reproduces the farmer attempts from an economic point of view (Hashemy Shahdany & Roozbahani 2016). Definitely, farming units with better efficiency (such as low irrigation losses, high production yields and use of better fertilizers) would have more water value and, subsequently, acquire more share during circumstances of water shortage. Additionally, because of water scarcity, some agricultural products are partially removed (mainly low-value crops are cut down) to offer an effective crop pattern with maximum benefit. Linking the above-mentioned elements creates a state-of-the-art platform whereby decisions on managing water can be investigated from various operational and economic perspectives. This, in turn, directs water shortages to low-value units, ultimately leading to an increase in the net profit in the irrigation district (Rosegrant *et al.* 1995). The implementation of this strategy should be supported by the delivery and the distribution system of the irrigation network in a scale that has never been investigated in formerly done researches.

The selected case study is the main canal of the Roodasht Northern Branch (RNB) irrigation network in central Iran. This canal includes a traditional delivery and distribution system and fixed duck-bill water regulating structures. Due to inefficient operation and poor performance of the water delivery and distribution system, especially in regions located at the downstream part of the canal, farmers face inadequate water supply for their agricultural units. On the other hand, water shortages and fluctuations of inflow to the canal headgate have negatively affected the irrigation network operation. For this reason, intelligent operational management of the water conveyance, distribution, and delivery systems, provided by optimal control systems, can significantly increase the flexibility of water distribution and reduce the operational water losses within the canals' networks related to the inflow fluctuations derived from drought periods. To this end, the function of the suggested framework was modeled in RNB (by gathering real data on canal operation and agricultural area for 2015) for coping with the canal inflow fluctuations and managing the water scarcity given the economic principles to find if this is an effective alternative for handling the water deficit (Shahdany *et al.* 2018).

The centralized configuration of a model predictive controller (MPC) has been widely applied in studies related to canal automation, and this controller has shown promising performance since it employs optimal control to provide a highly intelligent operational performance of the canal network (van Overloop et al. 2010a; Zafra-Cabeza et al. 2011; Maestre & Negenborn 2014). Thus, automated adjustment structures equipped with MPCs have been proposed as an alternative to fix overflow regulating structures for distributing water among offtakes based on their economic value. Practically, water's economic value in agricultural units determines the tasks of MPCs in supplying water to offtakes under defined water scarcity scenarios. Under this circumstance, each tertiary farming unit acquires a dedicated water share from the operation model wherein the economic model estimates the high-profit crop pattern. However, the MPC (an operation model) receives economic signals that change it into a water management plan and then, actually, prioritize the farming units. Water delivery and distribution activities were simulated by an open-source hydrodynamic model (Hashemy Shahdany et al. 2016a) under different operational scenarios, including fluctuation and normal inflow. To investigate the desirability of operation scenarios, the performance assessment criteria, introduced by Molden & Gates (1990), were employed.

The Positive Mathematical Programming (PMP) economic model was used for simulating the agricultural activities of farmers and predicting their reaction to water shortage scenarios based on their assumption of the highest benefit. The economic value of water for crops was considered as the economic criteria (Graveline 2016). By combining the PMP economic model and the MPC operation model, an operational-economic structure was developed to maximize network profits, while reducing operational losses under water scarcity circumstances. The results obtained from different delivery and distribution alternatives were compared.

MATERIALS AND METHODS

Study area

The Roodasht irrigation network located in the middle part of Iran is the study area of this research. Figure 1 shows a plan view of the irrigation canal networks in the irrigation district. Table 1 shows the hydraulic and physical characteristics of the trapezoidal RNB main irrigation canal.

The conventional farming produce, including the existing cropping pattern, in Roodasht district, are wheat, barley, alfalfa, safflower, and sugar beet, and the whole cultivated area of crops is shown in Table 2.

The study area, located in central Iran's arid region, suffers dryness strictly and water scarcity while extracting water from the Zayandeh-Rood River. The study area aims to get the latest priority for extracting water since other

Table 1 | Physical features of the RNB canal

Magnitude	Features
0.0003 m/m	Bed slope
1.5 m/m	Side slope
4.2 m	Canal bottom width
2.5 m	Canal normal depth
26	Number of offtakes
13	The number of water-level regulator stations

Table 2 | Current crop pattern in the irrigation RNB network

Crop	Wheat	Barley	Alfalfa	Safflower	Sugar beet
Cultivated area (ha)	10,343	1,941	873	530	22

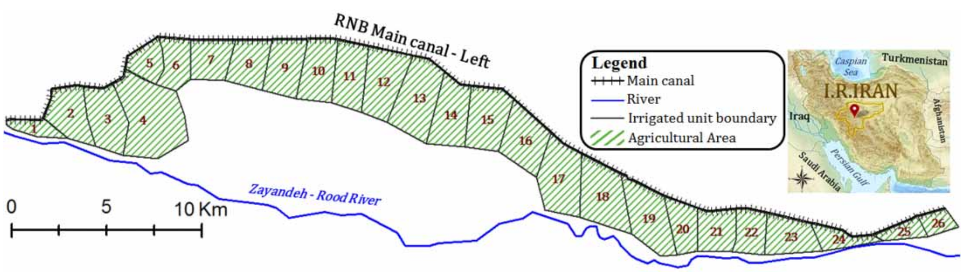

Figure 1 | Plan view of the Roodasht canal networks.

sections included the Isfahan metropolis and other five irrigation districts at the upstream of the basin, which is fulfilled before the Roodasht district. Briefly, the study area was selected by taking into account the factors that made the Roodasht Irrigation District the most vulnerable to water shortage in Iran. The logic behind this selection is as follows:

1. Unreliable supply of the required surface water by the river resulted in inflow fluctuations and water shortages in the main canal (Kaghazchi *et al.* 2021).
2. The region's social tensions due to limited water supply (Hashemy Shahdany *et al.* 2017).
3. The improper design and the multiplicity of water-level regulating structures that have led to a significant water-level drop along the main canal (Shahdany & Firoozfar 2017).
4. The multitude of groundwater wells and a substantial reduction in the region's aquifer (Khiabani *et al.* 2020).

Irrigation Conveyance System Simulation (ICSS), on the open-source hydrodynamic model, was used to simulate the RNB main irrigation canal operation under existing conditions (Table 1). This model was first developed by Manz (1990) to simulate flows in open canals under steady and unsteady conditions by solving the Saint-Venant (S-V) equations. The model calibration and validation were conducted using the root-mean-square error (RMSE) and coefficient of residual mass (CRM) indices. The RMSE and CRM indices for the calibration stage were 0.003 and 0.99, respectively. The corresponding indices for the validation stage were, respectively, 0.015 and 1.01 (Kaghazchi *et al.* 2021), indicating the model's acceptable precision in water delivery simulation and distribution.

