



HYDRAULIC AND AGRICULTURAL PERFORMANCE ASSESSMENT OF A REHABILITATED PUBLIC IRRIGATION SCHEME IN SEMI-ARID TUNISIA

EL AMRI A.¹, MAJDOUB R.^{1*}, BEN AYED S.², M'SADAK Y.¹

¹ Professor, Department of Horticultural Systems Engineering and Natural Environment,
Higher Institute of Agronomy of Sousse, University of Sousse, P.O. Box 47, 4042 Chott
Mariem, Sousse, Tunisia

² Assistant Professor, Public Irrigation Schemes Operations Division, Regional
Commissariat for Agricultural Development, Cité Layouni, El Hajjem,
Kairouan, Tunisia

() rmajdoub@yahoo.com*

Research Article – Available at <http://larhyss.net/ojs/index.php/larhyss/index>

Received October 2, 2025, Received in revised form September 3, 2026, Accepted September 5, 2026

ABSTRACT

The sustainable management of irrigation water has become a strategic priority in arid and semi-arid regions where increasing water scarcity, climate variability, and growing agricultural demands threaten food security and ecosystem sustainability. Tunisia has implemented extensive rehabilitation programs for public irrigation schemes to improve water-use efficiency and enhance agricultural productivity. This study presents a comprehensive performance assessment of the rehabilitated Zaafrana II public irrigation scheme located in the Kairouan Governorate, central Tunisia. The evaluation combines hydraulic, agronomic, and management indicators, including water allocation efficiency, distribution network performance, adoption of water-saving irrigation technologies, cropping intensity, crop water satisfaction, and irrigation water productivity.

The results demonstrate that the rehabilitation program significantly improved the operational performance of the irrigation network. The average distribution efficiency reached approximately 95%, while the adoption of pressurized irrigation systems exceeded national strategic targets. Agricultural intensification increased progressively, reaching full land utilization after rehabilitation, whereas crop water requirements were satisfied at an average rate of approximately 85%, indicating efficient allocation of available water resources. The rehabilitation also encouraged farmers to adopt modern irrigation technologies and improved the overall productivity of irrigation water despite increasing climatic constraints.

The findings confirm that infrastructure modernization, combined with appropriate irrigation management practices, substantially enhances the sustainability and resilience

of public irrigation systems operating under water-limited environments. The study further highlights the importance of continuous monitoring using integrated performance indicators to support evidence-based decision-making and long-term water resource management in Mediterranean irrigated agriculture.

Keywords: Irrigation performance, Water-use efficiency, Public irrigation schemes, Irrigation modernization, Water productivity, Hydraulic efficiency, Agricultural intensification, Irrigation management, Climate resilience, Tunisia.

INTRODUCTION

Water scarcity has become one of the major constraints to sustainable agricultural development worldwide. During the last decades, rapid population growth, urbanization, industrial expansion, environmental degradation, and climate change have substantially increased the pressure on available freshwater resources. Agriculture remains the largest freshwater consumer, accounting for nearly 70% of global withdrawals, and consequently occupies a central position in strategies aimed at achieving water, food, and environmental security. In arid and semi-arid regions, where rainfall is insufficient and highly irregular, irrigation represents the principal means of stabilizing agricultural production and reducing the vulnerability of farming systems to climatic variability (Ben Mechlia, 2004).

The Mediterranean region is recognized as one of the world's climate-change hotspots. Climate projections indicate increasing temperatures, declining precipitation, more frequent drought episodes, and greater interannual rainfall variability, all of which directly affect water availability for agriculture. Several recent investigations conducted in North Africa, West Africa and other semi-arid environments have confirmed significant modifications in rainfall regimes and hydrological processes, emphasizing the urgent need for adaptive water-management strategies (Doumounia et al., 2020; Adja et al., 2021; Choukrani et al., 2018; Benali Khodja and Ferdjouni, 2024). These climatic changes not only reduce renewable water resources but also increase crop evapotranspiration and irrigation requirements, thereby widening the gap between water demand and available supplies.

Groundwater resources, which constitute the principal source of irrigation water in many semi-arid countries, are increasingly threatened by excessive abstraction combined with declining natural recharge. Long-term overexploitation frequently results in groundwater-level decline, increasing pumping costs, deterioration of water quality, and salinity problems. Hydrogeological investigations performed in several Mediterranean basins have demonstrated that groundwater sustainability depends simultaneously on climatic conditions, recharge dynamics, irrigation withdrawals, and integrated water-management policies (Bahir et al., 2015; El Moukharay et al., 2015; Baiche et al., 2015; Bemmoussat et al., 2017; Chibane and Ali-Rahmani, 2015). Consequently, irrigation development can no longer be dissociated from the sustainable management of groundwater resources.

Beyond the issue of water availability, increasing attention has recently been devoted to improving water productivity rather than simply increasing water supply. Modern irrigation policies seek to produce more agricultural output with less water through improved infrastructure, efficient irrigation technologies, optimized crop management, and better institutional governance. These objectives are consistent with integrated water-resource management principles, which emphasize the simultaneous optimization of technical, environmental, social, and economic dimensions of water use (Argaz, 2018; Aroua, 2022; Berrezel et al., 2023).

Tunisia is among the countries experiencing the highest levels of water stress within the Mediterranean basin. Natural water resources are limited, unevenly distributed, and characterized by considerable temporal variability. Moreover, irrigated agriculture occupies only a relatively small proportion of the cultivated land while consuming the majority of mobilized freshwater resources. According to Gharbi (2007), irrigated agriculture represents approximately 8% of the agricultural area but accounts for nearly 80% of the country's mobilized water resources. Faced with increasing agricultural demand, limited conventional water resources and the expected impacts of climate change, Tunisia has progressively adopted a comprehensive national policy promoting irrigation-water conservation and improved management of public irrigation schemes (Al Atiri, 2004; Gharbi, 2007).

The Tunisian National Water Saving Strategy was established to improve irrigation performance through three complementary actions: rehabilitation and modernization of collective irrigation networks, promotion of on-farm water-saving irrigation technologies, and strengthening of regional capacities in research, extension, and irrigation management. The strategy also encourages the adoption of cropping systems capable of generating higher economic returns while reducing pressure on available water resources. This policy was largely motivated by the relatively low agricultural intensification observed in several public irrigation schemes, significant water losses within deteriorated distribution networks, limited adoption of efficient irrigation techniques, and insufficient irrigation experience among farmers (Zella and Smadhi, 2007; Louati, 2008).

Similar modernization strategies have been implemented in many countries facing structural water scarcity. Numerous studies have demonstrated that replacing deteriorated open canals with pressurized pipe networks substantially reduces conveyance losses, improves delivery reliability, and facilitates the adoption of drip and sprinkler irrigation systems (Douh et al., 2013; Jelisavka and Goran, 2018; Derdour et al., 2022). Nevertheless, modernization of hydraulic infrastructure alone does not necessarily guarantee efficient water use. Sustainable improvements require simultaneous optimization of irrigation scheduling, maintenance practices, farmer participation, institutional organization, and continuous performance monitoring (Ayari and Ayari, 2017; Faye, 2016; Jayasena et al., 2021; Kezzar and Souar, 2024).

Accurate estimation of crop water requirements constitutes another fundamental component of irrigation management and performance assessment. Irrigation scheduling and the evaluation of water delivery adequacy require reliable estimates of crop evapotranspiration, which are generally derived from reference evapotranspiration (ET_o).

The calculation of ETo provides the scientific basis for determining crop water requirements under different climatic conditions and for comparing irrigation water supplied with actual crop demand (Allen et al., 1994; Doorenbos and Pruitt, 1977).

Consequently, irrigation performance assessment has progressively evolved from purely hydraulic evaluations toward multidisciplinary approaches integrating engineering, agronomic, economic and environmental indicators. Modern performance assessment seeks not only to quantify water losses within distribution networks but also to determine whether the available water effectively contributes to improving agricultural production, increasing water productivity and ensuring the long-term sustainability of irrigated agriculture. Such integrated approaches have become indispensable decision-support tools for prioritizing rehabilitation investments and improving water governance under increasing climatic uncertainty.

The increasing scarcity of freshwater resources has progressively shifted irrigation management objectives from maximizing water delivery toward maximizing water-use efficiency and agricultural productivity. Consequently, irrigation-system evaluation has evolved considerably over the last four decades. Early assessment methods were mainly concerned with the hydraulic functioning of irrigation networks, focusing on conveyance efficiency, distribution efficiency and operational reliability. More recently, irrigation performance assessment has adopted a multidisciplinary perspective that combines engineering, agronomic, environmental and socioeconomic indicators to evaluate both the technical functioning and the overall effectiveness of irrigation systems (Bos, 1997; Molden et al., 1998; Pereira et al., 2012).

This evolution reflects the recognition that efficient irrigation cannot be assessed solely by measuring the volume of water conveyed through a distribution network. Rather, irrigation performance must be evaluated according to the extent to which water deliveries satisfy crop water requirements, improve agricultural productivity, conserve natural resources and ensure the long-term sustainability of irrigated farming systems. Integrated performance assessment therefore provides decision-makers with objective information for identifying operational constraints, prioritizing rehabilitation investments and improving water-allocation policies under conditions of increasing climatic uncertainty (Bos et al., 2005; Playán and Mateos, 2006).

Several international organizations, particularly the Food and Agriculture Organization (FAO), the International Water Management Institute (IWMI) and the International Programme for Technology and Research in Irrigation and Drainage (IPTRID), have developed standardized methodologies for evaluating irrigation-system performance. These approaches recommend combining hydraulic indicators with agronomic and economic criteria in order to provide a comprehensive diagnosis of irrigation schemes. Among the most frequently applied indicators are conveyance efficiency, distribution uniformity, irrigation adequacy, relative water supply, irrigation efficiency, water productivity and agricultural output per unit of water consumed (Molden et al., 1998; Bos et al., 2005; Pereira et al., 2012).

