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Assessment of Water, Food, and Energy Efficiency Indicators with a Nexus Approach and Sustainable Agricultural Management

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Abstract

Sustainable management of water, food, and energy resources and increasing efficiency is one of the key challenges in sustainable management and development. Given climate change, global population growth, and growing demands, sustainable utilization of these resources is essential to ensure the possibility of human survival and sustainable growth. Achieving sustainable development goals requires a comprehensive and interactive approach, and resource management with an integrative perspective is a necessary component of sustainable development, where all stakeholders participate in the decision-making process and implementation of actions. This study aims to enhance the efficiency of water, food, and energy in the Plusgan watershed and develop a validated tool for evaluating agricultural management strategies in relation to the nexus of water, food, and energy security. The study was conducted in two stages. In the first stage, management scenarios were identified to increase efficiency, and in the second stage, nexus-oriented management scenarios were evaluated and prioritized. In the second part of this research, among the 30 sub-scenarios introduced for improving efficiency, the sub-scenarios that involved a 20%, 10%, and 30% increase in forage maize cultivation showed positive effects on water, food, and energy efficiency indicators. After prioritizing the influential sub-scenarios using the TOPSIS multi-criteria decision-making model, the sub-scenario with a 30% increase in forage maize cultivation had the greatest positive impact on water, food, and energy efficiency. It was identified as the key scenario for evaluating efficiency in sustainable agricultural management.

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Introduction

One of the most significant challenges facing humanity today is water supply in the face of associated stresses, which highlights the need for effective water resource management (FAO, 2012). Population growth has increased the demand for appropriate allocation of water resources, and this issue has always been accompanied by stress due to the reduction of freshwater resources. It is crucial to have a proper understanding of the water resource system in a region for planning and making informed decisions, considering both climate and human-induced stresses (Tork et al., 2021). However, it seems that there is a lack of useful information for decision-making related to water management (Hirwa et al., 2022). Given the significant role of water availability in the social, economic, and environmental well-being of a region, a holistic approach to water resource management should consider the sustainable dimensions of resources and consumption. To achieve sustainability, a better understanding of the variables affecting the water supply and demand sustainability and their interrelationships is necessary. Therefore, there is a need for an index that connects the elements of the water balance to quantify the water sustainability status and the level of water protection required for proper water resource management (Karamouz et al., 2017). On the other hand, with the finite nature of water resources and the depletion of renewable water sources, optimal utilization of water resources, particularly in the agricultural sector, is of the utmost importance. On Iran's central plateau, surface water resources are limited. Therefore, the main volume of water supply, especially in terms of sustainability, relies on groundwater resources, which play a crucial role in meeting the region's water needs.

One of today's concerns is ensuring water supply in the face of associated stresses. This issue emphasizes the attention and importance of effective water resource management (FAO, 2012). Population growth has increased the demand for appropriate allocation of water resources, and this issue has always been accompanied by stress due to the reduction of freshwater resources. Understanding the water resource system of a region is of great importance for proper planning and decision-making regarding water management, considering climate and human-induced stresses (Tork et al., 2021). However, it appears that we face a lack of useful information for decision-making concerning water management (Hirwa et al., 2022). Given the crucial role of water availability in the social, economic, and environmental well-being of a region, a holistic approach to water resource management should focus on water resources considering the dimensions of resource sustainability and consumption patterns. To achieve sustainability, a better understanding of the variables influencing water supply and demand sustainability and their interrelationships is essential. Therefore, the use of an index that connects various elements of the water balance to determine the water sustainability status and the level of water protection required for proper water resource management is necessary (Karamouz et al., 2017). On the other hand, with the fixed amount of available water and the reduction of renewable water resources, optimal utilization of water resources and soil, especially in the agricultural sector, is crucial. On Iran's central plateau, surface water resources are limited. Therefore, the main source of water supply, especially in terms of sustainability, is related to groundwater resources. These resources play a significant role in meeting the region's water needs. Additionally, groundwater tables have been affected by unregulated extraction and imbalanced use, resulting in many Iranian plains being classified as prohibited areas. The failure of past water management policies and climate stresses has led to a significant reduction in water levels, resulting in a decline in groundwater levels and reservoir volume in aquifers.

The sharp decline in water levels in most of the country's aquifers and the importance of the issue have led to increased attention to the quantitative and qualitative development of groundwater resource balancing projects. The groundwater balancing and restoration project has started in recent years in collaboration with the Ministry of Energy and the Agricultural Jihad Organization in the country. The main objective of this project is to reduce aquifer depletion with minimal economic and social stress. Furthermore, in line with the implementation of the resolutions of the Supreme Water Council and the organizational goals of the Ministry of Energy, estimating and communicating the amount of water available for planning purposes is essential.

Considering the research objectives, the implementation of the groundwater balancing project in line with water scarcity adaptation programs should be approached with a nexus perspective. This should encompass the three dimensions of water, food, and energy efficiency. This approach represents a novel approach to integrated water resource management. To select an effective solution and prioritize the proposed solutions, the TOPSIS multi-criteria decision-making model will be utilized. This decision-making model aims to identify the best solution among the proposed alternatives and prioritize it.

