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Reducing Carbon Emission, Groundwater Over-Exploitation and Energy Consumption on Agricultural Lands by Off-Farm Water Management Practices: Modernization of Surface Water Distribution Systems

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ABSTRACT. A wide range of endeavors has been made to propose various approaches to reduce Greenhouse gas emissions in the agricultural sector. The present study investigates the impacts of Surface Water Distribution Systems (SWDS) modernization in reducing groundwater overexploitation, energy consumption, and carbon emission in the agriculture sector. Four modernization alternatives, including an improved manual-based system (A1, A2), off-line, and real-time automatic control systems (A3, A4), are developed and tested on a real test case in Central Iran, which is confronted with severe water shortages. The results reveal that SWDS's operating system modernization improves 4 ~ 21% surface water distribution through the alternatives A1 ~ A4. This surface water distribution enhancement led to groundwater over-extraction reduction. Spatial analysis reveals that 0.075, 0.100, 0.281, and 0.470 of the irrigation district's cultivated area was thoroughly fulfilled by the delivered surface water and no need for groundwater extraction due to alternatives A1 ~ A4, respectively. Closure of several active tubewells up to 1,668 semi-deep and 497 deep tube-well were verified. SWDS' modernization led to 5, 7, 20, and 30% of energy consumption and consequently 1,864.90, 2,714.33, 8,427.19, and 12,674.32 tC ha^{-1} carbon emission reduction in alternatives A1 ~ A4, respectively. This study's results show that modernization of off-farm operating systems – responsible for surface water conveyance and distribution from a dam reservoir to farms – resulted in significant environmental benefits through improving the reliability of systems supplied by surface water and reducing the tendency of the farmers to groundwater resources.

Keywords: carbon emission reduction, agricultural water distribution systems, groundwater overexploitation, modernization, automation, sustainable agriculture

1. Introduction

Ever-increasing Greenhouse gas (GHG) emissions are among the factors contributing to climate change resulting in a rapid increase in the earth's average surface temperature over the past century, which anthropogenic GHG release represents more than 90% of the global emissions (Wang et al., 2014; Chami et al., 2019). The agricultural sector is the world's second-largest emitter after the energy sector, and the primary source in developing nations (Qiao et al., 2019) as far as approximately 10% of total annual GHG emissions of the world (about 5.8 Gt CO$_2$) are released into the atmosphere due to human agricultural practices (WRI, 2020). Moreover, it is projected that over the following decades, GHG emissions from agriculture will increase tremendously, especially in Asia, Latin America, and Africa, due to the increasing demand for food and agricultural products (FAO, 2017; Ritchie et al., 2020). In this regard execution of various activities in the agricultural sector can play an essential role in mitigating GHG emissions.

Many types of researches have been conducted to investigate the impacts of different factors resulting in reducing anthropogenic GHG in the agricultural sector in different regions, including water management (water supply activities (i.e., water supply sources (Martin-Gorriz, 2014); water distribution through the on-farm systems (i.e., pressurized irrigation systems (Wang et al., 2015)), Soil management (i.e., soil Characteristics (Ogle, 2019)), tillage management (Necpalova et al., 2018), fertilizer management (i.e., increasing the productivity of fertilizers (i.e., Lam et al., 2017), improving fertilizers storing manner (Riaño and García-González, 2015), farming method (i.e., Organic farming (Venkat, 2012; Skinner et al., 2019); formulating policies (i.e., Dou, 2018; Solazzo et al., 2016), food managemant (i.e., Dietary Change (Aleksandrowicz, 2016)) and food loss (Heller, 2014)), energy management (i.e., Camargo et al. 2013; Elsoragaby et al., 2019), optimal use of resources (i.e., fukushima, 2009; Maraseni et al., 2020).

Reviewing the literature reveals that the studies to reduce GHG emissions in the agriculture sector targeted i) optimizing the energy consumption due to upgrading the irrigation systems

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at the farm scales and ii) enhancing the cultivation practices and fertilizers and pesticide management on on-farm scales. However, regarding the first category, it needs to declare that any improvement in on-farm water-energy resources management will be fulfilled if an integrated managerial approach includes both the on- and off-farm measures. The research gap in this field is a lack of investigation into off-farm water systems – including the conveyance, distribution, and delivery systems – operational performance appraisal, renovation, revitalization, and modernization. As Burt (2013) highlighted, many challenges facing the irrigation modernization projects originated from an overemphasis on the on-farm water management scale and a lack of an integrated on- and off-farm water management perspective.

Surface Water Distribution Systems (SWDS) are interconnected open canals and pipes responsible for carrying water. A set of flow measuring structures, water level control structures, and off-take structures are responsible for conveying, distributing, and delivering water from the primary source (in most cases, storage dams) to the farms. A review of previous studies on performance assessment of SWDS implies poor, unexpected, and non-satisfactory achievements in optimal water distribution (Mdemu et al., 2017). In many developing countries, the unreliable performance of SWDS resulted in an increasing dependence on groundwater resources within the district due to inadequate and unfair surface water distribution (Burt, 2013; Shahdany et al., 2018; Singh, 2014). For instance, a recent SWDS operational performance appraisal study showed that total water losses in one of the strategic irrigation districts in central Iran was about 200%, means that the diverted flow from the river was three times bigger than that of the total crops water demand.

These unreliable surface operating systems lead to groundwater resources pumping for irrigation purposes which is one of the most energy-consuming on-farm processes (Wang et al., 2012). Groundwater extraction from deep tube wells, with an average depth of 100 m scattered through the irrigated units, requires at least 28.5 MWh energy consumption, which increases expenses and GHG emissions (PISDES, 2002; Maraseni et al., 2010). Li and Zhang (2017) found that CO_2 emissions from groundwater extraction in China represent 65 to 88% of emissions from agricultural irrigation. This amount in the Middle East has increased by almost 450% since 1980, from 33.1 million metric tons per year to 146.8 million metric tons in 2008 (CDIAC, 2009). Therefore, the operational performance of SWDS is indirectly related to the amount of water extracted from the tube wells within the district, and the carbon dioxide reduction is related to the energy consumption for the groundwater abstraction.Automated operation schemes – employing centralized automatic control systems (CACS) – are compelling for SWDS operating systems' renovation and modernization (Horvath et al., 2015). These intelligent systems (i.e., CACS) enable the decision-makers to implement different managerial objectives and administrative strategies including on-demand agricultural water distribution (van Overloop, 2006), off-line reservoirs and in-line water-storing strategies (Hashemy and van Overloop, 2013), local and regional water market platforms (Hashemy Shahdany et al., 2017), and conjunctive operation of surface water and groundwater (Ibrakhimov et al., 2018). However, the literature shows that the impact of SWDS modernization (as an off-farm activity) on mitigating the GHG emissions in irrigation districts has not been investigated yet.

The present study investigates the potential impacts of four practical alternatives to improve the operational performance of SWDS as a central component of off-farm agricultural water management and the consequent reduction of environmental degradation aspects. The proposed alternatives include a vast range of operational methods, including enhanced manual operating systems (predictable inflow fluctuations (A1) and on rotation water delivery (A2)), Mobile-Canal Control Method (A3), and Centralized Model Predictive Controller (CMPC) (A4). The former approach is considered for countries where the implementation of automatic systems faces different obstacles due to social and economic considerations (Lozano et al., 2010). Although the proposed operational alternatives in this study were selected based on practical priorities, successful implementation of each requires considering various uncertainties. The district's inflow, delivered water to the irrigated subunits, demanded irrigation water, and water losses along the main canal are the variables confronted with different known/unknown sources of uncertainty.