Accurate estimation of crop water requirements constitutes the cornerstone of most irrigation-performance indicators. Irrigation adequacy can only be evaluated by comparing the volume of water supplied with crop water demand estimated from climatic conditions and crop characteristics. Consequently, the calculation of reference evapotranspiration and crop evapotranspiration remains an essential prerequisite for irrigation scheduling, performance diagnosis and water-allocation planning (Allen et al., 1994; Doorenbos and Pruitt, 1977). In semi-arid environments, where irrigation frequently compensates for highly variable rainfall, accurate estimation of crop water requirements becomes particularly important for minimizing both water deficits and excessive irrigation applications.

Numerous studies conducted in Mediterranean and North African countries have demonstrated that irrigation performance depends not only on hydraulic infrastructure but also on management practices implemented at both collective and farm levels. Rehabilitation of irrigation networks generally improves water-delivery reliability and reduces conveyance losses; however, significant gains in water-use efficiency can only be achieved when infrastructure modernization is accompanied by improved irrigation scheduling, farmer training, institutional coordination and regular performance monitoring (Douh et al., 2013; Derdour et al., 2022; Jayasena et al., 2021).

Research recently published has also highlighted the importance of integrating hydraulic and agronomic analyses when evaluating irrigation systems operating under water-limited conditions. Experimental investigations have demonstrated that irrigation performance is strongly influenced by irrigation method, irrigation scheduling, emitter characteristics, soil hydraulic properties and climatic conditions. For example, subsurface drip irrigation has been shown to improve soil-water distribution and reduce evaporation losses compared with conventional irrigation techniques, thereby contributing to higher irrigation efficiency and improved water productivity (Douh et al., 2013). Likewise, studies devoted to irrigation management under semi-arid conditions emphasize that continuous monitoring of soil moisture and crop water status considerably enhances irrigation performance while reducing unnecessary water applications (Hamimed et al., 2017; Derdour et al., 2022).

Beyond technical considerations, recent investigations increasingly recognize that irrigation performance must also be evaluated from the perspective of sustainability. Efficient irrigation systems should simultaneously ensure reliable agricultural production, preserve groundwater resources, maintain acceptable soil quality and optimize economic returns from limited water resources. This integrated perspective has become particularly relevant in Mediterranean countries, where recurrent droughts, groundwater depletion and increasing competition among water users require adaptive management strategies capable of balancing agricultural productivity with environmental conservation (Playán and Mateos, 2006; Pereira et al., 2012; Berrezel et al., 2023).

Consequently, modern irrigation-performance assessment is no longer restricted to describing the physical functioning of irrigation infrastructure. It has become a comprehensive decision-support approach that combines engineering measurements with indicators describing crop-water satisfaction, irrigation efficiency, water productivity and

environmental sustainability. Such integrated evaluation frameworks provide a robust scientific basis for assessing the effectiveness of rehabilitation programs and identifying opportunities for improving irrigation management under conditions of increasing water scarcity.

Although numerous methodologies have been proposed to assess irrigation-system performance, no single indicator is capable of describing the overall functioning of an irrigation scheme. Water distribution systems simultaneously involve hydraulic, agronomic, technical, economic and institutional processes, each of which influences the efficiency with which irrigation water is converted into agricultural production. Consequently, comprehensive performance assessment requires a combination of complementary indicators describing the different stages of water delivery, water application and agricultural response (Bos, 1997; Molden et al., 1998; Bos et al., 2005).

From a hydraulic perspective, the first objective is to evaluate the ability of the irrigation network to deliver water with minimum losses while ensuring equitable distribution among farmers. Distribution efficiency therefore remains one of the principal indicators used to assess the physical condition of irrigation infrastructure. High distribution efficiency reflects reduced conveyance losses resulting from seepage, leakage or operational deficiencies, whereas low efficiency generally indicates deterioration of hydraulic facilities or inadequate maintenance. Nevertheless, several authors have emphasized that hydraulic efficiency alone cannot accurately describe irrigation performance because a technically efficient network may still supply either insufficient or excessive quantities of water with respect to crop requirements (Bos et al., 2005; Playán and Mateos, 2006).

The adequacy of irrigation supply therefore constitutes a second fundamental dimension of performance assessment. This criterion evaluates the degree to which irrigation deliveries satisfy crop water requirements estimated from climatic conditions, crop coefficients and irrigation efficiencies. Reliable estimation of crop water demand, based on reference evapotranspiration and crop evapotranspiration, provides an objective framework for comparing theoretical water requirements with actual water deliveries (Allen et al., 1994; Doorenbos and Pruitt, 1977). Such comparisons are particularly important in semi-arid environments where limited water availability requires careful allocation of irrigation supplies throughout the cropping season.

Beyond the hydraulic functioning of irrigation systems, increasing attention has been devoted to the capacity of irrigation schemes to stimulate agricultural development. Rehabilitation projects are generally expected to improve cropping intensity, promote diversification towards higher-value crops and encourage the adoption of water-saving irrigation technologies. Consequently, indicators such as agricultural intensification rate, irrigation equipment rate and crop water satisfaction have become widely used for evaluating the effectiveness of modernization programs. These indicators quantify the extent to which farmers actually benefit from improved hydraulic infrastructure and whether rehabilitation investments contribute to better utilization of irrigable land and available water resources.

Experience accumulated in Tunisia has shown that rehabilitation of collective irrigation schemes generally produces significant improvements in farmers' behavior regarding irrigation practices. The replacement of deteriorated open canals by pressurized pipe systems facilitates the adoption of sprinkler and localized irrigation systems, reduces operational constraints and improves irrigation reliability. However, the benefits obtained remain closely associated with farmers' technical capacity, institutional organization and maintenance quality, confirming that modernization should be regarded as a continuous management process rather than a purely engineering intervention.

Several studies, recently published, support these conclusions. Experimental investigations conducted by Douh et al. (2013) demonstrated that subsurface drip irrigation considerably improves soil-water distribution and contributes to more efficient use of irrigation water under semi-arid conditions. Likewise, Ayari and Ayari emphasized that improving governance and users' participation remains an essential prerequisite for sustainable management of collective water services, while Aroua (2022) highlighted the necessity of integrating long-term urban and water-resource planning under increasing water scarcity. More recently, Berrezel et al. (2023) showed that decision-support systems considerably improve operational management of water-distribution networks by facilitating hydraulic regulation and optimizing water allocation.

Another indicator receiving increasing international attention concerns water productivity, which expresses agricultural production obtained per unit volume of water consumed. Unlike conventional efficiency indicators, water productivity simultaneously reflects irrigation performance, crop management and farmers' technical practices. Improvements in water productivity may therefore result either from reducing water consumption while maintaining crop yields or from increasing agricultural production without increasing water use. This concept has progressively become one of the principal objectives of irrigation modernization programs, particularly in regions where opportunities for developing additional conventional water resources are becoming increasingly limited (Molden et al., 1998; Pereira et al., 2012).

Recent studies further underline that irrigation performance should also be interpreted within the broader framework of sustainable water-resource management. Climate change, groundwater depletion, increasing competition among economic sectors and environmental constraints require irrigation systems capable of adapting to highly variable water availability while maintaining acceptable levels of agricultural production. Consequently, performance assessment has progressively evolved from a simple diagnostic tool into an essential component of integrated water-resources management, supporting strategic planning, investment prioritization and adaptive decision-making under uncertain climatic conditions (Playán and Mateos, 2006; Aroua, 2022; Berrezel et al., 2023).

Considering these scientific developments, the present study adopts a multidimensional evaluation framework based on six complementary performance indicators describing both the hydraulic functioning of the irrigation network and the effectiveness of agricultural development following rehabilitation. These indicators include the utilization rate of allocated water resources, distribution efficiency, adoption rate of water-saving

irrigation equipment, agricultural intensification rate, crop-water satisfaction rate and agronomic water-use efficiency. Their combined analysis provides a comprehensive diagnosis of the technical performance of the Zaafrana II public irrigation scheme while allowing assessment of whether the rehabilitation program has effectively improved irrigation management and enhanced the value of limited groundwater resources under semi-arid conditions. This integrated approach is fully consistent with the methodology originally proposed for the Zaafrana II irrigation scheme and with internationally recognized irrigation-performance assessment frameworks

Despite the considerable progress achieved in irrigation engineering and water-management practices during the past decades, comprehensive evaluations of rehabilitated public irrigation schemes remain relatively limited, particularly in semi-arid regions where groundwater constitutes the principal source of irrigation water. Most previous investigations have concentrated either on the hydraulic performance of irrigation networks or on the agronomic response of crops to irrigation practices, whereas relatively few studies have simultaneously integrated technical, hydraulic and agronomic indicators within a single evaluation framework. Consequently, decision-makers often lack comprehensive information allowing them to determine whether rehabilitation programs have effectively improved irrigation performance and enhanced the long-term sustainability of public irrigation schemes.

In Tunisia, substantial public investments have been devoted to the rehabilitation and modernization of collective irrigation systems as part of the National Irrigation Water Saving Strategy. Numerous irrigation schemes have been converted from deteriorated gravity-fed distribution systems to pressurized pipe networks with the objective of reducing water losses, encouraging the adoption of water-saving irrigation technologies and improving agricultural productivity. Nevertheless, relatively few published studies have quantitatively evaluated the actual impacts of these rehabilitation programs several years after their implementation, particularly through the simultaneous analysis of hydraulic efficiency, irrigation adequacy, agricultural intensification and water productivity. The scarcity of such comprehensive post-rehabilitation assessments limits the possibility of identifying the strengths and remaining constraints of modernization programs and of improving future investment strategies.