Water productivity, in simple terms, refers to producing more food or obtaining greater benefits with less water. In this regard, physical water productivity is defined as the ratio of the amount of product to the amount of water consumed. Economic water productivity represents the value obtained from each unit of water consumed. Water productivity is often calculated for specific crops or livestock (Molden., 2007). Nevertheless, the water saved from improving water productivity can be used in other sectors. There are various ways to improve water productivity, and international trade in agricultural products provides a pathway for enhancing global water use efficiency through virtual water transfers to water-stressed regions (Dalin et al., 2014). Since water use efficiency varies significantly in different regions, international or domestic trade in food can contribute to significant water savings at the global or national level (Chapagain et al., 2011). While virtual water transfers may not solve the inequities of water consumption globally (Seekell et al., 2011), they can reduce social vulnerability to drought under certain scenarios (D'Odorico et al., 2012). This model is based on maximizing food production, minimizing energy consumption, minimizing water use, and increasing groundwater reserves. Without water-energy-food trade-offs, risks in this sector increase. Therefore, it is necessary to analyze and address the risks affecting the water, food, and energy sector in the agricultural water supply and distribution system before any incidents occur. Examining the water-food-energy nexus based on risk can provide opportunities for improving the sustainability of these resources in agricultural water supply and distribution systems.

Economic and social development, population growth, and climate change pose significant challenges to sustainability and food security, which are among the most pressing concerns of societies (Vörösmarty et al., 2000; Gleick, 2008). Consequently, water resources, essential for human survival, sustainable livelihoods, food security, and ecosystem preservation, are under pressure. Many believe that the world is facing an unprecedented water crisis, and without progress and improved management of water resources, as well as integrated decision-making in developed and developing countries, water-related issues are expected to become increasingly critical in the coming decades (Scheierling et al., 2014). Iran, located in a dry and semi-dry climate, also faces severe water scarcity. In 2014, Iran's water per capita was 1644 cubic meters, indicating an unfavorable water availability compared to the global average of 6225 cubic meters per person per year (World Bank, 2014). The trend and patterns of water per capita are worrisome, with the country's water per capita decreasing from 5570 cubic meters in 1962 to 1876 cubic meters in 2008 and further to 1644 cubic meters in 2014 (Aquastat, 2010). The current status of water resources in Iran, the trends shaping them, and the inadequate spatial and temporal distribution of limited water availability highlight the need for demand management, consumption moderation, and achieving a balance between water supply and demand.

In this regard, understanding two facts is crucial to comprehending the role of agriculture in the water crisis. First, agriculture is the largest water user, accounting for a significant proportion (80%) of water consumption (Rost, 2008). Second, agricultural water use is relatively less efficient and productive compared to other water users (Yong, 2005). Therefore, when water becomes scarce in many parts of the world, other sectors and users tend to view agriculture as a potential water source (Scheierling et al., 2014). Many experts believe that in addition to the global water crisis, agriculture and related activities are facing an unprecedented crisis worldwide. Continuous population growth, changes in dietary patterns (increased consumption of dairy and meat), and the expansion of biofuel use have increased the pressure on the agricultural sector (Scheierling et al., 2014). Recent yield growth in major crops has raised concerns that without substantial investment in low-yield areas and the implementation of appropriate strategies to sustain yield increases in high-yield areas, agricultural productivity will not be sufficient to meet future demands quickly (Ray et al., 2013). To shed light on the subject, reviewing recent projections for agricultural production and its water requirements would be useful. It is projected that the world population will reach 9.6 billion by 2050 (United Nations, 2013). According to the FAO model for the period from 2005 to 2050, the growth rate of agricultural product consumption is estimated at 1.1% annually. To meet this global demand, agricultural production in 2050 needs to be 60% higher than the production in 2005. Consequently, the water required for irrigation needs to increase from 2761 to 2926 cubic kilometers (Bruinsma & Alexandratos, 2012). Considering the limited potential for increasing water supply in many parts of the world, it is strongly recommended to focus efforts and actions on improving water productivity in agriculture. Given the large amount of water consumed in agriculture and the relatively low efficiency, even slight improvements in agricultural water productivity can have a considerable impact on global and regional water budgets. This process of enhancing water productivity enables increased agricultural production with the same amount of water or the production of the same agricultural output with less water. Indicators of agricultural water efficiency are suitable tools for evaluating agricultural management, particularly in dry and semi-arid regions. Low water efficiency in the agricultural sector is one of the pressing issues that have caused significant changes and transformations in human life due to various reasons, including climate change, improper water management on farms, and the depletion of renewable resources as the primary supplier of water needs in the country.

It has been mentioned that to feed a growing population accompanied by improvements in per capita income and diverse dietary patterns, we will need more water based on per capita average needs. The increased demand for water in agriculture will put pressure on water and soil systems and intensify competition for water resources (Molden, 2007). In this regard, improving the physical water productivity in agriculture reduces the need for additional water and soil in irrigation and rainfed systems, thus providing a suitable response to increasing water scarcity.