Accordingly, the novelties of this study are: i) proposing an integrated technical-environmental appraisal framework to evaluate the potential alternatives that can be employed in irrigation modernization projects; and ii) investigating the effects of the modernization alternatives in mitigating environmental degradation – such as groundwater overexploitation, energy consumption, and carbon emission – in agriculture regions. The MDSGR index introduced in the present study for the first time – inspired by the MDWL index in Zhao et al. (2018) – systematically distinct the farms irrigated by the surface water resource and groundwater. This index operates because the groundwater withdrawal reduction (due to implementing modernization projects) must be compensated by the efficient distribution of the surface water. Accordingly, the MDSGR was calculated for each SIU (Secondary Irrigated Units, each including a hundred farms) and presented the results in Section 4.3.1. It is worth nothing that the MDSGR we estimated is calculated based on the computed "surface water adequacy indicator" by the hydrodynamic simulation model of ICSS (Irrigation Conveyance System Simulation) for each SIU to see the spatial difference of the indicator. The calculated "surface water adequacy indicator" and the MDSGR index values are inputs of the ArcGIS, and the "spatial maps" are the outputs created by ArcGIS's IDW tool.

The irrigation districts across the globe are supplied by the surface, groundwater, and reclaimed wastewater. Therefore, the framework and the alternatives developed in the present study can be employed for any irrigation district around the globe which is supplied by surface water resources. The main objecttives are:

- To design, calibrate and test the hydrodynamic simulation model of the status quo (A0) and Alternatives (A1 ~ A4) with the ICSS model.
- To quantify the reduction in groundwater abstraction (MDSGR method), energy consumption (selected formula), and

Steps	Input Data	Sources
Hydrodynamic Modeling	Main canal inflow Delivery discharge to each off-take Main canal inflow Delivery discharge to each off-take	Measured on-site during the field work Collected from the district's operating office
Energy Use Rate	Number of tube wells Working hours of tube wells groundwater extraction Pump efficiency of each tube well Type of tube well pumps according to their power source Transfer losses of each pump	Provided by the Isfahan Regional Water board Measured on-site/Interview by the farmers Calculated based on the working hours data Interview / brainstorming sessions with the operators and representatives of farmers unions
Agricultural Water Use	Cultivated area/water demands Irrigation schedules Water stress periods Cultivated area/water demands Irrigation schedules Water stress periods	Collected from the district's operating office Interview / brainstorming sessions with the operators, and representatives of farmers unions
CO_2 Emissions from Energy Consumption	Energy consumption of each pump type Net calorific value of each energy type CO2 emission factor of each energy type	Literature Review IPCC guidelines (2006)

Figure 1. Required data for each step of methodological framework.

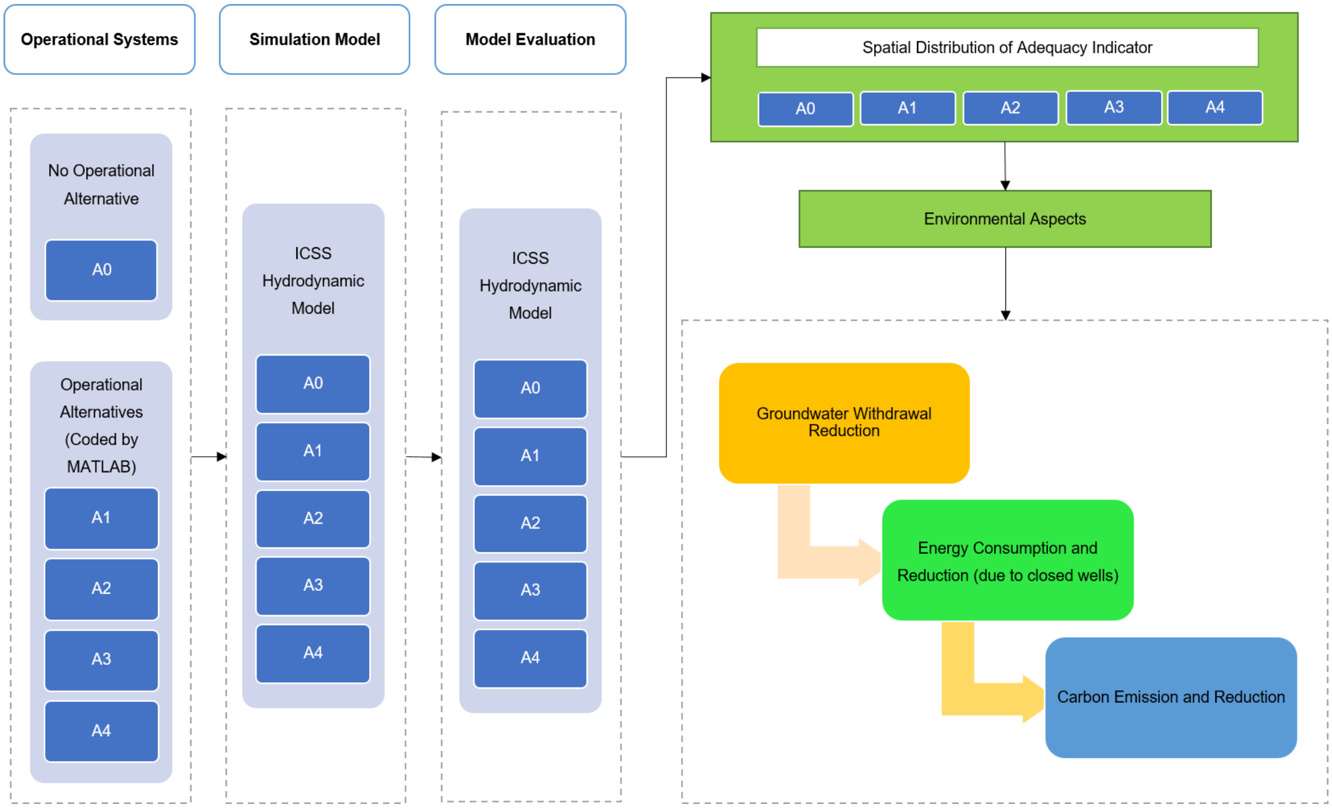

Figure 2. Different components of the proposed framework.

CO_2 emissions (IPCC 2006 guidelines) as a result of surface water conservation.

The methodology proposed here was developed and tested in the Nekou-Abad Irrigation District (NAID) located in the central part of Iran. The results of this study can be used to help decision-makers formulate policy remarks.

2. Data and Methodology

2.1. Data Sources

Primary data of NAID required for different steps of this research are presented in Figure 1. The information was collected from field visits of this study, the water board authorities' database, and gathered during the interviews and brainstorming sessions with the operational personnel. Therefore, NAID's primary data is required for different research steps, and their exact sources are presented in Figure 1. These input data are for a 150-day operational period in the 2015 ~ 2016 water-year.

2.2. Study Framework

Figure 2 depicts the methodology steps conducted in this study which is explained as follows:

(1) Developing Surface Water Distribution Simulation Model. The interconnected canal networks of the study area were created in ICSS hydrodynamic model to i) simulate the hydraulic behavior of the flow in SWDS; and ii) simulate the surface water distribution. The developed model is the main core of the simulation and is integrated with the different operating systems, representative of the existing system and the modernization alternatives.

(2) Developing the Operating Systems and Surface Water Distribution Simulation. The operating system investigated in the present study were developed in MATLAB and linked with the ICSS simulation model in (1). These systems are listed as follows:

- The manual-based operating system employed in the status quo.
- The improved manual-based systems (operational alternatives A1 and A2).
- The off-line control system using the mobile control approach (A3).
- The automatic control system using CMPC (A4).