The Zaafrana II public irrigation scheme represents an appropriate case study for investigating these issues. Created in the 1960s and rehabilitated in 2005 under the national irrigation modernization program, this groundwater-fed irrigation scheme offers the opportunity to evaluate the medium-term effects of rehabilitation on irrigation performance under representative semi-arid conditions in central Tunisia. Its relatively homogeneous hydraulic infrastructure, diversified cropping systems and long-term operational records provide favorable conditions for a comprehensive assessment of irrigation-system functioning.

Unlike many previous studies focusing on one or two technical indicators, the present research adopts an integrated evaluation approach based on six complementary performance indicators describing both the hydraulic operation of the irrigation network and the agricultural utilization of the irrigated perimeter. The selected indicators include

the utilization rate of allocated water resources, distribution efficiency, adoption of water-saving irrigation equipment, agricultural intensification rate, crop-water satisfaction rate and agronomic water-use efficiency. Together, these indicators provide a comprehensive diagnosis of the effectiveness of the rehabilitation program while identifying the principal factors affecting irrigation performance under conditions of increasing water scarcity.

The findings of this study are expected to contribute to the growing body of knowledge on irrigation-performance assessment in semi-arid regions and to provide practical information for irrigation managers, water authorities and policy-makers responsible for planning future rehabilitation programs. Beyond the specific case of Zaafrana II, the proposed methodological framework may also be applied to other public irrigation schemes facing similar technical and environmental challenges throughout Tunisia and the Mediterranean region.

Accordingly, the main objectives of this study are (i) to assess the hydraulic and agronomic performance of the rehabilitated Zaafrana II public irrigation scheme using a set of complementary performance indicators, (ii) to evaluate the effectiveness of the rehabilitation program in improving irrigation-water management and agricultural development, and (iii) to identify the principal constraints and opportunities for enhancing the sustainable use of limited groundwater resources under semi-arid conditions.

Although the irrigation-performance assessment frameworks proposed by Bos (1997), Molden et al. (1998) and Pereira et al. (2012) pursue the common objective of improving irrigation-water management, they differ substantially in their conceptual perspectives and practical applications. Bos (1997) primarily considered irrigation performance from an engineering standpoint by emphasizing operational indicators describing the hydraulic functioning of irrigation and drainage systems, such as conveyance efficiency, adequacy, dependability and equity of water distribution. This approach provides an effective diagnosis of network operation but gives relatively limited consideration to the agronomic response of irrigated systems.

Molden et al. (1998) considerably extended this perspective by introducing comparative performance indicators capable of simultaneously evaluating water delivery, agricultural production and water productivity at different spatial scales. Their framework shifted the emphasis from hydraulic efficiency alone towards integrated assessment of irrigation-system performance, recognizing that the ultimate objective of irrigation is not merely to deliver water efficiently but to maximize agricultural benefits derived from each unit of water consumed. This concept has profoundly influenced irrigation-performance assessment and remains the foundation of numerous evaluation methodologies currently adopted by the International Water Management Institute (IWMI).

Building upon these developments, Pereira et al. (2012) further broadened the evaluation framework by explicitly incorporating the principles of sustainable water management. Their approach recognizes that irrigation performance should not be assessed solely according to technical efficiency or agricultural productivity but should also consider long-term conservation of water resources, environmental sustainability and adaptation to increasing water scarcity. Consequently, they advocate the combined use of

complementary indicators capable of simultaneously evaluating hydraulic operation, crop-water relationships, water productivity and resource conservation.

These three approaches should therefore be regarded as complementary rather than competing. Hydraulic indicators remain indispensable for evaluating the technical performance of irrigation infrastructure, whereas agronomic and water-productivity indicators provide information on the effectiveness with which irrigation water is transformed into agricultural production. Sustainability-oriented indicators, in turn, enable assessment of the long-term resilience of irrigated agriculture under conditions of increasing climatic and hydrological uncertainty.

In this context, the methodology adopted in the present study combines these complementary perspectives through the simultaneous analysis of six performance indicators describing water-resource utilization, hydraulic efficiency, adoption of water-saving technologies, agricultural intensification, crop-water satisfaction and agronomic water-use efficiency. Such an integrated framework provides a more comprehensive assessment of rehabilitated public irrigation schemes than approaches based exclusively on hydraulic or agronomic criteria and is particularly appropriate for evaluating irrigation modernization programs implemented in semi-arid Mediterranean regions.

Beyond the assessment of a single irrigation scheme, this study contributes to the methodological development of integrated performance evaluation by combining hydraulic, agronomic and management indicators within a unified assessment framework applicable to rehabilitated public irrigation schemes operating under water-scarce Mediterranean environments.

Although the literature provides numerous indicators for evaluating irrigation-system performance, no universally accepted framework exists because each indicator reflects only one specific dimension of irrigation management. Consequently, the selection of performance indicators should be consistent with the objectives of the evaluation, the characteristics of the irrigation scheme and the availability of reliable field data. Following the critical analysis of existing evaluation frameworks, the present study adopts an integrated set of six complementary indicators that collectively assess water-resource utilization, hydraulic operation, irrigation modernization, agricultural development, irrigation adequacy and agronomic water productivity. These indicators were selected because they combine the principal concepts developed in international irrigation-performance assessment while remaining fully applicable to the operational conditions of Tunisian public irrigation schemes. Their respective roles within the proposed evaluation framework are summarized in Table 1.

Table 1 illustrates the conceptual structure of the evaluation framework adopted in this study. Rather than emphasizing a single aspect of irrigation-system performance, the selected indicators represent six complementary dimensions that collectively describe the entire pathway from water allocation to agricultural production. The first two indicators primarily evaluate the technical and hydraulic functioning of the irrigation infrastructure, whereas the following three indicators assess the effectiveness of rehabilitation in improving irrigation practices and agricultural development. Finally, agronomic water-

use efficiency provides an integrated measure of the productive value generated by irrigation water. This hierarchical organization reflects the progressive evolution of irrigation-performance assessment from engineering-oriented evaluations towards integrated approaches combining hydraulic efficiency, agricultural productivity and sustainable water management. Consequently, the proposed framework offers a comprehensive basis for evaluating rehabilitated public irrigation schemes operating under conditions of increasing water scarcity.

Table 1: Conceptual framework adopted for the integrated performance assessment of the Zaafrana II public irrigation scheme and scientific justification of the selected indicators

Performance dimension	Indicator	Scientific objective	Expected contribution to the assessment	Key references
Water resources management	Water resource utilization rate	Quantify water allocation	Measures the level of groundwater exploitation	Bos (1997); Molden et al. (1998)
Hydraulic performance	Distribution efficiency	Assess network performance	Identifies conveyance losses and operational efficiency	Bos (1997); Bos et al. (2005)
Irrigation modernization	Water-saving irrigation equipment rate	Evaluate technological adoption	Quantifies the impact of rehabilitation on irrigation practices	Al Atiri (2004); Gharbi (2007)
Agricultural development	Agricultural intensification rate	Assess land-use improvement	Measures agricultural expansion after rehabilitation	Louhichi (1999); Molden et al. (1998)
Irrigation adequacy	Crop water satisfaction rate	Evaluate irrigation adequacy	Determines the balance between water supply and crop demand	Allen et al. (1994); Doorenbos and Pruitt (1977)
Water productivity	Agronomic water-use efficiency	Assess productive efficiency	Measures the agronomic return obtained per unit of irrigation water	Pereira et al. (2012); Molden et al. (1998)

SCIENTIFIC RELEVANCE OF THE ZAAFRANA II CASE STUDY

The Zaafrana II public irrigation scheme constitutes a particularly relevant case study for evaluating the effectiveness of irrigation rehabilitation programs implemented under semi-arid Mediterranean conditions. Unlike newly developed irrigation schemes, Zaafrana II has experienced the complete transition from an ageing gravity-based distribution system to a modern pressurized irrigation network following its rehabilitation in 2005 within the framework of the Tunisian National Irrigation Water Saving Strategy. This transition provides a unique opportunity to assess the medium-term impacts of rehabilitation not only on the hydraulic performance of the distribution system but also on farmers' adoption of improved irrigation practices and on the overall agricultural development of the irrigated perimeter.

Furthermore, the scheme is supplied exclusively by groundwater resources, which represent one of the most vulnerable water sources in central Tunisia because of increasing abstraction, irregular natural recharge and growing competition among agricultural users. Evaluating the efficiency with which these groundwater resources are utilized therefore constitutes an important issue extending beyond the local scale and contributing to broader discussions concerning sustainable groundwater management in Mediterranean irrigated agriculture. The relatively homogeneous physical characteristics of the irrigation network, together with the availability of long-term operational and agricultural records, also provide favorable conditions for conducting a comprehensive performance assessment based on reliable quantitative indicators.

Finally, although numerous rehabilitation projects have been implemented throughout Tunisia during the last two decades, only a limited number of studies have reported detailed post-rehabilitation evaluations integrating hydraulic, agronomic and water-management indicators within a single analytical framework. Consequently, the Zaafrana II irrigation scheme provides representative evidence of the effectiveness of public investment in irrigation modernization and offers valuable lessons that may support future rehabilitation programs implemented under comparable environmental and institutional conditions.

OBJECTIVES OF THE STUDY

Against this background, the present study aims to provide a comprehensive assessment of the performance of the rehabilitated Zaafrana II public irrigation scheme in central Tunisia. Specifically, the study seeks to:

- (i) evaluate the hydraulic performance of the irrigation distribution network through indicators describing water-resource utilization and distribution efficiency;
- (ii) assess the effectiveness of the rehabilitation program in promoting water-saving irrigation technologies, improving agricultural intensification and satisfying crop water requirements;

- (iii) quantify the agronomic efficiency of irrigation water under the prevailing cropping systems;
- (iv) identify the principal strengths and remaining constraints affecting the long-term performance of the irrigation scheme; and
- (v) provide recommendations that may contribute to improving the management and sustainability of rehabilitated public irrigation schemes operating under semi-arid Mediterranean conditions.