Economic-operational strategy of water distribution

An essential step in achieving the study objectives is to combine the two economic and operation models and formulate an operation-economic framework to maximize the network's net profit. As seen in Figure 2, in the first step, preparative data on hydraulic structures and relevant equipment, canal geometry, and regional hydrology served for the operation model. The economic modelling needs agricultural inputs consumption and prices of the agricultural inputs and services. Employing collected and clustered inputs to models applied a base condition of the RNB operation with normal farming activities regardless of any deficits. Then, the operation alternatives under the water scarcity scenarios were evaluated for their effectiveness, following which they were considered the leading platforms for the water supply system to be combined with an economic model. The average economic value of water was extracted through the economic model to all farming units as a leading factor for an operating model. In fact, under conditions of water scarcity, the economic component in the operation model comes into play in the matter of

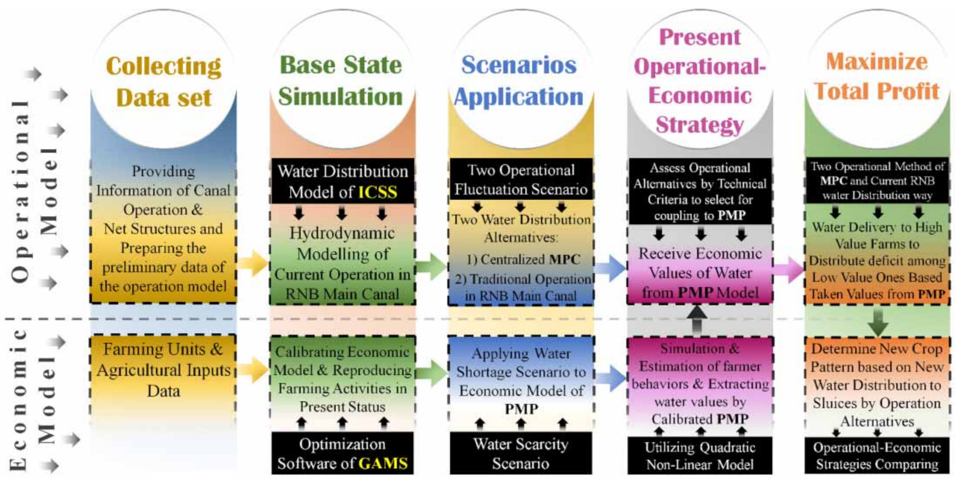

Figure 2 | A conceptual model of the operational-economic approach.

distributing water to agricultural units by determining the weighted average of the economic value of water at offtake headgates. In this way, high-value agricultural units will experience less water shortage than low-value units. Based on the volume of water allocated to each offtake, the new economic model then adapts to the new conditions of agricultural activities, ultimately resulting in a change in the cultivation pattern of agricultural units.

The operational scenarios need to explain that canal operation consists of all activities performed on canal structures to distribute and deliver agricultural water properly. Therefore, the operational scenario represents specific conditions in the canal; accordingly, the relevant activities must be implemented. All the operational conditions of a canal can be determined in various operational scenarios to simulate the hydraulic behavior of flow and the delivery discharges to offtakes in different states. Accordingly, operational scenarios were defined using patterns that are obtained from canal inflow data over the operational period. A wide range of operational scenarios occurred in the daily operation of an irrigation canal, including 'normal operational scenario,' 'fluctuation operational scenarios,' and 'water shortage operational scenarios.' The first two scenarios were selected as the operational scenarios for the present study's test case due to the frequent occurrence of these phenomena.

Operational model: model predictive control

The conventional method in the operation of irrigation canals is to deduct the water-level error with respect to a target level by adjusting the controllable regulators to keep the water-level error near zero (Schuurmans *et al.* 1992). In this paper, an MPC is utilized, a technique that has become famous due to its ability to manage the variable optimization goals, delays, uncertainties, and constraints in a systematic manner (Backman *et al.* 2012). An MPC is a control system that benefits from a feedback and feedforward control method, an optimization method for calculating the output controller variable and water levels in the water distribution system. The controller is responsible for making the water level reach the offtake's target level by regulating the regulator's degree of openness located upstream of every canal reach. The MPC uses the mathematical model of the controlled system (the internal model) to predict hydraulic variables (water levels adjacent to each offtake) within a specific time interval. This interval, which is named 'Horizon' in this controller, is defined following the automated control system's design goal. In this study, the interval was considered 24 h based on the recommendation of Maestre *et al.* (2014). The control commands were determined in each time step based on the simulated hydraulic conditions (in the internal controller model) along the canal's temporal horizon and real-time measurements. The measured water levels adjacent to each offtake (state variables) are transmitted to the central dispatching office via the remote terminal units. After the control commands are determined (separately for each regulator) by the controller, they are sent to executors located at each regulator's site to be executed. Therefore, thanks to the controller's perfect foresight, using the Horizon component, any variation in water extraction by the water holders is taken into account 24 h before water distribution. The mentioned ability makes this automated system robust enough to fulfill water conservation and reallocate water to different clients.

The mathematical model is based on the MPC system that is referred to as an internal model and demonstrates the system dynamics. In addition to the MPC model, control goals should be determined mathematically to form an objective function, and the process of water distribution and structure flow limitations should be considered. The MPC solves at any time step the Equation (1) optimization problem to compute the optimal control action (Shahdany *et al.* 2015):

$$U^* = \arg\min_{U} J(U, x_0) \tag{1}$$

where $U = (u(0), u(1), \ldots, u(N_h - 1))$ is the sequence of values of the manipulated variables on the perspective (N_h), and x_0 is a present state. According to the model and the operational and structural limitations, Equation (1) is solved at any sample time, and only the first response of the sequence of control actions is used.

For utilizing the control problem with automated control algorithms, the system must be defined as a mathematical form involving controlled variables, state variables, and control action variables (Aydin *et al.* 2019). The water levels and flows in an open irrigation canal can be fully expressed by the nonlinear S-V equations (van Overloop et al. 2010b). Water management's control theory applications are mainly based on linear systems, and simple linear models, such as the Muskingum model (Cunge 1969), integrator-delay (ID) model (Schuurmans et al. 1995), and Hayami model, and reduced S-V models (Xu et al. 2011) have been suggested to estimate the canal dynamics until a base is created to develop control procedures. In this study, the ID model is used as an internal model of the MPC system in water management for irrigation networks (Kamrani et al. 2020). The ID model considers that a canal reach is divided into a backwater section and a uniform flow. The delay time (T_c) and the storage area (A_s) are the two main parameters of any canal's reach in the model. Then, the discrete time-invariant canal's reach model utilized in this research is:

$$h(k+1) = h(k) + \frac{T_c}{A_s} q_{\mathrm{in}}(k-k_d) - \frac{T_c}{A_s} q_{\mathrm{out}}(k) - \frac{T_c}{A_s} q_{\mathrm{off-take}}(k) \tag{2}$$

where $q_{\mathrm{out}}(k)$ is the control flow in time step k that gate-conducts it to the downstream one (m^3/s), h is the level of water (m), $q_{\mathrm{in}}(k)$ is the inflow rate, $q_{\mathrm{in}}(k-k_d)$ is the inflow rate (m^3/s) to the backwater part, with k_d being the delay time step between control action and the change in the water level of middle downstream, T_c is the control time step (s), A_s is the average storage area (m^2), and $q_{\mathrm{off-take}}(k)$ is the outflow of the disturbance offtake rate (m^3/s). This disturbance originates from a predefined water distribution schedule.

By alleviating a constant h_{ref} from Equation (2), water-level error can be derived. Therefore, the internal model includes the state-space representation that will be used in the MPC. This type of representation based on inputs, states, and outputs allows direct matrix manipulations. Equation (3) defines the linear time constant state-space representation of the MPC system (van Overloop 2006):

$$x(k+1) = A(k)\cdot x(k) + B_u \cdot u(k) + B_d \cdot d(k), \tag{3}$$

where dimensional state vector containing water-level errors and all delayed flows; k is a discrete time step; dimensional u equals to dimensional control input vector containing the flow variations of the control structures; A is the dimensional state matrix; B_u is a dimensional control input matrix; d is a disturbance matrix consisting of the off-take flows grouped per reach; and B_d is the matrix of dimensional disturbance. The MPC utilizes hard constraints on the control system input and soft constraints on water-level deviations when exceeding the target levels. Thus, Equation (4) illustrates the irrigation canal system's state-space model for the first canal reach.