(3) Spatial Assessment of the Surface Water Distribution Within the Irrigation District. This stage of the study was conducted iteratively for operational approaches A0 ~ A4 based on i) "surface water adequacy indicator" calculated by the hydrodynamic simulation model of ICSS in (2); ii) The MDSGR index introduced in the present study for the first time – inspired from the MDWL index in (Zhao et al., 2018) – systematically distinct the farms irrigated by the surface water resource and groundwater "MDSGR index", which for the first time is introduced in the present study (inspired from Zhao et al., 2018), to distinct the farms irrigated by the surface water resource and groundwater in a systematic way; and iii) "spatial maps" created by the ArcGIS's IDW tool.

(4) Environmental Assessment of the District's Modernization. This assessment encompasses the calculation of i) decreasing groundwater overexploitation; ii) energy consumption reduction; and iii) carbon emission mitigation due to upgrading the operating system in the irrigation district.

2.3. Developing A Hydrodynamic Model of the Status Quo (A0)

The calibration and validation of the developed model, using the ICSS model, in the present study rests on measured data, including canal inflow and delivery discharges to each off-take, for a 150-day operational period in the 2017 ~ 2018 water year. Fifty percent of this data set is used for calibration, and the remains employed to validate the model. After calibration, the model was validated using the following data set. The Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) statistical indicators compared the simulated and measured values. It should be noted that the mentioned indicators have been used in studies such as (Isapoor et al., 2011; Dejen, 2015) to evaluate the accuracy of hydrodynamic models.

2.4. Developing Operational Alternatives

2.4.1. Improved Manual Operation (A1): Predictable Inflow Fluctuations

The first alternative is in reliance on predictable inflow fluctuations to the head-source of the canal. It can help enormously the managers in proper regulation and distribution of water. The principle of this method is that after distinguishing the fluctuation form and measuring its magnitude and wave velocity by the flow measuring stations that are located upstream of the districts along the river, the collected information is communicated with canal headquarters (canal head-gate) through a telemetry system. This notification allows rearranging the water delivery schedule to catch up with upcoming inflow fluctuation(s), and on this basis, the ditch-riders set new adjustments to the main canal. This alternative is an implementable, practical, and feasible suggestion for every irrigation district for increasing water efficiency. The telemetry system is linked to all over the network and can be eased at any other location via telephone/radio system. Consequently, any recognized fluctuation information is imparted to every corner simultaneously. A schematic view of the A1 alternative is represented in Figure 3.

2.4.2. Improved Manual Operation (A2): on Rotation Water Delivery

This method, illustrated in Figure 4, is based on traditional operational management under the water shortages in many irrigation districts located in the Middle East countries. Regarding this method, the district is divided into two equal sections. During the first section, all the off-takes upstream are opened, which can ultimately receive water, while the downstream off-takes are closed and do not collect water. In the second turn, the process is visa-versa, where the upstream off-takes are closed, and no water is obtained. In this way, water resources are controlled appropriately during water shortage periods.

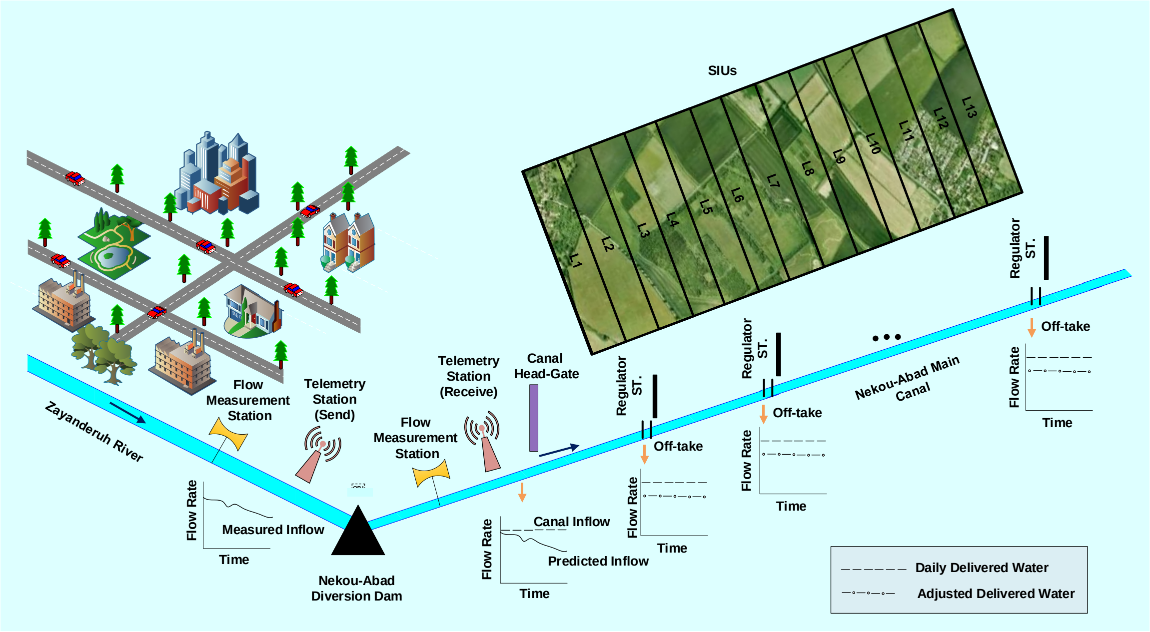

Figure 3. Schematic view of Nekou-Abad's water delivery system in improved manual operation (A1): predictable inflow fluctuations.

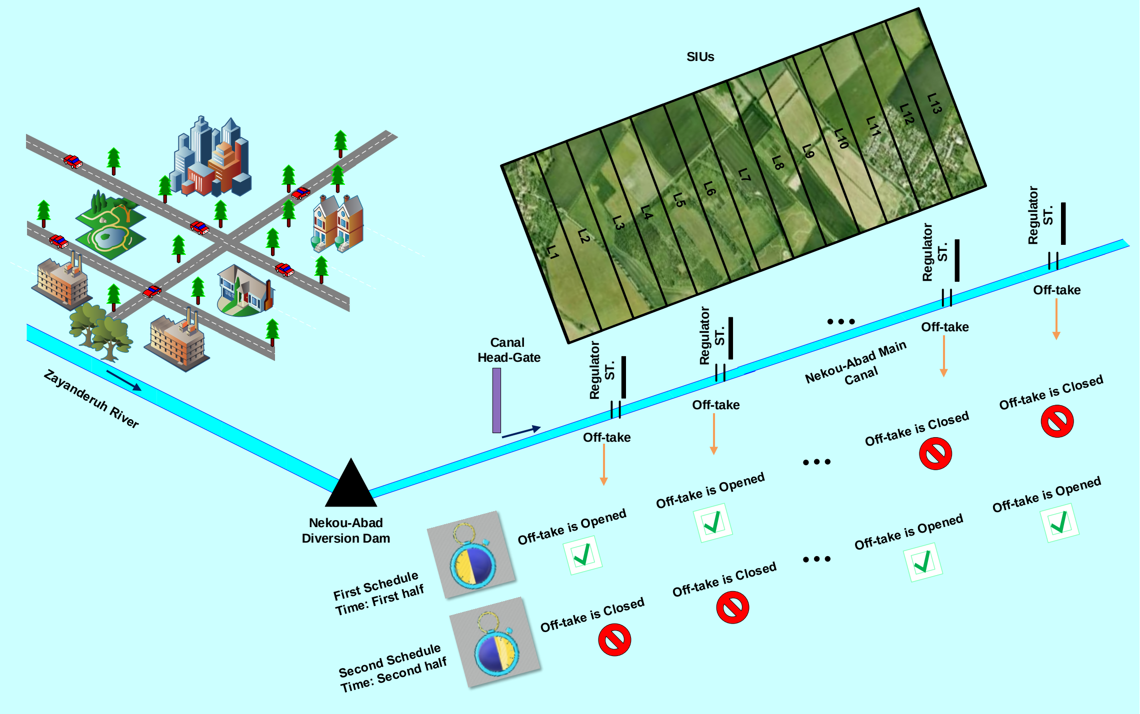

Figure 4. Schematic view of Nekou-Abad's water delivery system in improved manual operation (A2): on rotation water Delivery.