SCIENTIFIC CONTRIBUTION OF THE STUDY

Beyond the evaluation of a single rehabilitated irrigation scheme, this research contributes to the methodological development of irrigation-performance assessment in semi-arid environments. Its originality lies in the integration of complementary hydraulic, agronomic and management indicators within a unified evaluation framework capable of simultaneously assessing infrastructure performance, water-use efficiency and agricultural development. Rather than relying on a single efficiency criterion, the proposed approach combines indicators describing water allocation, network operation, crop-water satisfaction, agricultural intensification and irrigation-water productivity, thereby providing a comprehensive understanding of the factors governing the overall performance of public irrigation schemes.

The proposed framework also contributes to bridging the gap between engineering-based evaluations of irrigation infrastructure and broader sustainability-oriented approaches promoted in recent international literature. By linking hydraulic performance with farmers' irrigation practices and agricultural production, the methodology allows rehabilitation programs to be evaluated not only from a technical perspective but also in terms of their contribution to improving the productivity and sustainability of irrigated agriculture under conditions of increasing water scarcity.

Although developed using the Zaafrana II public irrigation scheme as a representative case study, the proposed methodological framework may readily be adapted to other rehabilitated public irrigation schemes operating under comparable climatic, hydrological and institutional conditions throughout Tunisia and other Mediterranean countries facing similar challenges related to groundwater management, irrigation modernization and agricultural water conservation.

MATERIAL AND METHODS

Study area

The present study was conducted in the Zaafrana II public irrigation scheme, located in the delegation of Bouhajla, Kairouan Governorate, central Tunisia. The irrigation scheme belongs to the public irrigated areas managed by the Regional Commission for

Agricultural Development (CRDA) and represents one of the collective irrigation projects rehabilitated under the Tunisian National Irrigation Water Saving Strategy.

The Zaafrana II irrigation scheme was initially established in 1964 and underwent complete rehabilitation in 2005 to improve the hydraulic performance of the distribution network and promote more efficient irrigation-water management. The scheme occupies a total irrigable area of approximately 145 ha, divided into 62 agricultural plots cultivated by 46 farmers. Since its rehabilitation, irrigation management has been entrusted to a local Agricultural Development Group (Groupement de Développement Agricole, GDA), responsible for the operation and maintenance of the collective irrigation infrastructure.

Geographically, the irrigation scheme is situated approximately 14 km from Bouhajla at an elevation of about 60 m above sea level, with geographic coordinates of approximately 35°40' N latitude and 10°05' E longitude. It occupies part of the alluvial plain of Oued Zeroud, one of the principal agricultural areas of central Tunisia. The topography is generally flat, facilitating pressurized water distribution and mechanized agricultural operations.

According to the bioclimatic classification of Tunisia, the study area belongs to the upper arid bioclimatic zone characterized by hot, dry summers and relatively cold winters. Mean annual rainfall is approximately 303 mm and exhibits considerable interannual variability. Summer temperatures frequently exceed 37°C during July, whereas winter minimum temperatures may decrease to approximately 5°C during January. The region is also characterized by high evaporative demand, frequent summer winds originating from the Sahara (Sirocco) and occasional winter frost episodes. These climatic conditions make irrigation indispensable for ensuring stable agricultural production throughout the year.

The soils of the irrigation scheme developed mainly on alluvial deposits of the Zeroud River plain. Two principal soil groups are encountered within the perimeter: young alluvial soils occupying the plain and calcareous brown soils developed on glacial formations located mainly in the southern part of the irrigation scheme. These soils are generally suitable for irrigated agriculture, although their productive potential strongly depends on appropriate irrigation scheduling and efficient water management.

Agricultural production is dominated by field crops, which occupy nearly 85% of the irrigated area, while the remaining land is mainly planted with olive trees at an average density of approximately 50 trees per hectare. Seasonal vegetable crops belonging principally to the Solanaceae and Cucurbitaceae families are cultivated during the summer season, whereas cereals and forage crops dominate winter cultivation. Farmers generally adopt biennial or triennial crop rotations adapted to local climatic conditions and irrigation-water availability.

The irrigation water supplied to the scheme originates exclusively from the Zaafrana II deep well drilled in 1958, which exploits the Quaternary aquifer underlying the Zaafrana plain. The well provides an average discharge of approximately 20 L s⁻¹. Irrigation water is characterized by moderate salinity (approximately 2.7 g L⁻¹) and a nearly neutral pH of

6.8, making it generally suitable for irrigation of the dominant crops cultivated within the perimeter under appropriate management practices.

Irrigation system

The Zaafrana II public irrigation scheme is supplied by groundwater extracted from the Zaafrana II deep well, drilled in 1958 and tapping the Quaternary aquifer of the Zaafrana plain. The well provides an average discharge of 20 L s^{-1} . Chemical analyses indicate that the irrigation water is moderately saline, with an average salinity of 2.7 g L^{-1} and a nearly neutral pH of 6.8. Under appropriate irrigation management, these characteristics allow the water to be used for the cultivation of the main crops grown within the irrigation scheme.

Water is conveyed from the pumping station through a pressurized distribution network. A main pipeline, 200 mm in diameter and 89 m in length, supplies three irrigation sectors designated A, B and C, covering areas of 52, 51 and 42 ha, respectively. The network also includes a regulating reservoir with a storage capacity of 10 m^3 . Water is delivered to the three sectors on demand, whereas water distribution within each sector is carried out according to a rotational irrigation schedule. The average flow rates supplied to sectors A, B and C are approximately 7.2 , 7.0 and 6.0 L s^{-1} , respectively.

Following the rehabilitation program, pressurized irrigation became the dominant irrigation method throughout the scheme. Drip irrigation is used on approximately 57 ha, sprinkler irrigation on about 68 ha and improved surface irrigation on the remaining 22 ha. The improved surface irrigation system uses pipelines installed between plots to regulate water discharge, improve water-distribution uniformity and reduce runoff losses at the upstream end of irrigation furrows. Some plots are irrigated using different methods depending on the cropping season; consequently, the total irrigated area slightly exceeds the actual area of the irrigation scheme.

The rehabilitation of the hydraulic infrastructure was intended to improve water-distribution efficiency, reduce water losses within the collective network and encourage farmers to adopt modern irrigation techniques compatible with the objectives of the Tunisian National Irrigation Water Saving Strategy. The effectiveness of this rehabilitation program was evaluated through a series of hydraulic and agronomic performance indicators described in the following sections.

Estimation of crop irrigation water requirements

Accurate estimation of crop irrigation water requirements constitutes a fundamental prerequisite for evaluating irrigation-system performance and optimizing irrigation-water allocation, particularly under arid and semi-arid climatic conditions where water resources are limited. Crop water requirements provide the reference against which the adequacy of irrigation water deliveries can be assessed and therefore represent an essential component of irrigation-performance evaluation (Doorenbos and Pruitt, 1977; Allen et al., 1994; Pereira et al., 2012).

In the present study, the gross irrigation water requirements were estimated from the corresponding net crop water requirements using the soil-water balance approach proposed by Doorenbos and Pruitt (1977). Net irrigation requirements were determined by considering crop evapotranspiration, while gross irrigation requirements were obtained by incorporating the overall irrigation efficiency of both the collective distribution network and the on-farm irrigation system. This methodology remains one of the most widely accepted procedures for irrigation planning and performance assessment under Mediterranean climatic conditions (Allen et al., 1994; Pereira et al., 2012).

Reference evapotranspiration (ET_o) was calculated using the FAO Penman-Monteith equation because of its sound physical basis and its internationally recognized accuracy for estimating atmospheric evaporative demand under a wide range of climatic conditions. This method, recommended by the Food and Agriculture Organization (FAO), has become the international standard for irrigation planning and crop water requirement estimation (Allen et al., 1994).

To estimate gross irrigation water requirements, an overall irrigation efficiency of 0.90 was adopted for localized irrigation systems and 0.80 for sprinkler irrigation systems. Since sprinkler irrigation represented the predominant irrigation method within the Zaafrana II irrigation scheme, an overall irrigation efficiency of 80% was considered representative of the study area. For plots irrigated by drip irrigation, gross irrigation requirements were reduced by 30%, corresponding to an actual irrigation requirement equivalent to approximately 70% of that estimated for sprinkler irrigation. These assumptions are consistent with the irrigation systems operating within the study area and with the methodology adopted in the original evaluation of the irrigation scheme.

Reliable estimation of crop water requirements is indispensable for assessing irrigation adequacy because it provides the theoretical water demand against which actual irrigation deliveries are compared. Several studies, recently published, have likewise emphasized that accurate estimation of evapotranspiration and irrigation requirements constitutes a prerequisite for improving irrigation scheduling, optimizing water allocation and enhancing irrigation efficiency under semi-arid climatic conditions (Douh et al., 2013; Chibane and Ali-Rahmani, 2015; Bahir et al., 2015). Likewise, international investigations have demonstrated that precise estimation of crop water requirements contributes significantly to improving irrigation-water productivity and supporting sustainable management of limited water resources (Allen et al., 1998; Pereira et al., 2012).

The estimated gross irrigation water requirements obtained using the above procedure were subsequently employed for calculating the crop water satisfaction rate, one of the principal performance indicators used in the present investigation. Comparison between theoretical crop water requirements and actual irrigation water deliveries provided an objective assessment of the adequacy of water supplied to the irrigation scheme and allowed evaluation of the effectiveness of irrigation management following rehabilitation.