There are promising pathways to increasing water efficiency in both rainfed and irrigated agricultural systems. Supplementary irrigation for rainfed lands, soil fertility preservation, deficit irrigation, small-scale operations for water storage, delivery, and utilization, modern irrigation technologies, soil moisture conservation through minimum or zero tillage, reduced biomass through increased pest and disease resistance, and rapid initial growth for quick ground cover are among these pathways. However, the benefits derived from improving water efficiency depend on specific conditions and can only be assessed through a holistic watershed-level perspective (Molden., 2007). Increasing water efficiency, especially the value created per unit of water, can be an important path to poverty reduction, provided that the benefits of water efficiency reach the poor, particularly rural women.

In general, the path to improving water efficiency can be achieved through evapotranspiration, soil fertility, international trade, and reducing evaporation or water delivery (Molden, 2007). Adopting methods to enhance water efficiency requires a capable institutional and political environment to balance the incentives of producers, resource managers, and the community and to develop a process for coordinating stakeholders. Despite sufficient managerial operations and technologies, realizing net benefits from water efficiency is challenging due to various reasons. The low price of agricultural products and the high production risks for farmers are factors that hinder significant progress (Molden, 2007). Increasing water efficiency through increased agricultural production puts pressure on the market prices of these products, and the benefits obtained by one group often come at the expense of other groups, indicating that incentive systems and the adoption of modern technologies do not support each other adequately. Proposed strategies need to identify these challenges and provide incentive policies and compensation schemes to promote greater fairness between those who benefit from the water efficiency process and those who are adversely affected (Molden., 2007).

Human economic efforts have always aimed to maximize results with minimal effort and resources. Water efficiency is defined as the ratio of output to the amount of water applied for plant growth (Choudhury and Bhattacharya, 2018). In essence, water efficiency determines how much produce is generated for a given amount of water used, and its unit is kilograms per cubic meter.

Determining and analyzing agricultural water efficiency indicators is not always a straightforward task because water is not solely used for agricultural production. In assessing and evaluating the effectiveness of water in plant production, besides the amount of produce, the value of the produced material should also be considered. For example, the income derived from the consumption of each cubic meter of water or the amount of protein and calories produced per a specific amount of water can also be important considerations in evaluations. Agricultural water efficiency is related to water resources and the benefits derived from them, and many parameters in this regard are qualitative and not easily measurable. Additionally, a significant challenge in studying water efficiency is the insufficient availability of basic information to calculate monetary and non-monetary indicators of agricultural water efficiency.

Integrated water resources management is a set of strategies and practices that aim to address the complex challenges related to the sustainable and equitable management of water resources and water-related services. It recognizes the interconnectedness, interdependencies, and interactions between water resources and various sectors, including agriculture, industry, energy, and the environment (Rogers and Hall, 2003).

Managing groundwater resources and their uses is a crucial component of integrated water resources management. It involves the sustainable utilization and management of groundwater and surface water resources to achieve a balanced and equitable distribution of water and the efficient utilization of water resources. Proper governance and management of water resources require effective administrative and legal frameworks, which can facilitate stakeholder participation and ensure effective decision-making processes (Saunier and Meganck, 2009). Such frameworks should consider the technical, economic, and social dimensions of water management to promote sustainable and integrated practices (GEF, 2015). Water governance and management in transboundary river basins, where different countries share water resources, require international cooperation, collaborative approaches, and sound governance mechanisms (Varady et al., 2012; Chilton and Smidt, 2014).

The implementation of integrated water resources management involves various challenges and constraints, including the fragmented nature of water-related institutions, limited financial resources, and the lack of coordination among different stakeholders (Halbe et al., 2015). Overcoming these challenges requires a holistic and interdisciplinary approach that integrates elements of water management, governance, and policy. Effective implementation of integrated water resources management can lead to improved water security, increased resilience to climate change impacts, and sustainable development (Megdal and Perlman, 2018).

In recent years, the concept of the linkage and nexus between water, food, and energy security has gained significant attention in the context of sustainable water management. Each of these elements, water, energy, and food, is influenced by increasing population growth, urbanization, changing lifestyles, and climate change, leading to complex interlink ages and challenges that require integrated solutions (Beisheim, 2013). The total cost includes the sum of energy, water supply, electricity generation, food production, and CO2 reduction costs.

WEFEN enables us to comprehensively and dynamically understand the interconnections and dynamics of water, food, and energy elements, allowing for safe and sustainable management and utilization. By effectively integrating equations and considering the interactions of these elements, we can achieve a coordinated and optimized approach to resource management (FAO, 2014).

In practical terms, WEFEN can be defined as an approach to assessing, developing, and implementing policies that simultaneously emphasize water, energy, and food security (Bizikova et al., 2014). Specifically, WEFEN provides a conceptual and analytical framework for socio-ecological systems and proposes a framework for the coordinated management and utilization of natural resources across all sectors and scales (FAO, 2014). Gupta (2017) emphasizes the interactions and collaboration of all involved elements, aiming to maximize the benefits derived from their utilization and preserve environmental integrity.