2.4.3. Mobile-Canal Control Method (A3)

This alternative is based on the proposed, designed control system by (Maestre et al., 2014). The possibility of damage to the onsite control equipment installed along the canal route due to weather conditions, thievery, or sabotage, is probable (Hashemy and van Overloop, 2013). This method works based on a combination of manual control and automatic centralized control. In a mobile control system, the location sequence and settings of the gates will be available to the operator through an SMS message in which the centralized controller's scheme does the planning as a decision support model. Due to several limitations in the optimization model caused by coordinated and sequential changes in gate structures, the feasibility area of decision making in this method is limited (Maestre et al., 2014). More comprehensive information about the formulation of the method is provided in (Maestre et al. 2014).

2.4.4. Centralized Model Predictive Controller (CMPC) (A4)

This method is a control system, which 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 target level at the off-take by regulating the degree of openness of the regulator located upstream of every canal reach. The model predictive controller (MPC) uses the mathematical model of the controlled system (the internal model) to predict hydraulic variables (water levels adjacent to each off-take) within a specific time interval. This interval, which is named "Horizon" in this controller, is defined following the design goal of the automated control system. In this study, the interval was considered to be 24 hours based on the recommendation (van Overloop et al., 2010a). Each time step, the control commands were determined based on the simulated hydraulic conditions (in the internal control- ler model) along the temporal horizon and real-time measurements in the canal. The measured water levels adjacent to each off-take (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 the site of each regulator to be executed.

In controlling a hydraulic system through the MPC method, the state-space model is employed to express the internal model because it makes it possible to compress the multivariate formulation of linear models. For example, the state-space model used in the primary canal of a water distribution system can generally be expressed in the form of a pair of Equation (1):

$$\begin{aligned} x(k+1) &= A(k)\cdot x(k) + B_u \cdot u(k) + B_d \cdot d(k) \\ y(k) &= C \cdot x(k) \end{aligned} \tag{1}$$

The objective function can be defined as Equation (2):

$$Min(J) = X^T \cdot Q \cdot X + U^T \cdot R \cdot U \tag{2}$$

where J is the objective function that must be minimized, X the state variables (including water level adjacent to each off-take), U the control commands (including the extent to which the degrees of openness of the regulators change), Q the weight matrix for state variables and R the weight matrix for control operations. With the definition of h_{ref} the target water level and the definition of error as Equation (3) and its placement in Equation (1), it is possible to determine the equation for water level error of each canal reach based on inflows and outflows:

$$e(k) = h(k) - h_{ref} \tag{3}$$

The water level in the main canal of the study area is regulated in the primary canal of the studied water distribution system using the two conventional methods of upstream control by employing 50 hydro-mechanical Amil structures and a Duck-Bill structure with a constant water level. Water distribution and delivery are performed along the primary canals by 36 off-takes used manually. In this study, the SWDS in the northern part of the irrigation network includes 13 agricultural areas to which 13 off-takes supply water. Given the structural conditions of the primary canal in the studied water distribution system, the state space matrix form is obtained following Equation (4) with matrix dimensions of X64 × 1, A64 × 64, Bu46 × 26, and Bd64 × 13. After transforming the equations obtained for all canal reaches, since matrices were considerable, only the space state matrix model for the first canal reach is presented in Equation (4):

$$\begin{aligned} \begin{bmatrix} Q_{hg}(k+1) \\ Q_{hg}(k) \\ Q_{hg}(k-1) \\ Q_{hg}(k-2) \\ e_1(k+1) \\ e_1^*(k+1) \end{bmatrix} &= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{T_c}{A_s} & 1 & 0 \\ 0 & 0 & 0 & \frac{T_c}{A_s} & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} Q_{hg}(k) \\ Q_{hg}(k-1) \\ Q_{hg}(k-2) \\ Q_{hg}(k-3) \\ e_1(k) \\ e_1^*(k) \end{bmatrix} \\ &+ \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} \nabla Q_{hg}(k) \\ u^*(k) \end{bmatrix} \\ &+ \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -\frac{T_c}{A_s} \\ -\frac{T_c}{A_s} \end{bmatrix} \cdot \left[Q_{off} - take_1(k) \right]^* \\ u^*(k) &\le h\min(k) - h_{ref}, \\ u^*(k) &\le h\max(k) - h_{ref}, \end{aligned} \tag{4}$$

In this Equation, the controlled rates of discharge released from the headwater regulating structure in the time step k-3 to k are shown by ($Q_{hg}(k)$), ($Q_{hg}(k-1)$), ($Q_{hg}(k-2)$), and ($Q_{hg}(k-3)$), respectively. The delay time between inflow from the headwater and the change in water level caused at the extreme downstream portion of the first canal reach was equal to 3-time steps. Moreover, $e_1(k)$ shows the calculated error (the difference between the measured and the water level) for the first canal reach and $e_1^*(k)$ the state variable added to the system that includes the soft constraint resulting from the violation of the permissible maximum and minimum water levels in the first canal reach by the measured water level. Furthermore, $u^*(k)$ refers to the value deducted from the error resulting from deviation from the target water level to obtain the value ($e_1^*(k)$). The variable ($u^*(k)$) has no physical interpretation and is merely a hypothetical variable for applying more penalties to the objecttive function when the water level violates the target water level's permissible minimum or maximum values. The value of this variable is obtained from Equation (5):

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

The objective function is turned into Equation (6) by adding the soft variables (van Overloop, 2006):

$$\begin{aligned} \min_{\nabla q, u^*} J = & \sum_{i=0}^{n} \sum_{j=1}^{m} \left\{ e_j(k+i\,|\,k) \cdot Q_{e,j} \cdot e_j(k+i\,|\,k) \right\} \\ & + \sum_{i=0}^{n} \sum_{j=1}^{m} \left\{ e_j^*(k+i\,|\,k) \cdot Q_{e,j}^* \cdot e_j^*(k+i\,|\,k) \right\} \\ & + \sum_{i=0}^{n-1} \sum_{j=1}^{1} \left\{ \Delta u_j(k+i\,|\,k) \cdot R_{\Delta u,j} \cdot \Delta u_j(k+i\,|\,k) \right\} \\ & + \sum_{i=0}^{n-1} \sum_{j=1}^{1} \left\{ u_j^*(k+i\,|\,k) \cdot R_{\Delta u,j}^* \cdot u_j^*(k+i\,|\,k) \right\} \end{aligned} \tag{6}$$

Here, (e_j^*) and (u_j^*) show the auxiliary variables of the system used to consider the soft constraints in the objective function and ($Q^*_{e,j}$) and ($R^*_{\Delta u,j}$) the weights (costs) considered for them, respectively (van Overloop et al., 2010b).