Performance indicators

Performance assessment of irrigation schemes requires the use of objective indicators capable of describing the different components of irrigation management, from water abstraction to agricultural production. Since no single indicator can adequately characterize the overall performance of an irrigation system, the present study adopted six complementary indicators that evaluate water-resource utilization, hydraulic performance, irrigation modernization, agricultural development and agronomic water-use efficiency. The selected indicators were originally proposed for evaluating public irrigation schemes under Tunisian conditions and are consistent with internationally recognized approaches for irrigation-performance assessment (Louhichi, 1999; Bos, 1997; Molden et al., 1998).

Water resource utilization rate

The water resource utilization rate expresses the proportion of the available water resources that is actually abstracted and used within the irrigation scheme. This indicator provides valuable information on the degree of exploitation of the available groundwater resources and allows identification of situations of either underutilization or excessive abstraction. Low values generally indicate insufficient agricultural development or limited use of the irrigation infrastructure, whereas values approaching 100% reflect effective utilization of the allocated water resources, provided that groundwater abstraction remains sustainable (Louhichi, 1999; Bos, 1997). The water resource utilization rate was calculated as follows:

$$T_e = 100 \times \frac{V_p}{V_{disp}} \quad (1)$$

where

T_e = water resource utilization rate (%);

V_p = annual pumped water volume (m³);

V_{disp} = annual available water volume (m³).

Eq. (1) expresses the water resource utilization rate, which quantifies the proportion of the annual groundwater resources available to the irrigation scheme that is effectively pumped for agricultural use. This indicator provides a first assessment of the degree of exploitation of the available water resources and reflects the capacity of the irrigation scheme to mobilize its allocated water supply.

From a management perspective, values close to 100% indicate that the available groundwater resources are almost fully utilized, suggesting efficient exploitation of the irrigation infrastructure. However, such values should not automatically be interpreted as optimal because excessive abstraction may increase pressure on groundwater reserves and

compromise the long-term sustainability of the aquifer, particularly under semi-arid climatic conditions. Conversely, low utilization rates generally indicate under-exploitation of the available water resources, which may result from insufficient agricultural activity, inadequate operation of the irrigation system, technical failures, or limited farmers' demand.

Therefore, this indicator should always be interpreted together with the other performance indicators adopted in the present study. For example, a high-water resource utilization rate associated with low distribution efficiency may reveal significant water losses within the distribution network, whereas high utilization associated with low crop-water satisfaction may indicate that the available groundwater resources remain insufficient to satisfy crop water requirements. Similarly, low utilization combined with low agricultural intensification may suggest that the irrigation infrastructure is not being fully exploited despite the availability of water resources.

Although this indicator does not directly evaluate irrigation efficiency or agricultural productivity, it constitutes an essential first step in the integrated assessment of irrigation performance because it describes the initial stage of the water-management process, namely the mobilization of groundwater resources before their distribution and utilization within the irrigation scheme. Consequently, it provides valuable information for water managers responsible for balancing agricultural water demand with the sustainable exploitation of groundwater resources (Louhichi, 1999; Bos, 1997; Molden et al., 1998).

Distribution efficiency

Distribution efficiency evaluates the hydraulic performance of the collective irrigation network by comparing the volume of water effectively delivered to farmers with the volume pumped from the groundwater source. This indicator reflects water losses occurring within the distribution system because of leakage, operational constraints or other hydraulic deficiencies. High distribution efficiency indicates satisfactory network operation and effective rehabilitation of the irrigation infrastructure (Bos, 1997; Bos et al., 2005).

$$E_d = 100 \times \frac{V_{dist}}{V_p} \quad (2)$$

where

E_d = distribution efficiency (%);

V_{dist} = distributed water volume (m³);

V_p = pumped water volume (m³).

Eq. (2) defines the distribution efficiency, which measures the ability of the collective irrigation network to convey water from the pumping station to farmers while minimizing water losses. This indicator evaluates the hydraulic performance of the irrigation

infrastructure by comparing the volume of water effectively delivered to users with the total volume pumped from the groundwater source.

Distribution efficiency represents one of the most widely used indicators in irrigation-performance assessment because it directly reflects the physical condition and operational performance of the water-distribution network. Water losses occurring between the pumping station and the delivery points may result from leakage, seepage, pipe deterioration, malfunctioning control devices, unauthorized water withdrawals or operational deficiencies. Consequently, improvements in distribution efficiency generally indicate successful rehabilitation of the irrigation infrastructure and more effective management of irrigation water (Bos, 1997; Bos et al., 2005).

High values of distribution efficiency indicate that most of the pumped water reaches the farmers with limited conveyance losses, reflecting satisfactory hydraulic performance of the distribution system. Conversely, low values reveal significant water losses within the collective network and suggest the need for maintenance, rehabilitation or improvements in operational management. In groundwater-fed irrigation schemes such as Zaafrana II, reducing conveyance losses is particularly important because every cubic meter of water lost during distribution represents an unnecessary abstraction from a limited groundwater resource.

Nevertheless, although distribution efficiency constitutes an essential indicator of hydraulic performance, it should not be interpreted as a direct measure of irrigation effectiveness. A distribution network may exhibit very high hydraulic efficiency while still supplying either insufficient or excessive quantities of water relative to crop water requirements. Consequently, this indicator evaluates only the technical performance of water conveyance and must be interpreted together with indicators describing irrigation adequacy, agricultural intensification and water productivity. Such an integrated interpretation provides a more realistic assessment of the overall performance of the irrigation scheme than consideration of hydraulic efficiency alone (Molden et al., 1998; Pereira et al., 2012).

The rehabilitation of the Zaafrana II irrigation scheme aimed primarily at improving this indicator by replacing the deteriorated distribution system with a pressurized pipe network capable of reducing conveyance losses and improving the reliability of water delivery. Therefore, distribution efficiency represents one of the principal criteria for evaluating the technical effectiveness of the rehabilitation program and constitutes the first step in assessing whether improvements in hydraulic infrastructure have subsequently translated into better irrigation management and enhanced agricultural performance.

Water-saving irrigation equipment rate

The water-saving irrigation equipment rate represents the proportion of the irrigated area equipped with modern irrigation technologies such as drip or sprinkler irrigation systems. This indicator evaluates the degree of technological adoption by farmers following rehabilitation of the irrigation scheme and reflects the effectiveness of irrigation

modernization programs in promoting efficient on-farm water management (Al Atiri, 2004; Louati, 2008).

$$T_{equip} = 100 \times \frac{S_{equip}}{S} \quad (3)$$

where

T_{equip} = water-saving irrigation equipment rate (%);

S_{equip} = area equipped with water-saving irrigation systems (ha);

S = total irrigable area (ha).

Eq. (3) defines the water-saving irrigation equipment rate, which expresses the proportion of the irrigable area equipped with water-saving irrigation technologies relative to the total irrigable area of the scheme. Unlike the previous indicators, which primarily evaluate water-resource utilization and hydraulic performance, this indicator measures the level of technological modernization achieved within the irrigation scheme following the rehabilitation program.

The adoption of modern irrigation systems, particularly drip and sprinkler irrigation, is widely recognized as one of the most effective measures for improving irrigation efficiency under conditions of increasing water scarcity. These technologies generally provide better control of irrigation water application, reduce conveyance and application losses, improve water distribution uniformity and facilitate irrigation scheduling according to crop water requirements. Consequently, the water-saving irrigation equipment rate constitutes an indirect measure of farmers' adoption of improved irrigation practices and reflects the success of rehabilitation programs in promoting technological innovation (Al Atiri, 2004; Louati, 2008).

High values of this indicator indicate that a large proportion of the irrigation scheme has been equipped with modern irrigation technologies, suggesting effective implementation of irrigation modernization policies and improved opportunities for efficient water management. Conversely, low values may reveal limited adoption of water-saving equipment due to financial constraints, insufficient technical support, inadequate farmer training or reluctance to replace traditional irrigation methods. Therefore, this indicator provides valuable information on the socio-technical dimension of irrigation-system performance, which cannot be evaluated through hydraulic indicators alone.

Nevertheless, the interpretation of this indicator requires particular caution. A high equipment rate does not necessarily imply efficient irrigation-water use. The presence of modern irrigation equipment does not guarantee its proper operation or appropriate management. Poor maintenance, inadequate irrigation scheduling, insufficient technical knowledge or inappropriate management practices may considerably reduce the expected benefits of modern irrigation technologies. Consequently, the water-saving irrigation equipment rate should always be interpreted together with indicators describing crop water satisfaction and agronomic water-use efficiency in order to determine whether

technological modernization has effectively translated into improved irrigation performance (Pereira et al., 2012).

In the Zaafrana II irrigation scheme, this indicator plays a central role in evaluating the effectiveness of the rehabilitation program implemented in 2005. One of the principal objectives of this program was to encourage farmers to replace traditional irrigation methods with more efficient irrigation technologies capable of reducing water consumption while maintaining or improving agricultural production. The water-saving irrigation equipment rate therefore provides direct evidence of the extent to which this objective has been achieved and contributes to the overall assessment of irrigation modernization within the study area.

Agricultural intensification rate

Agricultural intensification reflects the degree of agricultural utilization of the irrigable land. It measures the relationship between the cultivated irrigated area and the total irrigable area of the irrigation scheme. High values indicate efficient agricultural exploitation and successful development following rehabilitation, whereas low values suggest underutilization of the available land resources (Louhichi, 1999).

$$T_i = 100 \times \frac{S_{cult}}{S_{irrig}} \quad (4)$$

where

T_i = agricultural intensification rate (%);

S_{cult} = cultivated irrigated area (ha);

S_{irrig} = total irrigable area (ha).