$$\begin{bmatrix} Q_{\mathrm{hg}}(k+1) \\ Q_{\mathrm{hg}}(k) \\ Q_{\mathrm{hg}}(k-1) \\ Q_{\mathrm{hg}}(k-2) \\ e_1(k+1) \\ e_1^*(k+1) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{T_c}{A_s} & 1 & 0 \\ 0 & 0 & 0 & \frac{T_c}{A_s} & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} Q_{\mathrm{hg}}(k) \\ Q_{\mathrm{hg}}(k-1) \\ Q_{\mathrm{hg}}(k-2) \\ Q_{\mathrm{hg}}(k-3) \\ e_1(k) \\ e_1^*(k) \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} \Delta Q_{\mathrm{hg}}(k) \\ u_1^*(k) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -\frac{T_c}{A_s} \\ -\frac{T_c}{A_s} \end{bmatrix} \cdot [Q_{\mathrm{off-take1}}(k)],$$

$$\begin{aligned} &\Delta Q_{\mathrm{hg}}(k) \le \Delta Q_{\mathrm{hg,max}}(k) \\ &u_1^*(k) \ge h_{\min}(k) - h_{\mathrm{ref}} \\ &u_1^*(k) \le h_{\max}(k) - h_{\mathrm{ref}} \end{aligned} \tag{4}$$

where $Q_{\mathrm{hg}}(k)$, $Q_{\mathrm{hg}}(k-1)$, $Q_{\mathrm{hg}}(k-2)$, and $Q_{\mathrm{hg}}(k-3)$ are inflows of the reach at time step k to $k-3$ (the number of delay time steps in the first reach); e_1^* is the water level outside of the target band; e_1 is the deviation among h_1 and h_{ref}; and u^* is the computed signal according to van Overloop et al. (2008) given in the following equation:

$$u^*(k) = \begin{cases} e & h_{\min}(k) - h_{\mathrm{ref}} \le e \le h_{\max}(k) - h_{\mathrm{ref}} \\ h_{\max}(k) - h_{\mathrm{ref}} & e \ge h_{\max}(k) - h_{\mathrm{ref}} \\ h_{\min}(k) - h_{\mathrm{ref}} & e \le h_{\min}(k) - h_{\mathrm{ref}} \end{cases}. \tag{5}$$

Soft constraints are performed by utilizing the virtual input signal of its constraints, and the optimization process will try to maintain running the optimization when the hard constraint is violated (van Overloop 2006). The future sequence of the conditions and control variables was optimized over the future horizon in each time step by the objective function. A quadratic function for the MPC model in irrigation canals is defined in this study and can be solved with the quadratic programming function in MATLAB (Xu *et al.* 2011), which minimizes the subsequent performance criterion:

$$\text{Min } j = \sum_{i=0}^{n} [X^T(K) \cdot Q_e \cdot X(K) + U^T(K) \cdot R_{\Delta Q} \cdot U(K)] \tag{6}$$

where Q_e is the penalty matrix of the state variables, which consists of penalty weight on e and e^*; n is the step number of the prediction horizon; $R_{\Delta Q}$ is the penalty matrix on the control variables containing a penalty weight on ΔQ and u^*. Great penalties on water-level deviations from the target are included using high values for Q_{e^*}. Moreover, R_{u^*} (the virtual signal penalty) should have too low values. The penalties are adjusted to get a weighted compound of smooth control. Primitive weighting factors of water-level error (Q_e) and gate flow variations ($R_{\Delta Q}$) were chosen based on the maximum permissible value of the predicted factor (Xu *et al.* 2011). The maximum error of the water level is specified by the permitted ± 0.1 m bandwidth about the target band. The maximum gate flow variation at any time step is assumed to be 1 m^3/s. The final penalties are decided by trial and error and separately for the individual reaches. In other words, the reaches are penalized based on their own particular physical characteristics.

Economic model: PMP

The economic model of PMP, developed to calibrate agricultural supply simulations (Howitt 1995), assumes that the total net profit is maximizing. The model reproduces information from observed farming activities to specify a nonlinear objective function such that the ultimate nonlinear model accurately reproduces the observed farmers' behaviors. The standard method involves three stages.

Stage 1

This stage involves elaborating a linear planning model to maximize farmers' gross profit concerning resource constraints and calibration (land and labor, water volume, and other limitations). Furthermore, the economic values of production inputs and the shadow prices of calibration constraints are obtained in each agricultural unit. The mathematical form of this stage is given as follows (Howitt 1995):

$$\begin{aligned} &\text{Max GM} = \sum_{i=1}^{n} \{X_i[(P_i Y_i) + \text{SI}_i - \text{PW}_i W_i - \text{TC}_i)]\} \\ &\text{Subject to:} \\ &\textstyle\sum f_{ij} x_i \le b_j \quad \forall i, j \quad [\lambda] \\ &x_i \le x_0 + \varepsilon \quad \forall i \quad [\rho] \\ &x_i \ge 0 \quad \forall i \end{aligned} \tag{7}$$

where TC_i, W_i, PW_i, SI_i, P_i, and X_i refer to the area under cultivation, the crop price, the subsidiary incomes, the cost of using one unit of water, the amount of water consumed, and the mean total of the calculated costs of crop i in terms of a hectare, respectively, and f_{ij} denotes the technical coefficients of the sources used in the region. Moreover, the resource constraints in the region are shown in Equation (7). These constraints include water resources, land, machinery, labor, capital, pesticides, and chemical fertilizers. In this equation, b_j is the total inventory of resources in the region.

Similarly, the calibration limit of the model is presented. In Equation (7), the status of activity in the base year is shown by x_0, and ε refers to very few positive numbers included in the model to avoid linear dependencies and emergence of the zero-shadow price. λ and ρ represent the shadow price of system constraints and the calibration limit's shadow price. Equation (8) refers to a non-negative constraint for activities (Medellín-Azuara *et al.* 2010).

Stage 2

The information obtained in the first stage (the shadow prices and/or the economic values of production inputs and calibration constraints) is used to estimate the quadratic production function coefficients (vector a_{ij} and matrix q_{ikj} in Equation (8)) using the constant elasticity of substitution function (Howitt *et al.* 2012).

Stage 3

The quadratic production function estimated in the second stage is replaced in the linear objective function of the first stage, and along with its resource constraints (regardless of the calibration limitation), the function is exploited for simulation of the existing agricultural conditions and achieving an optimal set of inputs that maximize the gross income of farmers, as follows (Howitt *et al.* 2012):

$$\max \sum_{j=1}^{m}\left[p_j * \left(\sum_{i=1}^{n}\left[a_{ij} - \frac{1}{2}\sum_{k=1}^{n} q_{ijk}x_{ij}x_{kj}\right]x_{ij}\right) - \sum_{i=1}^{n} w_i x_{ij}\right]$$

subject to

$$\sum_{i=1}^{n} \mathrm{WC}_i x_i \le \mathrm{TW};\ \sum_{i=1}^{n} x_i \le \mathrm{TA};\ X_i \le M_i;\ \sum_{i=1}^{n} M_i X_i \le T_{\mathrm{m}}$$
$$\sum_{i=1}^{n} L_i X_i \le \mathrm{TL};\ \sum_{i=1}^{n} V_i x_i \le \mathrm{TK};\ \sum_{i=1}^{n} F_{if} X_i \le \mathrm{TF}_f;$$
$$\sum (X_i - X_{ii}) \le 0;\ x_{ij} \ge 0 \tag{8}$$

In this equation, WC_i is the amount of water consumed for each product ($\mathrm{m}^3\ \mathrm{ha}^{-1}$), TW is the total surface water (m^3), TA is the total cultivated area (ha), M_i is the area under cultivation due to market limitation (ha), M_i is the machinery ($\mathrm{h\,ha}^{-1}$), T_{m} is the total inventory of machinery in the region (h), L_i is the required labor force (n/day/ha), TL is the total available labor force (n/day), V_i is the cash costs per hectare of product i (monetary unit), TK is the total available cash investment (monetary unit), and f, F_{if}, and TF_f, respectively, represent the type, amount of consumption per hectare, and total available inputs of nitrogen and phosphorous fertilizers and chemical pesticides. Finally, X_i and X_{ii} represent the products that are grown alternately.