2.5. Operational Performance Appraisal Indicator

The performance indicators are related to the ability of the proposed operational alternatives to meet the primary objecttive of this study. Accordingly, the water distribution and delivery adequacy (Ad), criteria that were proposed by Molden and Gates (1990), is calculated during the operational periods to determine the ability of the alternatives, A1 ~ A4, to deliver enough water to users. The adequacy is defined as follows by Molden and Gates (1990):

$$A_d = \frac{1}{T} \sum_T \left(\frac{1}{R} \sum_R P_a \right), \text{with} \begin{cases} P_a = \left(\dfrac{Q_D}{Q_R} \right) & \text{if} \quad Q_D \le Q_R \\ P_a = 1 & \text{Otherwise} \end{cases} \tag{7}$$

A_d is the adequacy indicator, P_a is the delivery performance ratio defined as the ratio of the total water delivered (Q_D) to irrigation water requirement (Q_R) at each time step, T refers to the time step, and R refers to the off-takes in every canal reach. The Closer value of P_a to one, the more proper operation from the aspect of adequacy criteria (1 ~ 0.9 good, 0.89 ~ 0.8 fair, < 0.8 poor performance).

2.6. Potential Assessment for Reduction of CO_2 Emission

2.6.1. Matching Degree of Surface and Groundwater Resources (MDSGR)

In this study, an indicator named MDSGR is proposed to quantitatively specify the relationship between water resources (i.e., surface water and groundwater) in a specific agricultural district, which aims to represent the balance and matching status of spatial distribution. This method can be defined as Equation (8):

$$R_i^{SG} = \frac{SW_i}{GW_i} \tag{8}$$

Where R_i^{SG} is MDSGR in secondary irrigation unit (SIU) i ($m^3\ m^{-3}$), and SW_i and GW_i are total surfaces and groundwater resources consumption in (SIU) i (m^3), respectively.

2.6.2. CO_2 Emission Estimation

As a means to estimate CO_2 emissions from direct energy consumption by the tube wells scattering out of the irrigation district, a common approach is used. It was proposed by the International Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). This method can be seen in Equation (9):

$$CE_{Energy\text{-}i} = Q_{energy\text{-}i} \times H_{energy\text{-}i} \times C_{energy\text{-}i} \tag{9}$$

where $CE_{Energy\text{-}i}$ is carbon emission from energy consumption type i (10^3 t), $Q_{energy\text{-}i}$ is energy consumption type i (10^3 t, 10^3 m^3), $H_{energy\text{-}i}$ is the net calorific value of energy type i (KJ / t, KJ / m^3), and $C_{energy\text{-}i}$ is CO_2 emission factor of energy type i (kgC / KJ). It is worth noting that $H_{energy\text{-}i}$ value was obtained from IPCC Guidelines for National Greenhouse Gas Inventories (2006).

2.6.3. Energy Consumption Estimation

For calculating the energy consumption, after the literature was reviewed, a widely-used index was determined for calculating the required energy in groundwater extraction as follows (Equation (10)) (Karimi et al., 2012):

$$EC = \frac{2/73 \cdot D \cdot V}{OPE(1 - TL) \cdot 1000} \tag{10}$$

Here, EC shows the total energy consumption (kWh), D depth of groundwater below land surface, V the extraction volume, and *OPE* the pump efficiency. Furthermore, *TL* indicates transfer losses (this applies only to electrical pumps and is zero for other pumps).

3. Study Area

Nekou-Abad Irrigation District (NAID), located in the central part of Iran, is selected as the study area. Figure 5 shows the location of this irrigation district in the Zayanderud basin. Annually the area receives an average precipitation of 120 mm, much lower than the average annual rainfall in Iran, about 240 mm. Concurrently, the average evapotranspiration in this area is estimated at 1,500 mm per year. The main water supply for NAID is from the Zayanderud Dam Reservoir. The existing operational condition of the district is based on the manual operation conducted by operators and ditch-riders, based on the upstream control approach. The delivery and distribution of surface water along the main canals are carried out by 65 off-takes, operated manually. This study divided NAID into 13 irrigation districts named (L1 ~ L13). This division is based on the irrigation network system of this area.

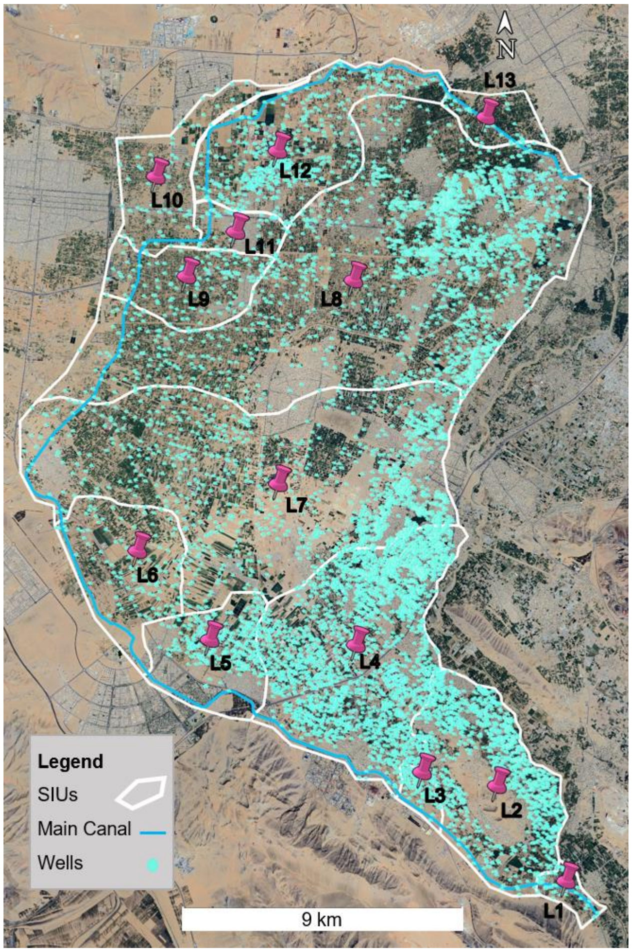

Figure 5. Map of Nekou-Abad irrigation district showing the main canal route; SIUs (L1 ~ L13) and scattering of tube wells.

According to data gathered during this study from the NAID headquarters office, poor operational performance resulted in a waste of about 30 to 40 percent of the inflow within the agricultural water conveyance, distribution, and delivery systems. Therefore, agriculture based on groundwater resources is expanded to compensate for deficit water delivery. According to the recent information revealed by the authorities, about 370 MCM is extracted annually from the aquifer by 15,000 active tube wells within NAID. The increasing number of tube wells, including deep and semi-deep drilled from 2003 to 2016, is presented in Figure 6. During this time frame, the NAID's aquifer witnessed an increase of 3.8% in digging semi-deep tube wells and a significant increase of 225.8% in deep ones.

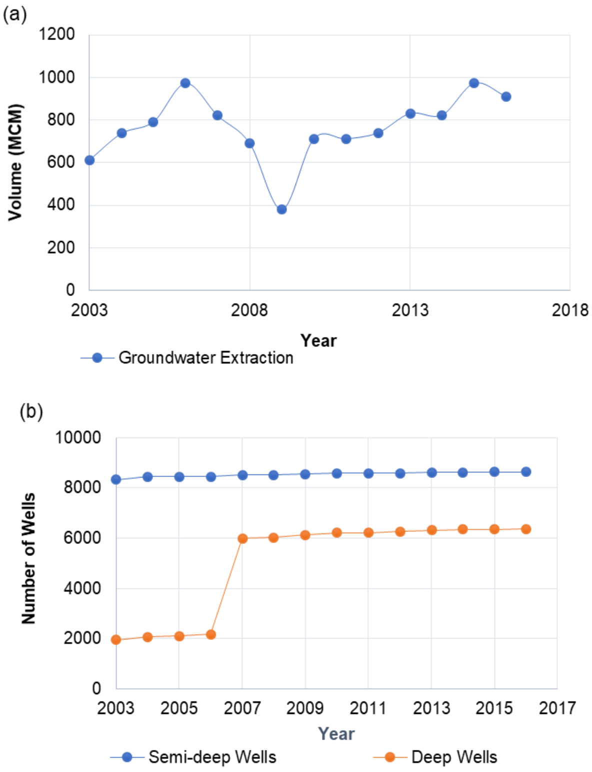

Figure 6. (a) The growth of the number of tube wells in NAID between 2003 ~ 2016; (b) time series of agricultural groundwater extraction in NAID between 2003 ~ 2016.