Eq. (4) defines the agricultural intensification rate, which expresses the proportion of the irrigable land that is actually cultivated under irrigation. This indicator evaluates the degree to which the available agricultural potential of the irrigation scheme is utilized and provides an overall measure of the effectiveness of land exploitation following the rehabilitation program.

Agricultural intensification is widely recognized as one of the principal objectives of irrigation development projects because the construction or rehabilitation of irrigation infrastructure is intended not only to improve water delivery but also to increase the productive use of agricultural land. Consequently, the agricultural intensification rate constitutes an important indicator for assessing whether investments in irrigation modernization have effectively encouraged farmers to cultivate a larger proportion of the irrigable area and to increase agricultural activity (Louhichi, 1999; Molden et al., 1998).

High values of this indicator indicate that most of the irrigable land is effectively cultivated, suggesting satisfactory utilization of the irrigation infrastructure and efficient

agricultural development. Such values generally reflect favorable technical, economic and organizational conditions, including reliable water supply, appropriate irrigation management, profitable cropping systems and active farmer participation. Conversely, low agricultural intensification rates reveal that a significant proportion of the irrigable area remains uncultivated despite the availability of irrigation facilities. This situation may result from insufficient water availability, high production costs, limited labor availability, inadequate farm management, land tenure constraints or unfavorable market conditions.

Unlike the previous indicators, agricultural intensification is influenced by numerous factors extending beyond the hydraulic performance of the irrigation network. Climatic variability, crop profitability, farmers' investment capacity, institutional support and agricultural policies may all affect the extent to which irrigable land is actually cultivated. Consequently, this indicator should not be interpreted exclusively as a measure of irrigation-system performance but rather as an indicator reflecting the interaction between hydraulic infrastructure, agricultural management and socio-economic conditions.

Furthermore, agricultural intensification should always be interpreted together with the crop water satisfaction rate and agronomic water-use efficiency. A highly intensified irrigation scheme may not necessarily operate efficiently if water supplies remain insufficient to satisfy crop water requirements or if agricultural productivity per unit of irrigation water is low. Conversely, moderate intensification associated with high water productivity may indicate a rational allocation of limited water resources towards high-value crops. Therefore, the combined analysis of these complementary indicators provides a more comprehensive evaluation of the effectiveness and sustainability of irrigation development than any single indicator considered independently (Bos, 1997; Pereira et al., 2012).

In the Zaafrana II public irrigation scheme, the agricultural intensification rate represents one of the principal indicators for evaluating the impact of the rehabilitation program on agricultural development. Beyond improving the hydraulic performance of the irrigation network, the modernization program sought to encourage more intensive and profitable use of irrigable land. Consequently, changes in agricultural intensification provide valuable evidence regarding the capacity of the rehabilitation program to stimulate agricultural production and enhance the overall performance of the irrigation scheme.

Crop water satisfaction rate

The crop water satisfaction rate evaluates the adequacy of irrigation water supplied relative to the theoretical crop water requirements previously estimated from the soil-water balance. This indicator constitutes one of the most important criteria for assessing irrigation management because it directly measures the extent to which irrigation satisfies crop water demand. Values close to 100% indicate appropriate irrigation scheduling, whereas lower values may reveal water deficits capable of affecting crop production (Doorenbos and Pruitt, 1977; Allen et al., 1994).

$$T_s = 100 \times \frac{V_{dist}}{V_{th}} \quad (5)$$

where

T_s = crop water satisfaction rate (%);

V_{dist} = distributed water volume (m³);

V_{th} = theoretical irrigation water requirement (m³).

Eq. (5) defines the crop water satisfaction rate, which expresses the ratio between the volume of irrigation water effectively supplied to crops and their theoretical irrigation water requirements. This indicator evaluates the adequacy of irrigation water delivery by comparing the actual water supplied with the quantity required to satisfy crop evapotranspiration under the prevailing climatic conditions. Consequently, it constitutes one of the most representative indicators for assessing irrigation management at the farm and irrigation-scheme levels.

The crop water satisfaction rate occupies a central position in irrigation-performance assessment because it directly reflects the balance between water supply and crop water demand. Unlike hydraulic indicators, which mainly evaluate the physical operation of the irrigation network, this indicator assesses whether irrigation management provides sufficient water to sustain normal crop growth and development. It therefore establishes the essential link between water-resource management and agricultural production (Doorenbos and Pruitt, 1977; Allen et al., 1994; Pereira et al., 2012).

Values approaching 100% indicate that irrigation water deliveries closely match crop water requirements, suggesting appropriate irrigation scheduling and satisfactory management of the irrigation system. Under these conditions, crop water stress is minimized, and agricultural production can generally reach its expected potential, provided that other production factors remain non-limiting. Conversely, values substantially lower than 100% indicate water deficits that may reduce crop transpiration, limit biomass accumulation and decrease crop yields. Persistent water deficits may also affect crop quality and reduce farmers' economic returns, particularly during periods of high evaporative demand.

However, values considerably exceeding 100% should also be interpreted with caution. Although additional irrigation water may occasionally be justified under particular agronomic conditions, systematic over-irrigation generally reflects inefficient irrigation scheduling and may lead to undesirable consequences such as deep percolation losses, nutrient leaching, soil waterlogging or secondary salinization. In groundwater-dependent irrigation schemes, excessive irrigation also increases unnecessary groundwater abstraction, thereby aggravating pressure on already limited water resources. Consequently, both under-irrigation and over-irrigation represent departures from optimal irrigation management.

The interpretation of the crop water satisfaction rate should therefore consider not only its numerical value but also its relationship with the other performance indicators adopted in this study. For example, a high distribution efficiency associated with a low crop water satisfaction rate may indicate that the irrigation network operates efficiently while the total water supplied remains insufficient to satisfy crop requirements. Conversely, a crop water satisfaction rate close to 100% combined with low agronomic water-use efficiency may suggest that adequate quantities of water are delivered but are not converted efficiently into agricultural production because of constraints unrelated to irrigation, such as inadequate crop management, poor soil fertility or adverse climatic conditions. The integrated interpretation of these indicators therefore provides a more comprehensive understanding of irrigation-system performance than the analysis of any single indicator considered independently (Bos, 1997; Molden et al., 1998).

Within the Zaafrana II public irrigation scheme, the crop water satisfaction rate constitutes one of the principal indicators for evaluating the effectiveness of the rehabilitation program. Since one of the primary objectives of irrigation modernization is to improve the adequacy and reliability of irrigation water delivery, this indicator makes it possible to determine whether the rehabilitated irrigation system is capable of satisfying crop water requirements while simultaneously promoting rational and sustainable use of groundwater resources.

Agronomic water-use efficiency

Agronomic water-use efficiency expresses the quantity of agricultural production obtained per unit volume of irrigation water consumed. Unlike purely hydraulic indicators, this parameter evaluates the productive efficiency of irrigation water and therefore establishes a direct relationship between irrigation management and agricultural production. It has become one of the principal indicators used for evaluating irrigation performance under conditions of increasing water scarcity because it simultaneously reflects irrigation practices, crop performance and water productivity (Molden et al., 1998; Pereira et al., 2012).

$$E_a = 100 \times \frac{R_t}{C_{water}} \quad (6)$$

where

E_a = agronomic water-use efficiency (kg m^{-3});

R_t = average crop yield (kg ha^{-1});

C_{water} = irrigation water consumption ($\text{m}^3 \text{ha}^{-1}$).

Eq. (6) defines the agronomic water-use efficiency, which expresses the amount of agricultural production obtained per unit volume of irrigation water applied. This indicator evaluates the productive performance of irrigation water by directly relating crop yield to water consumption. Unlike the previous indicators, which assess individual

components of irrigation management, agronomic water-use efficiency provides an integrated measure of the overall effectiveness of the irrigation system in transforming water resources into agricultural production.

Water productivity has become one of the principal objectives of modern irrigation management because increasing water scarcity no longer allows agricultural development to rely solely on expanding water supplies. Instead, sustainable irrigation strategies seek to maximize agricultural production while minimizing water consumption. Consequently, agronomic water-use efficiency has progressively evolved into one of the most widely accepted indicators for evaluating irrigation performance, particularly in arid and semi-arid regions where water constitutes the principal limiting production factor (Molden et al., 1998; Pereira et al., 2012).

High values of agronomic water-use efficiency indicate that irrigation water is effectively converted into agricultural production, reflecting the combined effects of satisfactory irrigation scheduling, appropriate crop management, adequate soil conditions and efficient operation of the irrigation system. Such values generally characterize irrigation schemes where water resources are rationally allocated and agricultural practices are well adapted to local environmental conditions. Conversely, low values indicate that relatively large quantities of irrigation water are required to produce a given amount of agricultural output. This situation may result from inadequate irrigation scheduling, excessive irrigation applications, poor crop management, unsuitable crop selection, soil limitations or unfavorable climatic conditions.

Unlike purely hydraulic indicators, agronomic water-use efficiency integrates the combined influence of numerous technical, agronomic and environmental factors. It therefore represents the final outcome of the entire irrigation process. Improvements in hydraulic infrastructure alone do not necessarily lead to higher agronomic water-use efficiency if they are not accompanied by appropriate irrigation scheduling, adoption of improved irrigation technologies, suitable cropping patterns and sound agronomic practices. Consequently, this indicator provides a comprehensive evaluation of the effectiveness of irrigation modernization programs by assessing whether improvements in water management are ultimately translated into increased agricultural productivity.

The interpretation of agronomic water-use efficiency should also consider the characteristics of the cultivated crops. Different crops naturally exhibit different water-productivity levels because of differences in physiology, growing period, biomass production and economic value. Therefore, comparisons between irrigation schemes should preferably be made under similar cropping conditions or after considering crop composition. Likewise, temporal variations in climatic conditions may influence crop yields independently of irrigation management and should therefore be taken into account when interpreting this indicator.