Holtz et al. (2013) integrated the land, energy, and water resources systems using the CLEWs framework. Instead of developing a completely new unified analysis tool, they integrated their perspectives based on existing evaluation methods for each of the three resources, which yielded good results. The land-use model, energy model, and water resource management model were connected using recent data and predicted scenarios. Outputs from one module served as inputs for the other two modules, which were then solved continuously, transferring data between the models. This process was iterated until a convergent solution was reached. The Republic of Mauritius was selected as the first CLEWs case study due to its water scarcity and contribution to climate change mitigation. The country's priority is to reduce energy imports while committing to greenhouse gas emissions reductions. The majority of the island's surface is dedicated to sugarcane cultivation, playing a significant role in the economy as the primary export and foreign exchange income. Reducing oil imports would increase energy independence, reduce oil import costs, and mitigate greenhouse gas emissions. Whether this strategy is desirable or not depends on the cost of domestic ethanol production, overall public and socioeconomic benefits, the price ratio between oil and sugar development, the value assigned to energy security and greenhouse gas emissions reduction, as well as the unintended and secondary effects.

The WEFO model was developed by Zhang and Vesselingh (2017) to answer the question of how to plan energy, water, electricity generation, and food production to minimize the overall system cost while controlling greenhouse gas emissions. A hypothetical system including two thermal power plants (coal and natural gas) for electricity generation was used to demonstrate the application of the WEF approach. The WEFO planning was conducted over three consecutive five-year periods. Electricity production requires water from three different sources: groundwater, surface water, and reclaimed water. The generated electricity is not only used within the WEF system (e.g., water supply for power plants and food production) but also for meeting social and economic needs. Water (excluding reclaimed water due to human health concerns) and energy (in the form of electricity in this study) are required for food production and processing. Additionally, greenhouse gas emissions are associated with electricity and food production. The interactions within the WEFO model, as well as the existing social-economic and environmental constraints, were examined. The decision variables in the WEFO model include1)) energy values available from coal and natural gas, (2) power plant capacity for electricity generation, (3) groundwater and surface water values required for food production, (4) groundwater, surface water, and reclaimed water values required for electricity generation, and (5) social and economic demands for WEF production over a planning horizon.

A comprehensive three-stage plan has been proposed in Taiwan to investigate the synergies of Nexus Water-Food-Energy through the optimization of a multi-purpose reservoir combined with short-term/long-term joint operation of irrigation ponds to address increasing urbanization. The three-stage plan has been implemented step by step. (1) Short-term optimization (daily scale) of reservoir operation to maximize hydropower generation and reservoir storage during typhoon seasons (July-October). (2) Long-term water scarcity simulation (ten-day scale) considering the inventory of irrigation ponds for the agricultural and public sectors during non-typhoon seasons (November-June of the following year). And (3) promotion of one-year horizon benefits of WFE Nexus through the integration of short-term optimization and long-term simulation of reservoir operation. The results of short-term/long-term joint operation throughout the year showed a potential reduction of water scarcity by more than 10%, food production increase up to 47%, and water-electricity benefits up to 9.33 million USD per year, in a wet year (Zhu et al., 2022). Karlberg et al. (2015) conducted a comprehensive study on the feasibility of integrating agriculture, energy, and water management in the Tana River basin in Kenya, with the aim of optimizing the water use efficiency. Their study revealed the potential benefits of optimizing water, energy, and agriculture sectors in terms of water savings, improved food production, and increased economic benefits. However, the implementation of such integrated approaches requires proper planning, management, and coordination to ensure sustainable water resources management and to overcome various technical, institutional, and socio-economic challenges (Garg and Dadhich, 2014).

Moreover, the integration of water, energy, and food sectors in water-scarce regions has been recognized as a key strategy to address the challenges of water scarcity, food security, and sustainable development. This integrated approach can help minimize water use conflicts, increase water use efficiency, and promote sustainable agricultural practices (El-Gafy, 2017). By considering the interdependencies and trade-offs among water, energy, and food, this approach can provide a more holistic and integrated framework for water resources management and planning (El-Gafy et al., 2017a). The optimization of water, energy, and food systems in water-scarce regions can lead to significant water savings, increased energy efficiency, and improved agricultural productivity (Sadeghi et al., 2020). The implementation of such integrated approaches requires a comprehensive understanding of the water-energy-food nexus and the development of innovative strategies to enhance resource efficiency and sustainability (El-Gafy et al., 2017b).

The report "Critical Challenges and Priorities for Integrated Water Resources Management in Iran" (2017CSS) addresses 100 important and challenging issues in Iran. Among these topics, 12 titles, including water scarcity, drought and desertification, water pollution and contamination, groundwater depletion, institutional coordination, climate change impacts, water basin management, agricultural practices, irrigation efficiency, low energy productivity, inefficient water markets, groundwater management, and social conflicts, are identified as crucial in achieving water, energy, and food security and sustainability.