A comparison of the results obtained from executing the model in this stage for the levels and combination of agricultural activities with the observed levels of these activities in the base year provides a criterion of calibration and simulation. Consequently, the economic value of water (as a dual value of constraint), farmers' incomes, and an optimal planting density of the cropping pattern will be determined.

Preparing the preliminary data of the economic model

Data required for the calibration and preparation of the economic model of agricultural activities were collected through interviews and questionnaires. Data were obtained from farmers, the office of management and operation of the Roodasht Irrigation Network, and government agencies. All necessary data, including the volume and cost of agricultural inputs, were collected for all 26 agricultural units. Table 3 lists the consumption of agricultural inputs per hectare and the price of inputs per agricultural unit used in the economic modeling.

Table 4 shows the yield and the sales price of agricultural products collected from farmers for the fourth agricultural unit.

After preparing the necessary information, the economic simulation of agricultural activities was carried out for a water scarcity of 32% (the mean water scarcity adopted from the Roodasht Irrigation Network Office) to extract the most cost-effective water distribution strategy and delivery to the offtakes.

Operational performance indicator

The operational performance assessment criteria introduced by Molden & Gates (1990), given in Table 5, were used to examine water distribution and delivery to offtakes. Table 5 also shows the definition, formulation, and standard levels of performance indices.

Here, Q_D is the volume of water delivered to the offtake, Q_R is the required discharge to the offtake in the time horizon T at the point R, and CV_R and CV_T, respectively, show the statistical parameters of spatial and time variations for the ratio Q_D/Q_R. P_A and P_F, respectively, represent Q_D/Q_R and Q_R/Q_D. If P_A and P_F are more significant than 1, their value is considered to be 1.

Operational test scenarios

Subject to the water shortage periods, in drought conditions, that induce inefficient performance on irrigation network operations and create the inflow fluctuations from the canal's headgate, this part only attempts to assess the functioning of suggested improvement operational options in fluctuating flow conditions. Indeed, to investigate the water's capability to deliver to sluices adequately through the main canal operation methods, two operational scenarios were included: first, Normal Condition Operation (NCO) and, second, Inflow Fluctuations of Upstream (IFU)'s headgate.

The normal scenario is arranged to show the conventional daily operation in the RNB main canal, given that data (Figure 3(a)) have been collected from the Roodasht

Table 3 | Statistics and information on agricultural input

		Land	Phosphate	Potassium	Urea	Manure	Poison	Job	Machinery	Water use
Wheat	Magnitude	921 ha	100 kg ha^{-1}	50 kg ha^{-1}	250 kg ha^{-1}	0 kg ha^{-1}	2 L ha^{-1}	9 one-day	22 h	11,180 m^3 ha^{-1}
	Cost (unit^{-1})	125 USD	0.36 USD	0.39 USD	0.25 USD	0.2 USD	27.5 USD	17.8 USD	16.1 USD	0.02 USD
Barley	Magnitude	176 ha	100 kg ha^{-1}	37 kg ha^{-1}	250 kg ha^{-1}	0 kg ha^{-1}	1 L ha^{-1}	6 one-day	16 h	8,952 m^3 ha^{-1}
	Cost (unit^{-1})	107.15 USD	0.36 USD	0.39 USD	0.25 USD	0.2 USD	27.5 USD	17.8 USD	16.1 USD	0.02 USD
Alfalfa	Magnitude	97 ha	150 kg ha^{-1}	150 kg ha^{-1}	50 kg ha^{-1}	0 kg ha^{-1}	5 L ha^{-1}	20 one-day	28 h	19,169 m^3 ha^{-1}
	Cost (unit^{-1})	142.86 USD	0.36 USD	0.39 USD	0.25 USD	0.2 USD	6.4 USD	17.8 USD	16.1 USD	0.02 USD
Safflower	Magnitude	71 ha	100 kg ha^{-1}	0 kg ha^{-1}	200 kg ha^{-1}	0 kg ha^{-1}	5 L ha^{-1}	7 one-day	10 h	16,596 m^3 ha^{-1}
	Cost (unit^{-1})	142.86 USD	0.36 USD	0.39 USD	0.25 USD	0.2 USD	10.7 USD	17.8 USD	16.1 USD	0.02 USD
Sugar beet	Magnitude	22 ha	200 kg ha^{-1}	0 kg ha^{-1}	300 kg ha^{-1}	425 kg ha^{-1}	6 L ha^{-1}	53 one-day	38 h	19,601 m^3 ha^{-1}
	Cost (unit^{-1})	214.29 USD	0.36 USD	0.39 USD	0.25 USD	0.2 USD	26.8 USD	17.8 USD	16.1 USD	0.02 USD

Note: Based on the official price of the US dollar, announced by the Central Bank of Iran in 2015.

Table 4 | Selected values from the information on the economic model of Unit 4

Production	Yield (ton ha^{-1})	Sale price (USD kg^{-1})
Wheat	4.41	0.41
Barley	4.21	0.33
Alfalfa	11.64	0.18
Safflower	1.94	0.77
Sugar beet	44.23	0.1

operational office. Accordingly, the average, minimum, and maximum inflow fluctuations of the canal's headgate, respectively, are 43, 19, and 70%. Furthermore, the most reduced amount of discharge, which is 38% reduction, had reached 1.7 CMS. It is noticeable that all the demands of RNB agriculture units total 2.78 CMS.

The IFU scenario, as shown in Figure 3(b) for 20 h of modeling, pertaining to 75% flow reduction, has reached even lower than 1 CMS.

RESULTS

Water distribution and delivery along the main canal were simulated and compared with the Current Operational Method of Roodasht (COMR), employing the developed MPC. Besides, the agricultural activities of farmers in 26 agricultural units were simulated through economic modeling. The performance of the operational-economic strategy in improving water distribution and delivery to offtakes was also evaluated.

Operational performance indicator results

The ICSS hydrodynamic model was used for COMR and MPC simulation under NCO and IFU scenarios. The four performance indices for both operation scenarios were calculated. The color spectrum in Figure 4, for both operational scenarios shows the adequacy of water delivery to offtakes under the NCO scenario. As shown in Figure 4(a), COMR fails to supply the water required under normal operating conditions. The farmers living downstream, midstream, and upstream of the canal received 88, 82, and 72% of their water requirement on average. According to the standards in Table 5, water supply to these offtakes is evaluated as good, fairly good, and poor, respectively,

Table 5 | Operational performance assessment criteria (Molden & Gates 1990)

Index	Description	Equation	Ranges
Adequacy	Water delivered relative to the total water requirement	$A_d = \frac{1}{T}\sum_T\left[\frac{1}{R}\sum_R P_A\right]$	1–0.9 good 0.89–0.8 fair <0.8 poor
Efficiency	Excess water delivered relative to a specific water requirement	$A_f = \frac{1}{T}\sum_T\left[\frac{1}{R}\sum_R P_F\right]$	1–0.85 good 0.84–0.7 fair <0.7 poor
Equity	The uniformity of supplying water requirement in canal intervals	$A_e = \frac{1}{T}\sum_T \mathrm{CV}_R\left(\frac{Q_D}{Q_R}\right)$	0–0.1 good 0.11–0.25 fair >0.25 poor
Dependability	The uniformity of supplying water requirement of the offtake within a given time interval	$A_p = \frac{1}{R}\sum_R \mathrm{CV}_T\left(\frac{Q_D}{Q_R}\right)$	0–0.1 good 0.11–0.2 fair >0.2 poor

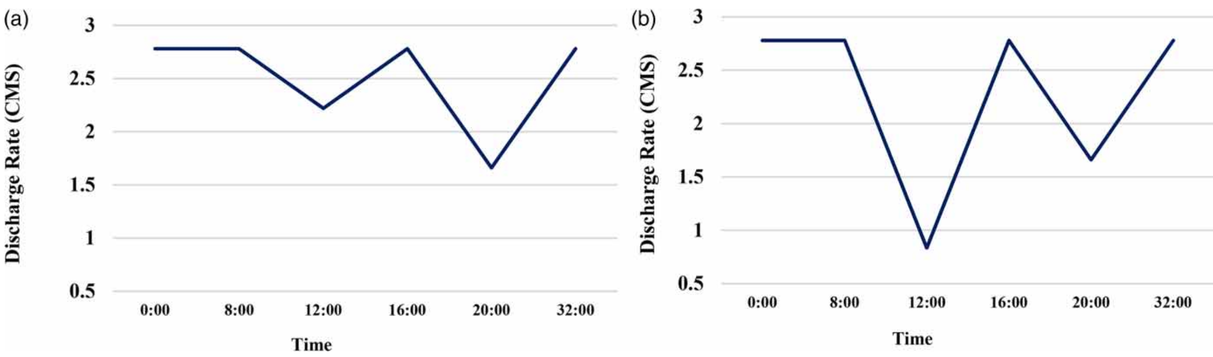

Figure 3 | (a) Normal operation scenario diagram. (b) Fluctuation scenario diagram.