Within the Zaafrana II public irrigation scheme, agronomic water-use efficiency constitutes the final indicator used to evaluate the effectiveness of the rehabilitation program. Since the principal objective of irrigation modernization is not merely to improve water conveyance but ultimately to increase the productivity of limited

groundwater resources, this indicator synthesizes the combined effects of water allocation, hydraulic performance, technological modernization, agricultural intensification and irrigation adequacy. Consequently, it provides the most comprehensive assessment of the overall performance of the rehabilitated irrigation scheme and represents the ultimate criterion for evaluating the sustainability of irrigation-water management under semi-arid conditions.

Data collection and performance evaluation

The evaluation of the Zaafrana II public irrigation scheme was based on technical, hydraulic and agricultural data collected from the Regional Commission for Agricultural Development (CRDA) of Kairouan and from the Agricultural Development Group (GDA) responsible for managing the irrigation scheme. Additional information concerning cropping patterns, irrigation practices, cultivated areas and irrigation equipment was obtained through field surveys and interviews conducted with farmers operating within the irrigated perimeter. These complementary sources of information made it possible to establish a comprehensive database describing both the hydraulic functioning of the irrigation system and the agricultural exploitation of the irrigated area.

Hydraulic data included annual pumped water volumes, distributed irrigation water volumes, characteristics of the irrigation network and operational information concerning water allocation among the three irrigation sectors. Agricultural data comprised irrigated areas, crop distribution, irrigation methods, agricultural production and the adoption of water-saving irrigation technologies. Climatic data required for estimating crop water requirements were obtained from the meteorological records used in the original study. These data provided the basis for calculating the different performance indicators presented in the previous section.

Performance assessment was conducted by comparing the observed values of the selected indicators with the expected objectives of the rehabilitation program. Rather than analyzing each indicator independently, the six selected indicators were interpreted collectively in order to obtain an integrated diagnosis of the irrigation scheme. This approach recognizes that satisfactory irrigation performance cannot be evaluated solely on the basis of hydraulic efficiency but must simultaneously consider water-resource utilization, technological modernization, agricultural development and the adequacy of irrigation water supplied to crops (Bos, 1997; Molden et al., 1998; Pereira et al., 2012).

The simultaneous analysis of these complementary indicators also makes it possible to identify the principal factors limiting irrigation performance. For example, satisfactory hydraulic efficiency associated with low agricultural intensification may indicate insufficient utilization of the available irrigation infrastructure, whereas high water-resource utilization combined with low crop-water satisfaction may reveal increasing pressure on groundwater resources or deficiencies in irrigation scheduling. Consequently, integrated interpretation of the different indicators provides a more comprehensive evaluation than consideration of individual indicators separately (Bos et al., 2005).

This methodological framework was therefore adopted to evaluate the effectiveness of the rehabilitation program implemented in the Zaafrana II irrigation scheme and to determine whether modernization of the hydraulic infrastructure effectively contributed to improving irrigation management and agricultural development under the semi-arid conditions of central Tunisia.

RESULTS AND DISCUSSION

Estimation of crop irrigation water requirements

The estimation of crop irrigation water requirements constitutes the first step in evaluating the performance of the Zaafrana II irrigation scheme because it provides the reference against which the adequacy of irrigation water delivery can subsequently be assessed. Gross irrigation water requirements were calculated according to the methodology described in a previous section using the FAO Penman-Monteith approach for estimating reference evapotranspiration and considering an overall irrigation efficiency of 80%, which corresponds to the dominant sprinkler irrigation system operating within the study area (Doorenbos and Pruitt, 1977; Allen et al., 1994; Pereira et al., 2012). The monthly variation of the estimated gross crop irrigation water requirements is presented in Fig. 1.

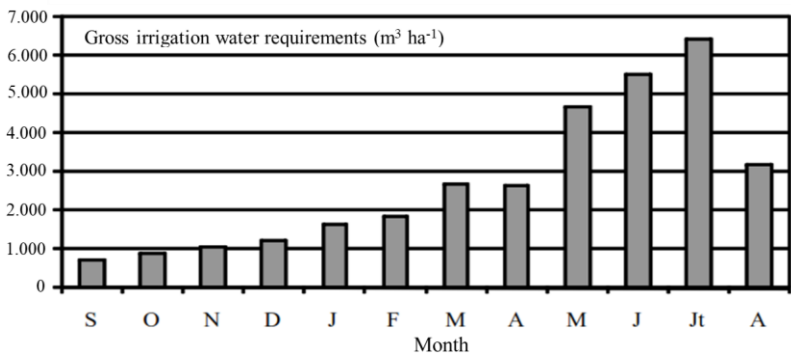


Figure 1: Monthly variation of gross crop irrigation water requirements in the Zaafrana II irrigation scheme

As illustrated in Fig. 1, irrigation water requirements varied considerably throughout the agricultural year, reflecting the combined influence of climatic conditions and crop evapotranspiration. Gross irrigation requirements progressively increased from autumn to spring before reaching their maximum during July, when atmospheric evaporative demand was highest. The peak gross irrigation requirement was estimated at approximately 6422.5 m³ ha⁻¹, corresponding to a reference evapotranspiration of 1626.9 mm year⁻¹.

The pronounced seasonal variation observed in Fig. 1 is characteristic of semi-arid Mediterranean environments, where high summer temperatures, low relative humidity

and intense solar radiation considerably increase atmospheric evaporative demand. Similar seasonal patterns have been reported in numerous irrigated regions subjected to Mediterranean and semi-arid climates, confirming that crop water requirements are governed primarily by climatic forcing and crop development stages (Allen et al., 1994; Pereira et al., 2012; Douh et al., 2013).

The estimated peak gross irrigation requirement corresponds to a peak irrigation demand of approximately $785 \text{ m}^3 \text{ ha}^{-1}$, equivalent to a design flow rate of $0.3 \text{ L s}^{-1} \text{ ha}^{-1}$. Under these operating conditions, the irrigation network is capable of supplying a maximum irrigated area of approximately 67 ha during the peak irrigation month. Field observations indicated that the actual irrigated area reached 68 ha, consisting of 33 ha of pepper, 7 ha of watermelon, 6 ha of melon and 22 ha of olive trees. This close agreement between the theoretical irrigation capacity and the actual irrigated area confirms that the hydraulic design of the rehabilitated irrigation network is well adapted to the irrigation demand during the period of maximum water consumption.

Accurate estimation of irrigation water requirements is fundamental for irrigation-performance assessment because it provides the theoretical benchmark required for evaluating crop water satisfaction and irrigation adequacy. Overestimation of irrigation requirements may result in excessive water application and reduced water productivity, whereas underestimation may induce water stress and consequently reduce crop yields. Therefore, reliable estimation of crop water requirements represents an essential prerequisite for improving irrigation scheduling and ensuring rational utilization of limited groundwater resources.

Overall, the results indicate that the estimated irrigation requirements are fully consistent with the hydraulic capacity of the rehabilitated irrigation network. They also confirm that the design discharge adopted for the Zaafrana II irrigation scheme is capable of satisfying peak crop water requirements under normal operating conditions while supporting efficient irrigation-water management throughout the agricultural season.

Water resource utilization rate and distribution efficiency

The annual evolution of the water resource utilization rate and the distribution efficiency before and after rehabilitation was evaluated using Eqs. (1) and (2), assuming that the irrigation network operated for 16 h day^{-1} , $25 \text{ days month}^{-1}$ and $10 \text{ months year}^{-1}$, as adopted in the original study. The calculated annual values of the water resource utilization rate and the corresponding distribution efficiency before and after the rehabilitation program are presented in Table 2.

Table 2: Annual pumped water volume, available water volume, distributed water volume, water resource utilization rate (T_e) and distribution efficiency (E_d) before and after rehabilitation of the Zaafrana II irrigation scheme.

Agricultural campaign	V_p (m ³)	V_{disp} (m ³)	T_e (%)	V_{dist} (m ³)	E_d (%)
2002/2003	14,356	288,000	5.0	14,00	97.5
2003/2004	15,033	288,000	5.2	14,650	97.4
2004/2005	16,558	288,000	5.8	16,010	96.7
2005/2006	7,950	288,000	2.8	7,600	95.6
2006/2007	194,658	282,962	68.8	185,150	95.1
2007/2008	239,657	269,568	88.9	229,775	95.9
2008/2009	303,239	308,160	98.4	286,278	94.4

The results presented in Table 2 indicate a remarkable improvement in the utilization of the groundwater resources allocated to the Zaafrana II irrigation scheme following rehabilitation. Before modernization of the irrigation network, the average water resource utilization rate remained below 5%, indicating substantial underutilization of the available groundwater resources. Such low values suggest that only a very limited proportion of the allocated water was effectively mobilized for agricultural production, reflecting poor exploitation of both the irrigation infrastructure and the available water resources.

Following rehabilitation, however, the utilization rate increased considerably. The indicator reached approximately 68.8% during the 2006/2007 irrigation season, increased further to 88.9% in 2007/2008, and finally attained 98.4% in 2008/2009, indicating that almost all of the available groundwater resources were effectively utilized. These results clearly demonstrate that rehabilitation substantially improved the operational capacity of the irrigation scheme and enabled a much more efficient exploitation of the allocated water resources.

The progressive increase observed after rehabilitation may be attributed to several complementary factors. Modernization of the pressurized distribution network improved the reliability of water delivery and increased farmers' confidence in the irrigation service, thereby encouraging greater utilization of irrigated land. Simultaneously, improvements in water management and operation of the collective irrigation system facilitated a more effective allocation of groundwater resources according to agricultural demand. Similar trends have been reported in several irrigation modernization programs, where rehabilitation of hydraulic infrastructure significantly enhanced the utilization of available water resources and promoted more intensive agricultural development (Bos, 1997; Molden et al., 1998; Pereira et al., 2012).