Water plays a vital role in agricultural production, industrial processes, domestic consumption, and hydropower generation. Its efficient use, proper allocation, sustainable management, and the nexus between water, energy, and food are significant factors in Iran's development. Moreover, understanding the complexity of interrelationships in multi-sectoral systems is essential for achieving a safe and prosperous future (Rasul and Sharma, 2016; Cai, X et al., 2018).

By adopting an integrated approach, cohesive structures, and continuous linkages, the report aims to develop strategies and approaches for water, food, and energy security and sustainable development. Learning from trial and error experiences, it seeks to rectify the deficiencies and shortcomings in the decision-making processes of managers and stakeholders. It also emphasizes the importance of adopting comprehensive, cross-sectoral approaches to address water, food, and energy challenges and to promote resilience in the face of uncertainties (Hettiarachchi and Ardakanian, 2016). In this study, a suitable model has been developed to prioritize solutions for enhancing water and land productivity, reducing resource uncertainties, and optimizing water, food, and energy interlinkages at the regional level. The model considers the interconnectedness between the water, food, and energy sectors in order to guide decision-making processes and formulate effective strategies for sustainable water, food, and energy management.

Material and Methods

Study Area

Study area considering the objectives and needs of this research, the Plasjan watershed, located upstream of the Zayandehrud Dam in Iran, was selected as the study area. The Plasjan watershed is situated in the northwestern part of the upstream region of Zayandehrud Dam, covering an area of 1854 square kilometers, ranging from eastern longitude °50 to °45 and northern latitude °32 to °33. The location of the study area is depicted in Figure (1). The maximum elevation of this watershed is 3877 meters, while the minimum elevation in the outlet section is 2056 meters above mean sea level. The watershed is divided into three sub-basins: Damandan (code 4214), Chehelkhaneh (code 4213), and Boein-Miandasht (code 4212). An examination of the water resources in this watershed reveals that 218 million cubic meters of water are utilized, with 177 million cubic meters sourced from groundwater and 41 million cubic meters from surface water. The selection of this area was based on the declining groundwater levels and reservoir deficits in the aquifers within the study area, emphasizing the need for aquifer balancing. Additionally, the availability of remote sensing data in the study area played a role in choosing the Plasjan watershed. In these three aquifers, water level measurements are conducted monthly using 53 observation wells. Analysis of groundwater levels in these aquifers indicates a decline of 1.1 meters and 0.5 meters in the Boein-Miandasht and Chehelkhaneh regions, respectively, and a decrease of 1.5 meters in the Damandan aquifer. Therefore, the Plasjan watershed was selected as the study area for further investigations.

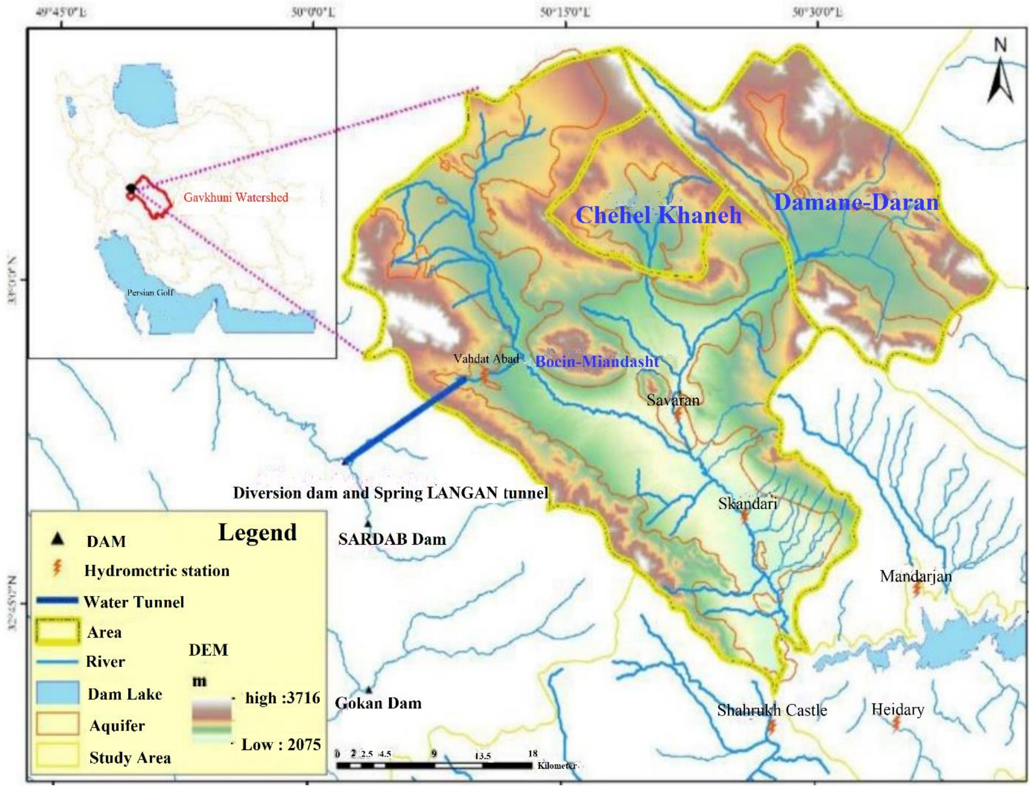


Fig 1. Study Area (Rahimzadeh et al., 2021)