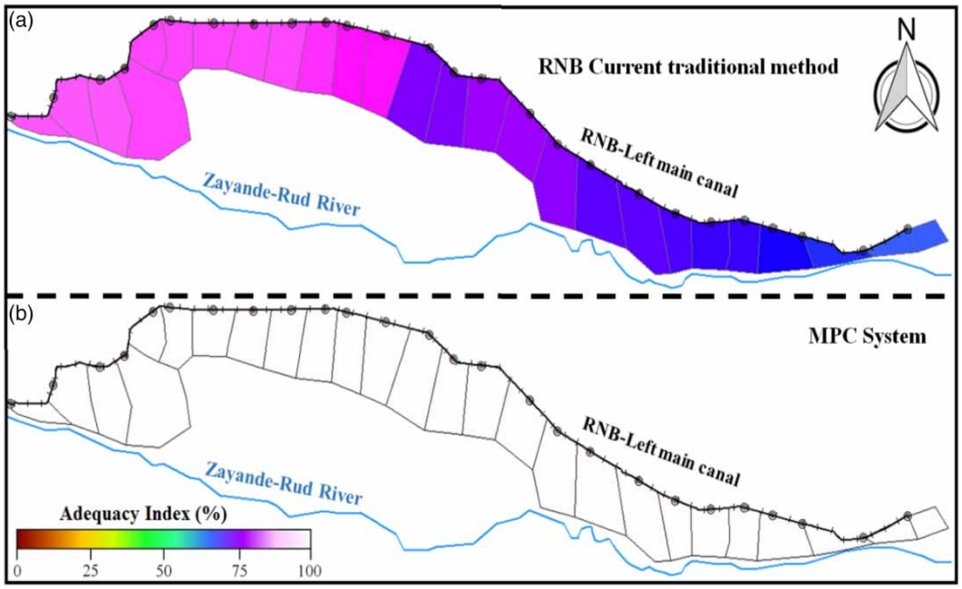

Figure 4 | Adequacy index results in NCO in methods of (a) COMR and (b) MPC. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/hydro.2021.008

indicating the inefficiency of duck-bill water regulating structures in desired water delivery to the cultivated areas. The performance of the MPC intelligent system (Figure 4(b)) under the NCO scenario indicated maximum improvement in water distribution and delivery to offtakes. In other words, all agricultural units were able to receive 100% water requirement through the MPC system.

As shown in Figure 5(a), COMR cannot deliver water to offtakes adequately in the IFU scenario and fails to supply even more than 50% of the water requirement of the downstream and midstream offtakes of the main canal. Moreover, the water delivered to the farmers upstream of the canal met only 70% of their requirements. Fluctuations of inflow to the canal headgate exacerbate water distribution when compared with normal operation. Table 5 shows the poor water distribution by COMR. However, based on Figure 5(b), the MPC system has been able to meet the water requirement of all agricultural units by overcoming the inflow fluctuations. As a result, the downstream and midstream offtakes of the main canal, which were suffering from water scarcity in existing operating conditions, could receive their water requirements. Thus, the water delivery by MPC increased by 85% when compared with COMR.

Table 6 shows the efficiency assessment index for the COMR and MPC systems under the NCO scenario. As shown, the water delivery efficiency of COMR for the upstream offtakes is 93% on average. Moreover, the performance of relevant farming units is affected by the average 7% extra delivery to the upstream offtakes caused by NCO fluctuations. The efficiency of the midstream and downstream offtakes is at their highest without any extra delivery. According to Molden & Gates (1990) standards in Table 5, COMR shows a reasonable water delivery efficiency. However, according to the results in Table 6, under the NCO scenario, the MPC system can deliver water to all offtakes without excess water (100% efficiency), which means a 7% improvement in efficiency compared with COMR for the upstream offtakes.

By increasing inflow fluctuations in the IFU scenario, the excess water delivered to the upstream and midstream offtakes by COMR is increased, consequently reducing water delivery efficiency to the aforementioned agricultural units compared with NCO. The average water delivery efficiency for the upstream and midstream offtakes is 90%, indicating water delivery's good efficiency to offtakes according to the standards in Table 5. In other words, the efficiency of water delivery to the downstream offtakes is 100%. The duck-bill overflow control structures in the RNB canal cause a hydraulic discontinuity between the upstream and downstream flows, reducing fluctuations transferred to the downstream. However, the MPC system with an average improvement of 12% can eliminate the effect of water fluctuations in the delivery of excess water to the offtakes so that all offtakes show an efficiency of 100%. The vertical motion of automatic gates

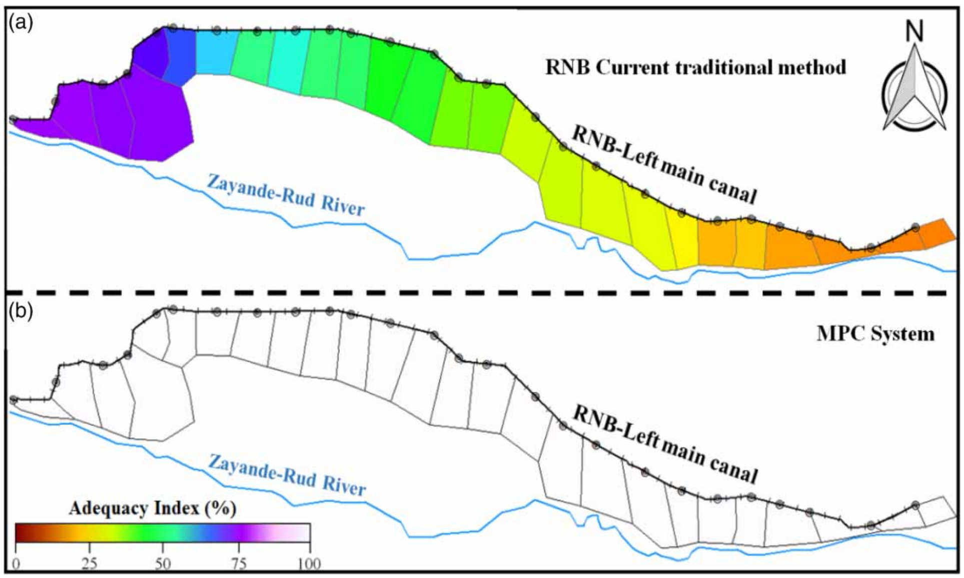

Figure 5 | Adequacy index results in IFU in methods of (a) COMR and (b) MPC.