4. Results and Discussion

The obtained results consist of three main components of i) investigating the impacts of modernization alternatives implementation on surface water distribution through the irrigation district; ii) assessing the effects of surface water distribution enhancement in reducing groundwater overexploitation by the farmers, and eventually; iii) calculating the energy consumption and carbon emission reduction due to off-farm operating system modernization. In other words, to explain what the obtained results mean, the study's achievements are classified into the following three categories: (1) technical results explained the impact of modernization projects implementation in daily water distribution (Sections 4.1 and 4.2); (2) water resources management results revealed the modernization effects on aquifer recovery and storage due to increasing the reliability of surface water distribution (Section 4.3.1); and (3) environmental inherent achievement from a carbon footprint perspective (Section 4.3.2).

4.1. Hydrodynamic Simulation Model: Calibration and Validation

The calibration and validation of the hydrodynamic model (i.e., ICSS model), through statistical indicators, including RMSE, MAE, and CRM, are given in Table 1. Comparing these results with similar studies regarding the mentioned indicators shows the desirability of calibration and validation processes. For example, the RMSE and MAE are respectively within the ranges of (0.0349, 0.0369) and (0.020, 0.022) cubic meters per second in Shahrokhnia and Javan (2005) and in Dejen (2015), RMSE and CRM indicators are reported acceptable within the ranges of (0.06, 0.09) and (–0.07, –0.02) cubic meters per second, respectively. Therefore, according to the findings of Table 1, it can be concluded that the present study's results are closer to zero in comparison to the acceptable ranges of studies mentioned above. Therefore, the accuracy of the developed hydrodynamic model is confirmed.

Table 1. Statistical Indicators for ICSS Calibration and Validation

Statistical Indicator	Calibration	Validation
MAE (m^3/s)	0.0017	0.002
RMSE (m^3/s)	0.0019	0.003
CRM	–0.031	–0.055

After calibration and validation of the developed simulation model, the operational models of the alternatives are integrated into this model.

4.2. Operational Management Improvement Using the Modernization Alternatives

Upgrading the SWDS means improving conveyance, distributing, and delivering agricultural water to the farms from a surface water resource. To evaluate the impacts of alternatives A1 ~ A4 in the operational status, the SWDS, the models of the status quo (alternative A0), and the operational alternatives were designed and coupled with the developed ICSS hydrodynamic model. Then the operational performance of alternatives is evaluated by the adequacy performance indicator and compared with A0. The results are presented in Table 2, comparing the calculated adequacy indicators per each SIU and for every alternative, with each other and the alternative A0. It reveals the degree of satisfaction for the employed alternative in the district. Besides, a spatial view of this indicator for A0 ~ A4 is provided in Figures 7(a) ~ (e). The classification of this spatial view is according to the classes of the adequacy indicator presented in Equation (6).

Table 2 and Figure 7 show the poor performance of the current status of the surface water distribution within the study area. Overall, the upstream canal reaches (L1 ~ L6) perform better in distribution and delivery tasks than the SIUs L7 ~ L13, located in the downstream regions. The average of the obtained adequacy indicator in the canal test case is 0.78, where this amount is 0.88 for the upstream SIUs, 0.76 for the middles, and 0.71 for the downstream ones. Accordingly, the operational performance of A0 is "fair" in the upstream and "poor" for the middle and downstream regions of the study area. Besides, spatial assessment of the adequacy ratio indicates that the mean adequacy of water delivery and distribution varies from 0.94 in the third SIU, L3, to 0.7 in the L11 ~ L13. This implies that, in the L11 ~ L13 SIUs, farmers have to rely on another water source to compensate for the 0.3 delivered water shortage, for which they resort to groundwater sources.

According to the results in Figure 7(b) ~ (e) and given in Table 2, the operational performance has improved using the proposed alternatives (A1 ~ A4). The improvement mentioned above is directly related to each alternative's abilities and robustness, so that the approaches' priorities based on the obtained average adequacy indicator is A4 > A3 > A2 > A1. The capability of the non-structural alternatives, A1 and A2, is similar; since the average adequacy indicator for the entire SIUs becomes 0.807 and 0.808 (almost 0.81), respectively. Therefore, even though these two methods are less capable of improving the condition than the other two methods, they are still able to improve the performance of the canal from "poor" to "fair" status. In alternative A3, the mean value of the water delivery and distribution adequacy indicator has improved by 0.07 concerning the A0 (the mean value becomes 0.85). However, the performance condition is still evaluated as a "fair" status. Despite the operational performance improvement in A1 ~ A3 alternatives, adequate water is delivered to merely 15% of the SIUs in A1 ~ A2, and about 31% of the units in A3 receive adequate water supply.

On the other hand, alternative A4, due to the robustness of CMPC, Alternative A4 is more effective, whereby the entire SIUs have witnessed "good" water delivery and distribution performance. The adequacy indicator average value becomes 0.99 in A4, which signifies a 0.22 improvement concerning the A0 alternatives, in a way that the indicator values for 70% of the SIUs are 1. The latter means there is no need to withdraw groundwater in the SIUs mentioned above for irrigation purposes. Therefore, the A4 is the only alternative that has been capable of significantly improving the adequacy indicator of water delivery and distribution downstream of the canal test case.

4.3. Potential Assessment of the Alternatives in Reducing CO_2

4.3.1. Spatial Assessment of MDSGR throughout the District

The MDSGR index, introduced for the first time in the present study, distinguishes the farms irrigated by the surface water resource and groundwater systematically. The index works because the groundwater withdrawal reduction must be

Table 2. Numerical Values of Performance Assessment Indicator (Adequacy) for the A0 ~ A4

Modernization Scenarios		Adequacy													
		L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	Ave
Current Condition	A0	0.93	0.85	0.94	0.8	0.78	0.78	0.75	0.73	0.73	0.7	0.7	0.7	0.7	0.78
	A1	0.98	0.89	0.95	0.81	0.81	0.8	0.78	0.76	0.76	0.7	0.74	0.7	0.73	0.81
DSS + Manual Operation	A2	0.91	0.88	0.91	0.87	0.83	0.82	0.82	0.76	0.76	0.8	0.73	0.7	0.73	0.81
	A3	0.97	0.91	0.94	0.88	0.81	0.77	0.91	0.82	0.85	0.8	0.8	0.79	0.75	0.85
Centralized System	A4	1	1	1	0.98	1	1	0.98	0.98	1	1	1	1	1	0.99