The majority of water consumption in this area is allocated to agricultural users, while less than 10 million cubic meters of water are allocated to the industrial and drinking water supply sectors. The central part of this region is influenced by agricultural activities, which have resulted in the highest water consumption from available resources. However, less emphasis has been placed on the industrial and drinking water supply sectors, indicating that agriculture holds greater importance in this area. The cropping pattern and agricultural productivity of this watershed, based on land use classification as presented in Table 1 according to the Agricultural Statistical Yearbook of Isfahan Province in the water year 2017-2018, are provided.

The agricultural cropping pattern in the Plasjan watershed in the water year 2017-2018 in Isfahan province primarily consisted of wheat and barley cereals, oilseeds such as rapeseed, and forage crops including alfalfa and maize. The agricultural productivity in the region shows that wheat and barley, despite having lower yields compared to forage

Table 1. Cropping pattern and representative crop yields in the Plasjan watershed (Agricultural Statistical Yearbook 2017-2018, Jihad-e Agriculture of Isfahan Province)

Class	Product Representative	Yield (Kg/ha)	Cultivation type	Cultivated area (ha)
Cereal	Wheat	4000	Irrigated	3000
	Wheat	700	Rainfed	2000
	Atmosphere	4000	Irrigated	700
Oil Seeds	Canola	2214	Irrigated	14
Fodder plants	Alfalfa	10000	Irrigated	5000
	Fodder corn	60000	Irrigated	1200

crops (alfalfa) and forage maize, were cultivated on a larger area. Additionally, rapeseed, as an oilseed crop, holds a special position in the cropping pattern of this watershed with a smaller cultivated area but higher yields compared to wheat and barley. This agricultural cropping pattern and crop performance can serve as a basis for appropriate planning by farmers and relevant authorities in Isfahan province to optimize water and soil resources, increase agricultural productivity and efficiency. Furthermore, the wheat cropping pattern in the Plasjan watershed in the water year 2017-2018 was divided into two types: irrigated and rainfed. This division, based on the water availability for cultivation, indicates lower wheat yields in rainfed cultivation compared to irrigated cultivation. Based on this agricultural cropping pattern and crop performance in the Plasjan watershed in Isfahan province, efforts can be made in agricultural planning to increase productivity and efficiency by optimizing irrigated and rainfed cultivation of different crops, utilizing improved technologies in production and water and soil resource management, and selecting high-performance and climate- and water-compatible crops.

Considering the research objectives, the work is structured into five sections:

The first section introduces scenarios for improving water efficiency based on the opinions of experts and specialists.

The second section determines the effectiveness of scenarios for improving efficiency by employing a linked approach in three indices of water, food, and energy efficiency.

The third section identifies the changes in the impact of implementing scenarios for improving efficiency, employing a linked approach to three indices of water, food, and energy efficiency compared to the current situation.

The fourth section determines scenarios with positive impacts on improving water, food, and energy efficiency.

The fifth section prioritizes scenarios for improving efficiency using a linked approach in three indices of water, food, and energy efficiency through the multi-criteria evaluation method of Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS).

Management Scenarios

Considering the current status of water resources and the water balance in the study area, and based on the opinions of agricultural experts and specialists, 30 sub-scenarios were defined to enhance and achieve positive effectiveness in efficiency from a linked perspective. These sub-scenarios focused on changes in the cultivated area of crops.

Based on the defined approach for increasing efficiency, which is essentially a comprehensive approach, 30 sub-scenarios were identified for each dominant crop in the region. These sub-scenarios were based on six conditions: a 20%, 10%, or 30% increase in the cultivated area, or a 10%, 20%, or 30% decrease in the cultivated area. In this case, simulations were conducted based on a set of scenarios using the three indices of water efficiency, food efficiency, and energy efficiency.

Nexus Assessment of Water, Food, and Energy Efficiency Scenarios

One of the tools used to study these relationships is the Water-Food-Energy Nexus concept. The water-food-energy nexus has gained international attention since the Bonn Nexus Conference in 2011 (Salam et al., 2017). The linkage of water, energy, and food resources is highly complex, as the impacts of each sector have direct and indirect consequences for the others. The demand for each of these resources has been increasing over time, and it is expected to continue in the future, raising important questions about sustainable resource management (Shinde, 2017).

Link-related indicators will be used to assess the nexus based on the introduced scenarios in the previous step. The methodology involves calculating the linkage indicators before and after implementing the scenarios and evaluating the changes for each scenario. Three efficiency indicators, namely water efficiency, energy efficiency, and food efficiency, will be calculated based on available regional statistics and information.