Table 6 | Results of water delivery efficiency index for operational methods

	Operational scenarios					Operational scenarios			
	NCO		IFU			NCO		IFU	
Offtake number	COMR	MPC	COMR	MPC	Offtake number	COMR	MPC	COMR	MPC
1	92	100	89	100	14	100	100	90	100
2	92	100	89	100	15	100	100	100	100
3	95	100	89	100	16	100	100	100	100
4	96	100	90	100	17	100	100	100	100
5	87	100	84	100	18	100	100	100	100
6	90	100	85	100	19	100	100	100	100
7	92	100	87	100	20	100	100	100	100
8	99	100	90	100	21	100	100	100	100
9	97	100	90	100	22	100	100	100	100
10	99	100	90	100	23	100	100	100	100
11	99	100	90	100	24	100	100	100	100
12	100	100	90	100	25	100	100	100	100
13	100	100	90	100	26	100	100	100	100

allows the adjustment structure to reduce fluctuations and surface waves in the case of a fluctuating water surface, eventually leading to an increase in the efficiency of water delivery to agricultural units.

Figure 6(a) shows the dependability and uniformity of water delivery and distribution by COMR under the NCO scenario with a color spectrum. The average dependability index for water delivery to upstream, midstream, and downstream offtakes was 22, 26, and 31%, respectively. According to the standards in Table 5, all offtakes are evaluated as poor regarding dependability during water delivery. The inefficiency of COMR in uniform water delivery to offtakes, particularly to the downstream ones, can be related to fluctuations in the inflow from the canal headgate leading to a low dependability index for the offtakes.

According to Figure 6(b), the MPC system with uniform water delivery to all 26 units during simulation led to a 100% dependability index for all the offtakes. The mean improvement in the dependability index of the MPC system under the NCO scenario was 27%, while this index was obtained as 31% for the downstream offtakes. However, the average COMR dependability index under the IFU scenario for the downstream and upstream offtakes of the main canal was, respectively, 42 and 38%, as shown in Figure 7(a). However, Figure 7(b) shows the MPC system's good performance in uniform delivery of maximum water to the offtakes.

The equity index was also investigated for water distribution. According to the equity index in Table 7, the MPC system shows the highest index value in both operation scenarios because all offtakes have received the same volume of water (Figures 4 and 5). The COMR system, however, shows a non-uniform heterogeneous performance in supplying the water requirements of offtakes. According to Molden & Gates (1990) standards, the NCO and IFU scenarios' distribution equity index was measured as fair and poor, respectively.

The improvement in the operating conditions of the Roodasht irrigation network by the MPC system was confirmed from four different aspects (four indices of Molden & Gates 1990). The results indicated a reduction in operating losses and flow fluctuations by implementing automated water delivery and distribution as the alternative approach.

Simulation results of applying the operational-economic strategy

By developing a mathematical model, farmers' economic activities in 26 agricultural units were calibrated and

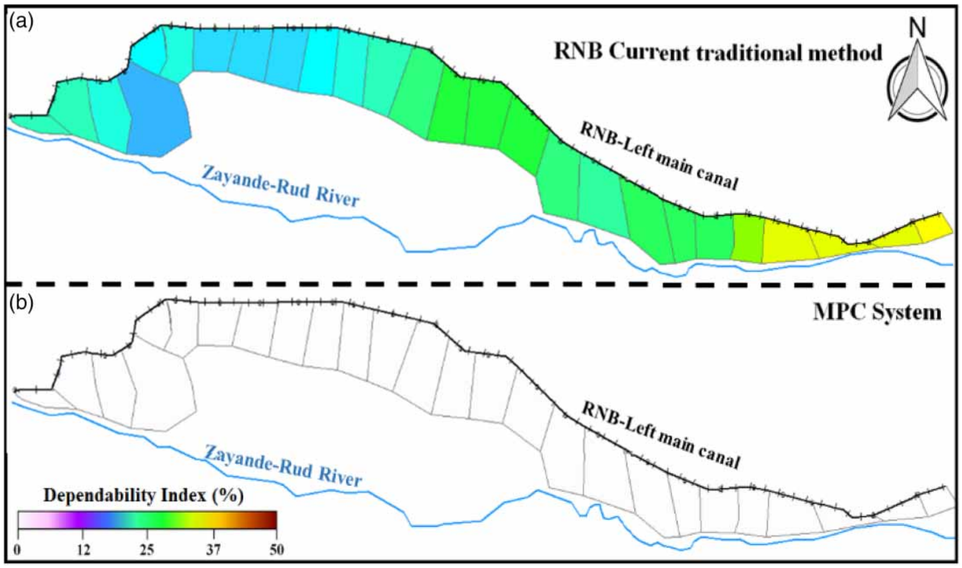

Figure 6 | Dependability index results in NCO in methods of (a) COMR and (b) MPC. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.10.2166/hydro.2021.008

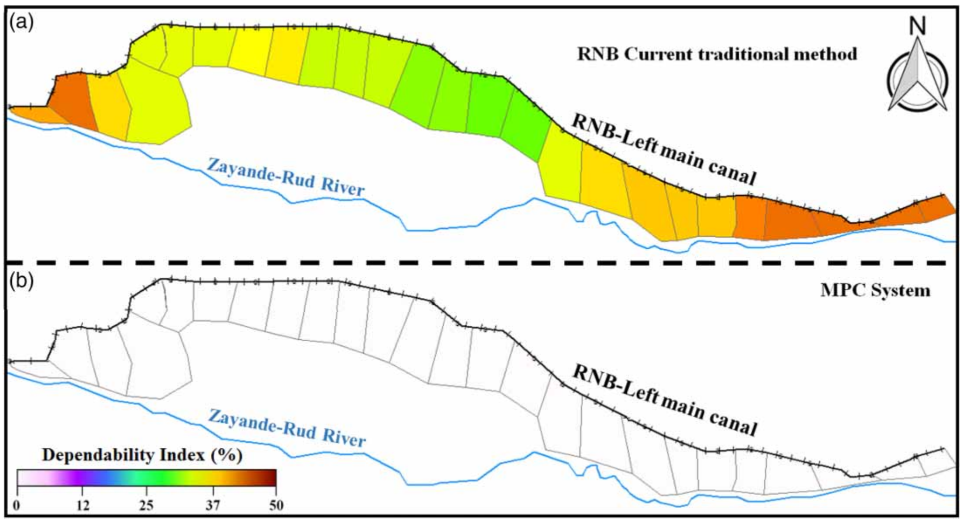

Figure 7 | Dependability index results in IFU in the methods of (a) COMR and (b) MPC.

Table 7 | Equity index percentage of operational methods

	Operational methods	
Operational scenarios	**COMR**	**MPC**
NCO	13.21	0
IFU	39.23	0

simulated. All calculations were carried out by GAMS optimization programming. By reproducing farmers' agricultural activities under water scarcity conditions, the PMP economic model calculated the cost, revenues, profit, and, most importantly, the economic value of water for all 26 agricultural units. Water's economic value is estimated as the marginal value product of water from the calibrated profit maximization program.

The average economic value of water in the Roodasht irrigation network under water scarcity is 0.039 USD m^{-3} with the maximum value of 0.046 USD m^{-3} for sugar beet in the fourth unit – the economic value of water changes in the entire network by 9.2%. The high-value products were cultivated in 34% of the entire network, equivalent to 4,620 ha.

The operational-economic strategy can be used under water scarcity conditions by determining the economic value of water for crops and water distribution and delivery systems in the RNB irrigation network. The results are presented in the form of two main operation scenarios, namely Automated Operation-Economic (AOE) and Traditional Operation-Economic (TOE), with two sub-scenarios of Automated Operation-Fair (AOF) and Traditional Operation-Fair (TOF). In both sub-scenarios, the water volume available for distribution is equal to that distributed in the main scenario. However, the sub-scenarios lack an economic approach, so that water shortages are divided fairly and equally among offtakes. The operation scenarios mentioned above affect the performance of the water distribution network, leading to the irrigation of different cultivated areas. Figure 8 shows the area under cultivation and uncultivated areas due to water scarcity.