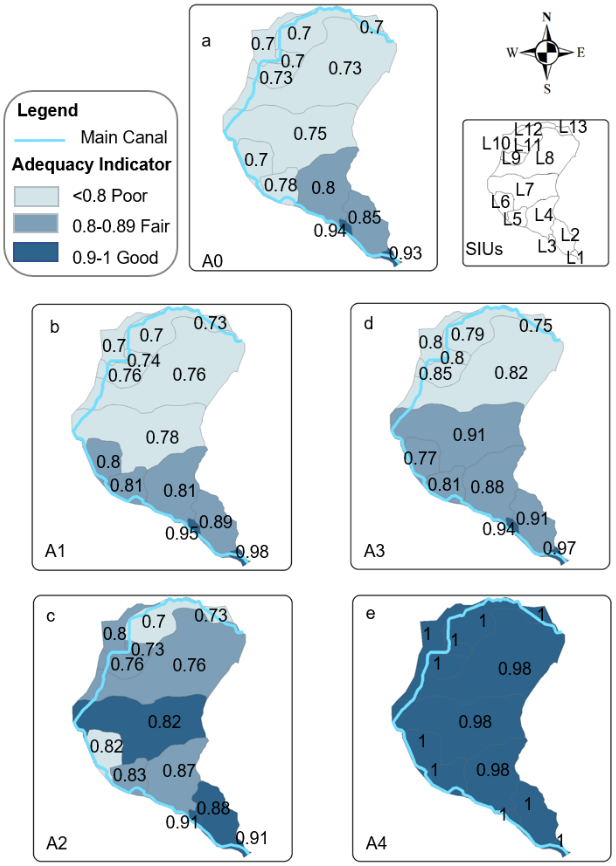

Figure 7. Spatial dispersion of adequacy performance assessment indicator within SIUs (7(a) ~ (e)).

compensated by efficient use of the surface water. The objective mentioned above is achieved by employing the MDSGR index spatial assessment. According to the obtained results in Section 4.2, it is observed that alternatives A1, A2, A3, and A4 made the lowest to the most considerable improvements in the status of water distribution and delivery between the SIUs, respectively. Likewise, the MDSGR index gets the average values of 0.075, 0.100, 0.281, and 0.470 (m^3 m^{-3}) in the mentioned alternatives (Figure 8). As expected, A4 leads to the most efficient application of supplied water from the surface water resources, leading to the most significant reduction in the dependence on groundwater sources.

According to the bar chart presented in Figure 8, spatial assessment of MDSGR in each SIU shows that the MDSGR index in A4 ≥ A3 ≥ A2 ≥ A1 in all cases.

It is worth noting that the spatial distribution of the calculated MDSGR index is mainly influenced by the tube wells dispersion and the total extraction. The MDSGR gets higher values on average in upstream units L1 ~ L7, where the number of tube wells used and total groundwater abstraction is higher than the downstream units L8 ~ L13. It should be mentioned that higher values of the MDSGR index do not necessarily mean a significant reduction in groundwater withdrawal since the distribution of groundwater tube wells is not similar within SIUs. For instance, the amount of reduction in groundwater withdrawal within L1 and L12 under the A4 alternative is 2,028,089 m^3 and 6,403,803 m^3, respectively. However, the obtained value of the MDSGR index for L1 becomes 0.682 (m^3 m^{-3}) compared to the correspondent values in L12, 0.544 (m^3 m^{-3}).

4.3.2. Estimation of CO_2 Emission

As mentioned earlier, the indirect consequence of the operational management improvement is translated to groundwater extraction reduction due to the closure of several active tube wells within SIUs. In other words, the amount of water loss reduction in the process of conveying, distributing, and delivering water supplied from the surface source is the basis for reducing the amount of energy consumed by groundwater extraction. For this purpose, the energy consumption status of each SIU was analyzed in A0. After the tube wells located within the district were identified, it was observed that nearly 4181 wells were active within the district boundaries. Therefore, Equation (9) was employed to measure the energy consumption to pump water from the tube wells within the district boundaries. Figure 9 shows the energy consumption using the alternatives A1 ~ A4 compared to the status quo. Moreover, the information about shutting down the tube wells after employing alternatives A1 ~ A4 is presented in Table 3. It shows that by employing the alternatives, at least 264 deep wells and 95 semi-deep wells (in A1) and at most 1,668 deep wells and 497 semi-deep wells (in A4) will be shut down. Thus, reducing groundwater abstraction means less pumping from deep and semi-deep tube wells. The amount of energy consumed by different SIUs in the status quo (A0), and by employing the modernization alternatives is presented in Figure 9. Among the agri-

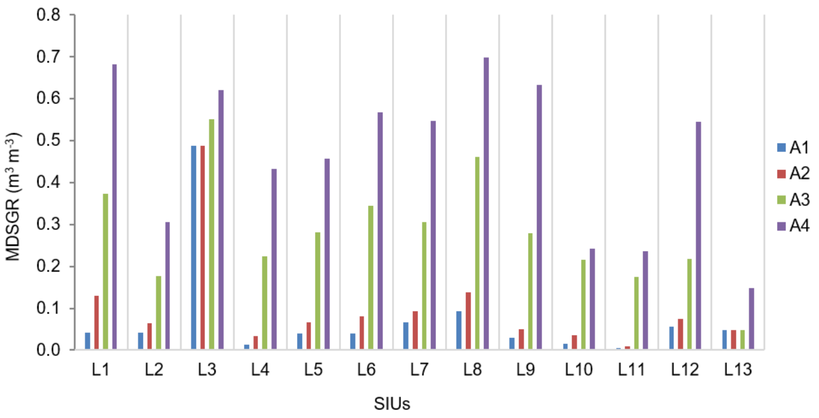

Figure 8. The MDSGR for the operational alternatives within the SIUs.

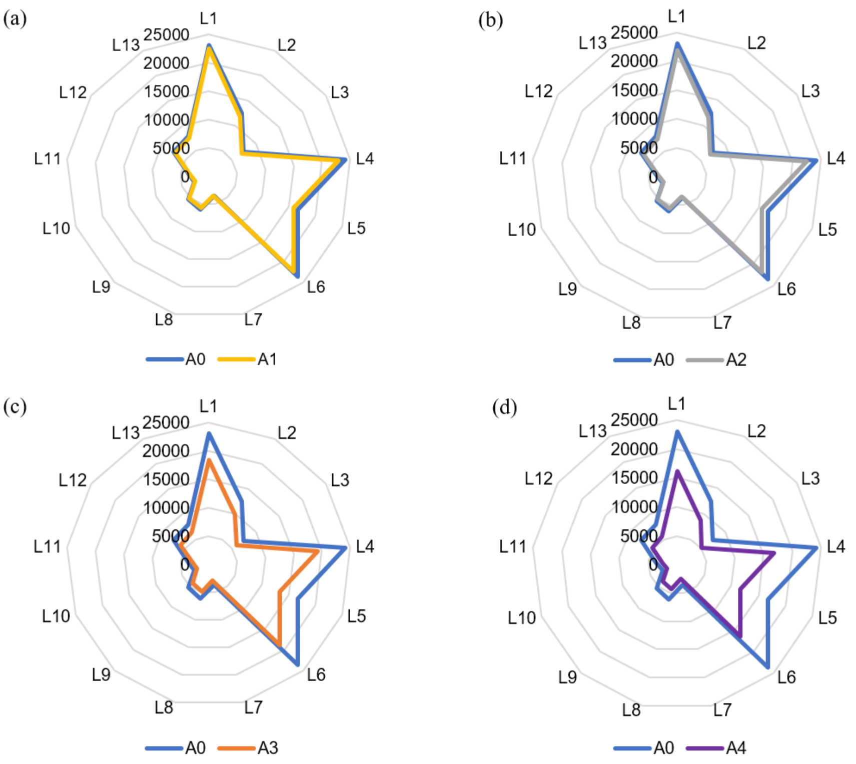

Figure 9. Energy consumption for operational alternatives versus A within different SIUs (kW ha^{-1}).

cultural units, L4 and L10 have the highest and lowest energy consumption levels before applying the scenarios, with the values of 24,125.74 and 2,717.87 kW ha^{-1}, respectively. The results indicate that A1, A2, A3, and A4 alternatives lead to a 5, 7, 20, and 30% reduction in energy consumption of SIUs, respectively.