Water Efficiency Indicator: In the study by El-Gafy (2017), the water efficiency indicator (, ton/m^3) is presented as Equation 1:

$$W_{pro.t} = Y_{c.t}/w_{c.t} \tag{1}$$

Where $Y_{c,t}$ represents the performance of product c in time period t, and $W_{c,t}$ represents the amount of water consumed for producing product c at time t.

The energy efficiency indicator is defined by El-Gafy (2017) in Equation 2:

$$E_{pro.t} = Y_{c.t}/E_{c.t} \tag{2}$$

Where $Y_{c,t}$ represents the performance of product c, and $E_{c,t}$ represents the energy consumed for product c at time t.

The food efficiency indicator is introduced in this study to analyze the water-energy-food nexus more effectively, and it is defined by Equation 3:

$$F_{pro.t} = Y_{c.t}/Y_{TOTAL} \tag{3}$$

Where $Y_{c,t}$ is the absolute difference between the food supplied and the food demand, and Y_{TOTAL} represents the total food supplied in the specified region.

The parameters of this model include the level of water resources exploitation (surface and groundwater), the energy extraction from water resources, the production and consumption of non-conventional water in the region, water consumption in the drinking, agricultural, and industrial sectors, and the energy flow in the agricultural production system of the region.

To calculate the energy indicators for the studied products, the energy of input factors, including seeds, fertilizers, pesticides, machinery, water, labor, etc., used in agricultural operations, along with the product yield, were calculated based on their energy equivalents.

The inputs in agricultural systems can be divided into two forms: direct (renewable) and indirect (non-renewable) energy. Based on this categorization, direct energy includes human labor, diesel fuel, irrigation water, and electricity, while indirect energy includes seeds, chemical fertilizers, animal manure, pesticides, and machinery (Yilmaz et al., 2005). Furthermore, human labor, seeds, irrigation water, and animal manure are considered renewable energy sources, while chemical fertilizers, diesel fuel, pesticides, and machinery are classified as non-renewable energy sources (Yilmaz et al., 2005). In the present study, the input energy for the studied products was calculated according to these categorizations.

Results and Discussion

Water, Food, and Energy Efficiency Indices under Different Scenarios

Based on the introduced efficiency indices in the previous step, the values of each of these indices were calculated (Table 2) to evaluate their interrelationships. The methodology involved calculating the levels of all three efficiency indices in the current state and after implementing each of the scenarios, thereby assessing the changes in the indices for each scenario. Considering the constraints considered for this optimization, a set of solutions (30 solutions) was obtained, and the results, according to the definition of the three water, food, and energy efficiency indices, are presented in Table 2. The aim was to select an optimal level of cultivation to achieve aquifer balance using a nexus approach with the three indices of water, food, and energy. Accordingly, the water, energy, and food efficiency indices was calculated based on the available statistics and information in the region.

Nexus Evaluation

After introducing corrective management sub-scenarios and determining the efficiency indices, these sub-scenarios were subjected to a nexus evaluation. Ultimately, out of the 30 defined sub-scenarios, 3 sub-scenarios were selected for increasing efficiency in the three indices of water, food, and energy, taking into account their positive impact on these three indices simultaneously. These sub-scenarios were ranked using the TOPSIS method. In this method, the sub-scenario with the highest score is ranked first. Table 3 presents the final scores and rankings using this method.

Among the 30 proposed sub-scenarios, the sub-scenario of a 30% increase in the cultivation area of forage maize ranked first as the selected sub-scenario in terms of its positive impact on all three efficiency indices of water, food, and energy. As observed, according to this method, the sub-scenarios involving changes in the cultivation area of other dominant crops in the region such as wheat, barley, alfalfa, and canola had a negative impact on the efficiency indices.

Considering the environmental conditions of the region, recommending a 30% increase in the cultivation area of forage maize not only leads to an increase in food efficiency but also improves water and energy efficiency. This is because with the same amount of water and energy consumption, the crop yield increases within the same cultivation area. It should be noted that this prioritization is based on equal weighting of the three efficiency indices of water, food, and energy.

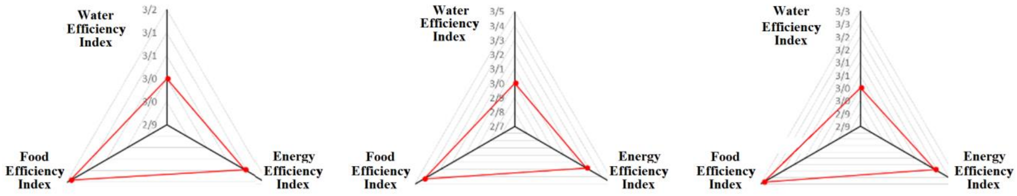
Figure 2 illustrates the performance comparison of implementing efficiency enhancement sub-scenarios with a nexus approach. As mentioned earlier, sub-scenarios involving changes in wheat varieties with full irrigation had the greatest positive impact on the nexus indices.