Accordingly, the total capacity of the network is 13,709 ha under base conditions. The occurrence of water scarcity from the canal headgate in the TOF scenario will cause an 18% reduction (2,497 ha) in the cultivation area. However, AOE maintains 93% of the cultivation area than the existing RNB operation scenario, which is equal to an improvement of 11%. The economic approach used in the present study significantly affects the two sub-scenarios (lacking an economic approach), such that AOF and TOF were able to irrigate 92 and 82% of the total network capacity, respectively.

In the AOE scenario, 37% of water shortage was allocated to high-value plants. According to Table 8, the volume of water distributed among offtakes and water scarcity in the network are comparable in the main operation scenarios (note that the total volumes of consumed water and water shortage are equal in each main operation scenario and its corresponding sub-scenario).

Table 8 | Water distribution features in main operational scenarios

	Operational scenarios		
Features	**AOE**	**TOE**	**COMR (base state)**
Operation circumstance	Water scarcity condition	Water scarcity condition	Normal condition
Delivered water to headgate of the network (m^3)	104,319,013	88,018,198	129,438,526
Volume of water loss (m^3)	7,102,943	19,215,781	28,258,501
Percentage of water loss	7	32	32
Water saving amount (m^3)	50,961,123	28,130,473	–
Volume of lacking water in the network (m^3)	7,102,942	71,446,697	71,494,187
Percentage of lacking water in the network	7	54	45

According to Table 8, AOE has been able to meet 93% of the water requirement of agricultural units under water scarcity conditions. In other words, it has been able to overcome water scarcity in the region. At the same time, TOF supplied about 50% of the water requirement of agricultural units under water scarcity conditions using the RNB water distribution system. In the meantime, the losses in the operation scenarios will justify their performance. Figure 8 shows the volume of water delivered per hectare for different scenarios. This figure shows the effect of automation and economical approach on water distribution in different scenarios.

AOE reduces the volume of water consumed per hectare by 27%. Figure 9 shows the improvement of water distribution using an economic approach. The implementation

Figure 8 | Planted and unplanted areas in operational scenarios.

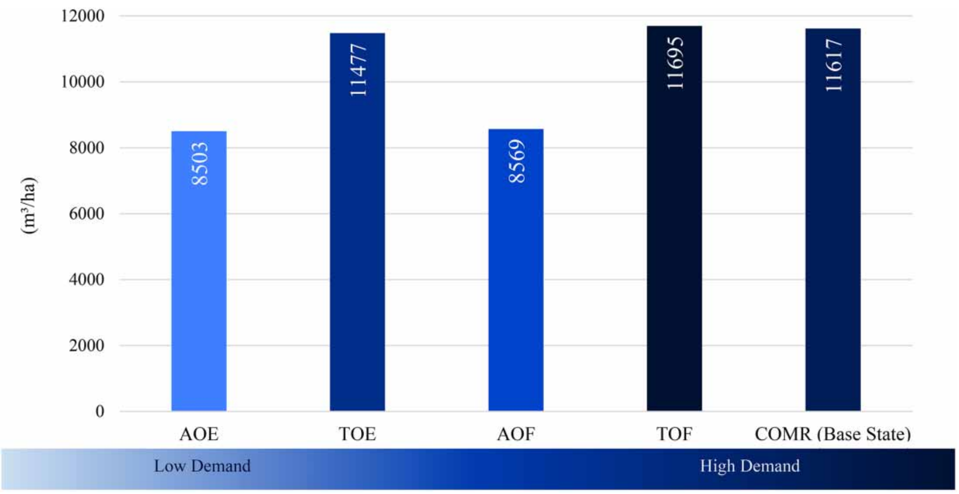

Figure 9 | Water demand per hectare in operational scenarios.

of the main scenarios and their respective sub-scenarios affects the performance (yield) of agricultural units in various agricultural products. Figure 10 shows the cultivation area of each crop under different operation scenarios.

In all scenarios, a large volume of water in the irrigation network is consumed by wheat. Through integrated AOE strategy management, the water distribution system directed most water shortages to wheat-cultivated areas, leading to the distribution of 3% water shortage among other products when compared with AOF. In the TOE scenario, the most considerable water shortage affected wheat-cultivated areas. Compared with TOF in which water shortage is divided equally between offtakes, 61% of the network is under wheat cultivation in TOE. An inverse pattern is observed for alfalfa-cultivated areas in the TOF scenario, where a 2% increase is obtained compared with TOE. Water shortage distribution in economic scenarios favors high-value units, as shown in Figure 11. The sugar beet-cultivated area (with the highest economic value of water) decreased by a maximum of 0.02%.

Applying different scenarios for the distribution of water among the main RNB canal's offtakes led to different economic outcomes like revenues and costs. Figure 11 shows the revenues, costs, and net profits of various scenarios.

The changes in the cultivation area caused by the implementation of different operation scenarios result in a difference in revenues, costs, and the network's net profit. Figure 11 shows the optimal management of AOE under water scarcity conditions to increase the network's net profit. Despite $9.93 million for the AOE operation

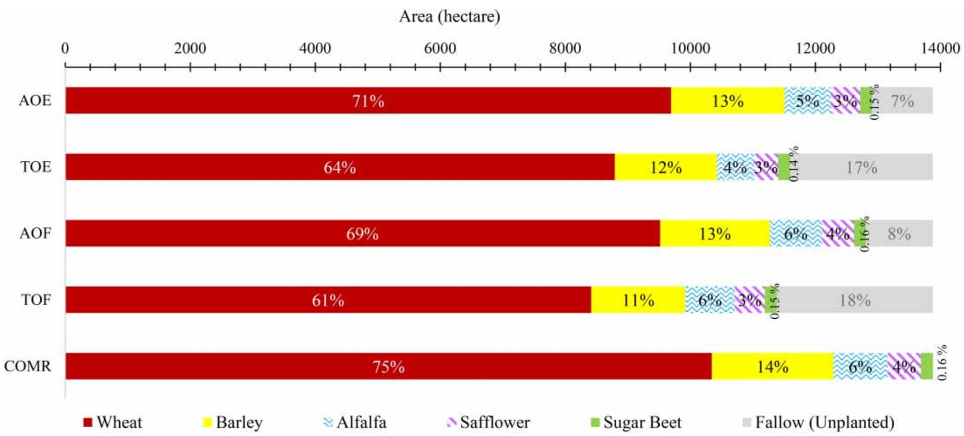

Figure 10 | Crop pattern in different operational scenarios.

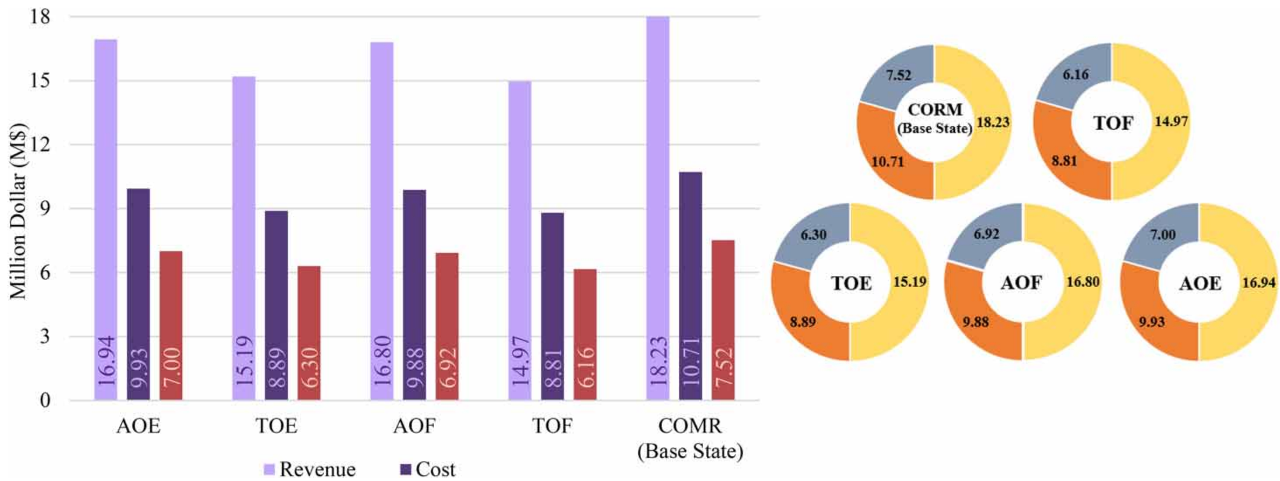

Figure 11 | Whole revenue, cost, and profit of performing different operational scenarios.

method, which is about $1 million higher than that of the TOE, the $7 million net profit of AOE indicates this scenario's superiority compared with others concerning profitability. Besides, a revenue difference of $140,000 and a net profit difference of $50,000 with the AOF show the positive impact of this strategy. The profit from equipping TOE with the economic model equals $140,000. Considering TOF as the base scenario under water scarcity conditions, the percentage of increase in revenues, cost, and the net profit of the automated control systems or those equipped with an economic model can be calculated as shown in Table 9.