Reducing CO_2 due to reducing energy consumption in modernization alternatives is calculated based on Equation (8) and presented in Figure 10. According to the results, the priorities of the modernization alternatives' impact on reducing CO_2 is A4 > A3 > A2 > A1. A1 resulted in CO_2 reduction around 1,864.90 tC ha^{-1} (4.4%), A2 led to 2,714.33 tC ha^{-1} (6.4%), A3 conducted to 8,427.19 tC ha^{-1} (19.9%), and finally A4 resulted in 12,674.32 tC ha^{-1} (29.9%) reductions of CO_2. The highest reduction in carbon production per hectare is related to the L4 unit in A4, with about 2,159.19 tC ha^{-1} 18% of the total reduction of this alternative. As expected, employing the robust CMPC system in the A4 alternative results in greater energy saving and carbon emission reduction values.

4.3.3. The Limitation of This Paper

Implementing the framework proposed in this study has some limitations and obstacles. One of the primary challenges in the modernization of SWDS in the agricultural sector is the

Table 3. The Number of Active Tube Wells under the Circumstance of Employing the Operational Alternatives

Indexes	Number of Closed Wells							
	A1		A2		A3		A4	
	Deep Wells	Semi-Deep Wells	Deep Wells	Semi-Deep Wells	Deep Wells	Semi-Deep Wells	Deep Wells	Semi-Deep Wells
L1	0	2	2	1	3	5	6	7
L2	6	43	10	58	24	171	28	264
L3	2	2	3	3	6	12	6	22
L4	73	34	109	43	336	98	516	133
L5	10	5	15	6	50	10	74	17
L6	3	2	6	2	18	4	26	7
L7	49	6	66	11	210	9	311	18
L8	87	0	118	4	335	12	498	21
L9	7	0	9	0	21	6	40	1
L10	3	0	5	0	14	0	21	0
L11	2	0	3	0	9	0	12	0
L12	20	1	30	0	80	5	120	7
L13	2	0	2	0	7	0	10	0
Total	264	95	378	128	1113	332	1668	497

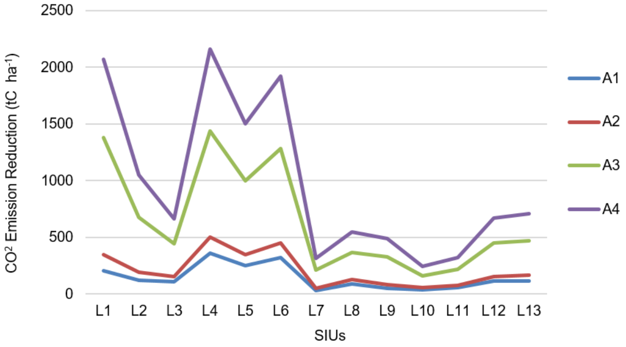

Figure 10. CO_2 emissions reduction within different SIUs (kW ha^{-1})

economic justification of these projects. These projects would be justifiable if the environmental damage (e.g., groundwater overexploitation and carbon emissions in this study) can economize. To achieve this justification, it is proposed to employ agro-economics models, like the Positive Mathematical Programming, to determine the economic value of water in agriculture and the environment.

It is worth noting that the framework developed in this study is designed to be employed for upgrading the primary water distribution system (i.e., the main canal), due to the limitations of the budget in the districts. In other words, upgrading the main and lateral water distribution systems with automatic control systems is only feasible when its implementation is economically justifiable. This will achieve when the price of surface water distributed is equal to the economic value of water so that modern agricultural systems (precision agriculture) are accessible for all in-farm activities along with a fully automatic distribution system. This limitation made it one of the most severe challenges for the researchers to determine the optimal distribution of agricultural water supplied from surface water resources. Accordingly, this study modeled the lateral distribution system (a canal network that receives water from the primary system and conveys it to the individual farms) based on the current manual operation. The method is based on an up-down management approach and manually adjusts the off-takes according to a scheduled water delivery programming. The development of an automatic control model for the lateral system and examining the performance of the full-automatic system (from reservoirs to farms) are, therefore, leading suggestions for future research so that the real impact of using automatic control systems on the exploitation of agricultural water distribution systems can be measured.

5. Conclusion

This study tried to draw the attention of authorities and decision-makers to the necessity of performance enhancement of the off-farm water conveyance, distribution, and delivery systems. Both potential managerial and environmental impacts using modernization alternatives were assessed in this study. In this regard, a systematic framework is proposed to investigate the impacts of implementing 4 modernization alternatives within Nekou-Abad irrigation district which is located in the Zayandehrood Basin, central Iran. The results reveal that water conveyance and delivery efficiency significantly improve within the study area by employing modernization alternatives and, consequently, reduce the main canal's operational losses. The adequacy indicator increases from 78%, in A0, to 81, 81, 85, and 99% in alternatives A1 ~ A4, respectively. This enhancement reduces groundwater extraction and associated benefits in decreasing energy consumption and CO_2 emissions.

The proposed MDSGR index shows that groundwater withdrawal reduction is compensated by efficient use of the surface water in A1 ~ A4. It gets the average values of 0.075, 0.1, 0.281, and 0.47 (m^3 m^{-3}) in alternatives A1 ~ A4, respecttively. Due to the closure of several active tube wells within irrigation districts, modernization of SWDS could save around 5, 7, 20, and 30% of energy consumption, which is directly related to declining CO_2 emission by around 1,864.90, 2,714.33, 8,427.19, and 12,674.32 tC ha^{-1} in alternatives A1 ~ A4, respectively. The findings of this research show that each of the modernization alternatives can, in turn, contribute to improving the surface water system and help reduce the excessive withdrawal of groundwater, as well as energy consumption and carbon dioxide production, but the A4 alternative (CMPC) has the best performance in both technical and environmental point of view.

The comprehensive evaluation framework proposed in this study can be applied as a decision support model to prioritize the operating systems included in the modernization, rehabilitation, and renovation projects of irrigation districts. This evaluation framework will help local managers to investigate environmental impacts (including reducing over-exploitation from the aquifer and consequently reducing energy consumption in the area) and the technical consequences of upgrading the agricultural water distribution system. This framework would be more effective in developed countries, where the private sector manages the irrigation districts. This is important from two main perspectives i) considering the importance of maintaining agricultural activities in water shortage periods and achieving the intended economic goals since reduced losses in agricultural water distribution systems can compensate for a large part of water allocated to the irrigation district; ii) Any improvement of irrigation systems within the farms must be consistent with the capabilities of the water distribution system within the district to maximize the level of physical and economic productivity of water at the farm.

Symbols and Abbreviation

Abbreviation	Description
GHG	Greenhouse gas
NAID	Nekou-Abad Irrigation District
SIU	Secondary Irrigation Unit
SWDS	Surface Water Distribution Systems
CACS	Centralized Automatic Control Systems
CMPC	Centralized Model Predictive Controller
Symbol	**Scenario**
A0	Status quo
A1	Manual operation – predictable inflow fluctuations
A2	Manual operation – on rotation water delivery
A3	Off-line Automatic System Mobile-Canal Control Method
A4	Realtime Automatic System Centralized Model Predictive Controller

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