Prioritization of Selected Sub-scenarios with Equal Importance of Indices

Using the TOPSIS method and considering the specified weighting, the selected sub-scenarios are evaluated for prioritization.

Table 2. Water, Food, and Energy Efficiency under Different Scenarios

Scenario	sSb-scenarios	Energy efficiency (joules/kg)	Food efficiency	Water efficiency
The scenario of optimizing the cultivated area	Scp1	26.716	0.808	8.537
	Scp2	25.292	0.745	8.537
	Scp3	23.825	0.682	8.537
	Scp4	28.100	0.871	8.537
	Scp5	28.102	0.871	8.537
	Scp6	28.105	0.871	8.537
	Scp7	28.979	0.845	8.537
	Scp8	29.971	0.819	8.537
	Scp9	31.096	0.793	8.537
	Scp10	28.195	0.869	8.537
	Scp11	28.293	0.867	8.537
	Scp12	28.393	0.864	8.537
	Scp13	28.538	0.863	8.537
	Scp14	29.001	0.855	8.537
	Scp15	29.487	0.847	8.537
	Scp16	29.440	0.934	8.537
	Scp17	30.744	0.997	8.537
	Scp18	32.012	1.061	8.537
	Scp19	28.095	0.871	8.537
	Scp20	28.090	0.872	8.537
	Scp21	28.095	0.871	8.537
	Scp22	27.309	0.898	8.537
	Scp23	26.601	0.924	8.537
	Scp24	25.960	0.950	8.537
	Scp25	28.001	0.874	8.537
	Scp26	27.906	0.876	8.537
	Scp27	27.812	0.879	8.537
	Scp28	27.677	0.880	8.537
	Scp29	27.275	0.888	8.537
	Scp30	26.891	0.896	8.537



Scenario Scp16 Scenario Scp17 Scenario Scp17

Fig 2. Radar graph of productivity increase scenarios with a Nexus approach

The TOPSIS method is a multi-criteria decision-making method used to prioritize different options based on various criteria. In this method, the importance of the indices is determined through weighting. Here, equal weights are assigned to the three efficiency indices of water, food, and energy, meaning that each of these indices is considered equally important in the prioritization process.

Table 3 illustrates the results of this prioritization. Based on this table, the sub-scenarios can be ranked in order of priority based on the importance of different indices. By considering the importance level of each index, the prioritization of the proposed scenarios can be determined. In this study, for prioritizing the selected sub-scenarios conducted through the TOPSIS method (Table 3), equal weights are assigned to the three efficiency indices of water, food, and energy. However, it is possible to modify these weights based on specific decisions and policies.

Table 3. Prioritization of Selected Sub-scenarios using the TOPSIS method.

Prioritizing sub-scenarios	Description of sub scenarios	Sub-scenarios	Energy efficiency (joules/kg)	Food efficiency	Water efficiency
1	30% increase in the area under fodder corn cultivation scenarios	Scp18	3/279	3/431	3
2	20% increase in the area under fodder corn cultivation scenarios	Scp17	3/188	3/286	3
3	10% increase in the area under fodder corn cultivation scenarios	Scp16	3/096	3/142	3

Conclusion

The integration of water and energy consumption indices and food production in the analysis of management planning scenarios using a multi-criteria decision-making method can provide a more accurate analysis in selecting a powerful decision-making scenario for increasing efficiency with a nexus approach. By using a nexus approach, the effects of different scenarios on water, food, and energy can be evaluated simultaneously. Ranking and analyzing the impact of implementing management scenarios in each of the water, food, and energy sectors enables managers to have a broader insight into the interests of the involved sectors. By considering the comprehensive impacts of these three interconnected sectors and weighing the effects of each criterion based on variable policies, the management system of water resources and consumption can be directed towards increasing efficiency in water, food, and energy simultaneously. To improve the decision-making structure in agricultural production, the focus should shift from providing purely technical and structural scenarios to the modification of policies and infrastructures in the three sectors of water, food, and energy that significantly affect water and energy consumption and food production. This includes considering water, food, and energy efficiency and conducting detailed assessments of water resources and consumption.

The nexus approach to water resources and consumption management indicates that providing solutions to address crises in one sector without considering the other sectors will lead to greater problems. According to the nexus evaluation, sub-scenarios for changing the cultivation area of dominant crops in the region such as wheat, barley, alfalfa, and rapeseed not only carry high risks in terms of water supply, but also exhibit low efficiency in water, food, and energy criteria, resulting in negative scores compared to other sub-scenarios. Finally, among the 30 introduced sub-scenarios for improving efficiency, sub-scenarios for a 20%, 10%, and 30% increase in the cultivation area of forage maize showed positive impacts on the water, food, and energy efficiency indices. After prioritizing the influential sub-scenarios using the TOPSIS multi-criteria decision-making model, the sub-scenario for a 30% increase in the cultivation area of forage maize had the highest positive impact on water, food, and energy efficiency and was identified as the key scenario for evaluating efficiency in sustainable agricultural management.

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