The results in Table 9 indicate the ability of automated operation scenarios in increasing income and network profits. The superiority of the net profit per hectare in TOE relative to AOE is due to the difference in the total cultivation area in the two methods, lower for the TOE. The financial losses due to each scenario's reduced cultivation area are given in the last row of Table 9. Accordingly, AOE was able to maintain the net profit at the highest possible level. By improving water supply to agricultural units, AOE reduced the financial losses caused by water scarcity and also the cultivation area to $197,162 compared with TOF.

DISCUSSION

The automated (MPC) and economic (PMP) operation components were combined to maximize the network's net profit in the event of unbalanced water demand and supply. The results of economic effects are shown in Figure 11 and Table 9. The operation scenarios with an

Table 9 | Amount of income, cost, and profit per hectare and their percentage changes

	Operational scenarios				
Features	**AOE**	**TOE**	**AOF**	**TOF**	**COMR (base state)**
Incomes per hectare (USD ha^{-1})	1,329.84	1,329.73	1,329.63	1,334.74	1,330.05
Percentage of increasing net revenue	13	2	12	–	–
Cost per hectare (USD ha^{-1})	779.90	778.06	781.68	785.45	781.43
Percentage of increasing net costs (%)	13%	1%	12%	–	–
Profit per hectare (USD ha^{-1})	549.94	551.68	547.95	549.29	548.62
Percentage of increasing net profit	14	2	12	–	–
Financial loss of water scarcity (USD)	1,296,741.15	3,041,425.02	1,403,059.31	3,268,363.27	No scarcity

economic approach outperformed those without such an approach under similar conditions. Compared with automated operation as a modern alternative, this caused a slight increase in the net profit. It is noteworthy that the study area's dimensions affect the net profit of the network, which is of great importance in large-scale areas like the basin in this study.

In the studied network, COMR could not supply the water requirement of agricultural units under normal and fluctuating conditions. The simulation results for COMR are displayed in Figures 4 and 5. Therefore, the AOE strategy was considered an alternative to reducing water delivery and distribution losses and managing water scarcity. For better understanding, Figure 12 shows the AOE adequacy index in supplying offtakes' water needs.

As shown in Figure 12, high-value units (including the first, fifth, and sixth units) received the least water shortage, while low economic units like the nineteenth unit received the highest water shortage.

The most essential factor in overcoming water scarcity in AOE is to reduce water delivery and distribution losses (42 million cubic meters) to offtakes. Furthermore, in-line storage, multi-objective function, and the ability to change irrigation planning by the MPC system also affected the water requirement of agricultural units. By modifying the cultivation pattern, management of water scarcity, and distribution of water shortage among agricultural units using the economic component (PMP) of the AOE method, efforts were made to increase the revenues and, ultimately, farmers' net profit. The use of this strategy increased farmers' revenues up to $2 million when compared with the existing conditions, which distinguishes the AOE operation scenario from other alternatives. An 11% increase in the cultivation area is essential, considering the importance of food security.

Other scenarios were designed to understand better the impact of both automated water delivery and distribution and economic component concerning financial aspects, the volume of consumed water, and cultivation area. The importance of both automated and economic components was identified individually. For example, automated operation increased the cultivation area by 10%. An economic approach in the operation scenario, on the other hand, increased the cultivation area by 1%. Thus, an increase of 1.3% ($0.9 million) in the net profit by AOE compared with existing operating conditions (TOF) under water scarcity conditions can be justified. It should be noted that 84% ($0.76 million) of increased profit is due to automation and the rest (16% equals to $0.14 million) is due to the economic component of the COMR.

The advantages of such plans can be shown by evaluating and comparing the efficiency of traditional operation methods with modern delivery and distribution methods from different economic and operational aspects and the development of various operational-economic scenarios that are not seen in similar studies (Hashemy Shahdany *et al.* 2016b). Most studies have been conducted on large-scale areas such as basins. However, this study focuses on an irrigation network with direct contact with the final consumer. Perhaps, this is the connecting loop between macro and field research works because interconnected management of water resources, and water distribution and delivery to the second- and third-degree units, in fact, connect macro- and micromanagement.

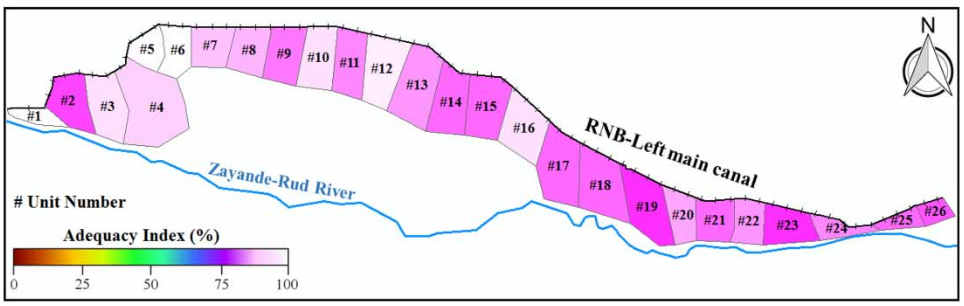

Figure 12 | Adequacy index results of automated operational-economic scenario in water shortage.

CONCLUSION

The evaluation of the RNB water network (as a case study) distribution and delivery system indicated the inefficiency of this system in meeting the water requirements of cultivated areas under normal and fluctuating inflow conditions. Water delivery to offtakes, particularly to downstream ones, will be exacerbated under water scarcity conditions. For this reason, the MPC automated system for increasing flexibility in water distribution and delivery and the PMP economic model for determining the distribution of water shortages were combined according to the economic value of water to maximize the net profit of farmers under water scarcity conditions. Accordingly, four operating management scenarios were developed. Automated operation scenarios led to a significant reduction of operational loss compared with conventional methods (COMR). This critical factor reduced the impact of water scarcity on canal operations. Compared with traditional TOE and TOF operation methods, the cultivation area experienced a smaller decrease in the AOE and AOF methods. As a result, the cultivation area, revenues, and net profit obtained from derived AOE and AOF were found to be higher than TOE and TOF. Comparing the performance of scenarios indicated the significant impact of the economic approach. Water shortage management with an economical approach for maximizing network profit led to an improvement in farmer's livelihood through the irrigation network operating system. Even though the current study concentrated on irrigation scale, watershed (low resolution) and tertiary agricultural region (high resolution) could also be considered as fit for investigation. Moreover, different variables, such as groundwater sources, area, or other input limitations depending on the region's potentials, could be regarded for developing models. Likewise, implementing such effective plans for the operation of irrigation networks to reduce water delivery and distribution losses and increase farmers' profit is a suitable solution for dealing with drought and migration from rural areas to cities. This is why modern operation strategies based on economic principles provide opportunities for sustainable development and increased food security, increase the economic efficiency of water, and reduce operational losses.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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