From the viewpoint of integrated water-resource management, the increase in the utilization rate represents one of the principal achievements of the rehabilitation program. Nevertheless, values approaching full utilization should be interpreted carefully. Although they indicate efficient use of the allocated groundwater resources, they also

imply that future agricultural expansion will become increasingly constrained by water availability. Under such circumstances, any additional increase in irrigation demand will need to rely primarily on improvements in water productivity rather than on increased groundwater abstraction. Consequently, continuous monitoring of groundwater withdrawals and irrigation performance remains essential for ensuring the long-term sustainability of the irrigation scheme.

Overall, the results demonstrate that rehabilitation transformed the Zaafrana II irrigation scheme from a severely underutilized irrigation system into one capable of exploiting almost all of its allocated groundwater resources (El Amri et al., 2012). This remarkable improvement confirms the effectiveness of the modernization program and provides quantitative evidence of the substantial enhancement achieved in irrigation-water management under the semi-arid conditions of central Tunisia (Benslimane et al., 2011; Bekhira et al., 2019; Bouly et al., 2019; Morsli and Habi, 2026).

Water-saving irrigation equipment rate

The adoption of water-saving irrigation technologies constitutes one of the principal objectives of the Tunisian National Irrigation Water Saving Strategy, since modernization of on-farm irrigation systems is expected to improve irrigation efficiency while reducing water losses and enhancing agricultural productivity. Consequently, the water-saving irrigation equipment rate provides an appropriate indicator for evaluating the effectiveness of the rehabilitation program implemented in the Zaafrana II irrigation scheme.

The distribution of the different irrigation systems currently used within the irrigation scheme is summarized in Table 3.

Table 3: Distribution of irrigation systems adopted in the Zaafrana II irrigation scheme

Irrigation techniques		
Drip	Aspersion	Enhanced gravity
39%	46%	15%

The results presented in Table 3 indicate that the Zaafrana II irrigation scheme is characterized by a high adoption rate of modern water-saving irrigation technologies. Drip irrigation represents approximately 39% of the irrigated area, whereas sprinkler irrigation accounts for 46%. Consequently, modern irrigation systems collectively cover approximately 85% of the irrigated land, while improved surface irrigation occupies only 15% of the irrigation scheme.

This overall equipment rate exceeds the national target of 75% established within the framework of the Tunisian National Irrigation Water Saving Strategy, demonstrating the effectiveness of the rehabilitation program in promoting the adoption of modern irrigation technologies. The widespread use of drip and sprinkler irrigation reflects farmers' willingness to adopt improved irrigation practices when reliable hydraulic infrastructure

and adequate technical support are available. Similar observations have been reported in several irrigated areas where modernization programs have considerably accelerated the dissemination of water-saving irrigation technologies and improved on-farm irrigation management (Al Atiri, 2004; Louati, 2008).

The predominance of localized and sprinkler irrigation systems is particularly advantageous under the semi-arid climatic conditions prevailing in central Tunisia. These technologies generally improve irrigation uniformity, facilitate irrigation scheduling according to crop water requirements and substantially reduce application losses compared with conventional surface irrigation methods. Consequently, they contribute not only to improving irrigation efficiency but also to enhancing crop productivity and reducing pressure on limited groundwater resources (Pereira et al., 2012; M'Sadak et al., 2012; Douh et al., 2013).

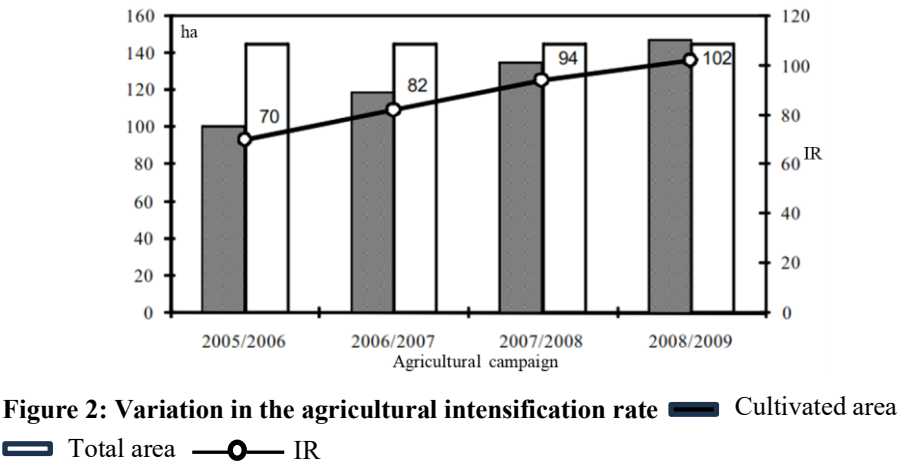
Nevertheless, the presence of modern irrigation equipment should not automatically be interpreted as evidence of optimal irrigation management. The efficiency of water-saving technologies depends largely on their operation, maintenance and the technical capacity of farmers to schedule irrigation according to crop water requirements. Inadequate irrigation scheduling, insufficient maintenance or poor system management may considerably reduce the expected benefits of these technologies. Therefore, the water-saving irrigation equipment rate should be interpreted together with the subsequent indicators describing agricultural intensification, crop water satisfaction and agronomic water-use efficiency.

Overall, the high equipment rate observed in the Zaafrana II irrigation scheme confirms that the rehabilitation program successfully promoted irrigation modernization and contributed to achieving one of the principal objectives of the national strategy for irrigation-water conservation. This result provides strong evidence that the public investments devoted to irrigation modernization have effectively encouraged the adoption of improved irrigation technologies capable of supporting more efficient and sustainable agricultural water management under semi-arid conditions (El Amri et al., 2012).

Agricultural intensification rate

Agricultural intensification constitutes one of the principal indicators for assessing the effectiveness of irrigation rehabilitation because it reflects the extent to which the available irrigable land is effectively utilized. Improvements in water delivery generally encourage farmers to increase the cultivated area, diversify crop rotations and adopt more intensive production systems. Consequently, the agricultural intensification rate (IR) provides valuable information on the agricultural response to irrigation modernization beyond the purely hydraulic performance of the distribution network.

The annual evolution of the agricultural intensification rate observed during the study period is presented in Fig. 2.



As illustrated in Fig. 2, agricultural intensification increased progressively following rehabilitation of the irrigation scheme. During the first years after modernization, farmers gradually expanded the cultivated irrigated area as confidence in the reliability of the water distribution system increased. This gradual evolution reflects the adaptation period generally observed after rehabilitation programs, during which farmers progressively modify their cropping strategies and irrigation practices.

The progressive increase in agricultural intensification demonstrates that rehabilitation generated benefits extending beyond the hydraulic infrastructure itself. Reliable irrigation services encouraged greater utilization of irrigable land and facilitated the introduction of cropping systems requiring more regular water supply. Similar conclusions have been reported in studies devoted to irrigated agriculture under semi-arid conditions, where improvements in irrigation infrastructure stimulated agricultural development while increasing the productive use of cultivated land (Argaz, 2018; Berrezel et al., 2023).

An agricultural intensification rate approaching or exceeding 100% indicates that the irrigable area is fully utilized and that, in some years, multiple cropping systems are practiced on the same land. Such values are generally considered indicators of efficient land utilization because they demonstrate that irrigation infrastructure contributes not only to stabilizing agricultural production but also to increasing annual cropping intensity. Nevertheless, increased cropping intensity inevitably results in higher seasonal water demand and requires careful irrigation scheduling to avoid unnecessary pressure on groundwater resources.

The interpretation of this indicator should therefore be associated with the results obtained for the crop water satisfaction rate and the agronomic water-use efficiency. High agricultural intensification accompanied by adequate crop water supply and satisfactory water productivity indicates that irrigation modernization has effectively improved both land and water utilization. Conversely, high intensification associated with inadequate irrigation scheduling may increase competition for water resources and reduce the long-term sustainability of irrigated agriculture (Nichane and Khelil, 2015; Saidi et al., 2016;

Aroua, 2018; Asseman et al., 2021; Nakou et al., 2023; Qureshi et al., 2024; Chowgule and Kulkarni, 2026).

Several investigations recently published have likewise shown that agricultural intensification can only be sustained when irrigation management, maintenance of hydraulic infrastructure and optimization of water allocation evolve simultaneously (Mezenner et al., 2022; Verma et al., 2023; Trivedi and Suryanarayana, 2023; Shaikh et al., 2024). Studies carried out in North African semi-arid environments have emphasized that the long-term success of irrigation modernization depends on continuous technical monitoring, efficient management institutions and adaptation of agricultural practices to the available water resources (Aroua, 2022; Kezzar and Souar, 2024; Choukrani et al., 2018).

Overall, the results demonstrate that rehabilitation of the Zaafrana II irrigation scheme significantly enhanced agricultural land utilization. The observed increase in agricultural intensification confirms that modernization of the irrigation network created favorable conditions for expanding irrigated agriculture while contributing to the objectives of sustainable agricultural development under conditions of increasing water scarcity.

Crop water satisfaction rate (SR)

The crop water satisfaction rate constitutes one of the most representative indicators of irrigation management because it evaluates the extent to which the volume of water delivered to the irrigation scheme satisfies the theoretical crop water requirements estimated from the soil-water balance. This indicator provides a direct assessment of irrigation adequacy and therefore represents a key criterion for evaluating the effectiveness of the rehabilitation program.

The annual evolution of the crop water satisfaction rate is presented in Fig. 3.

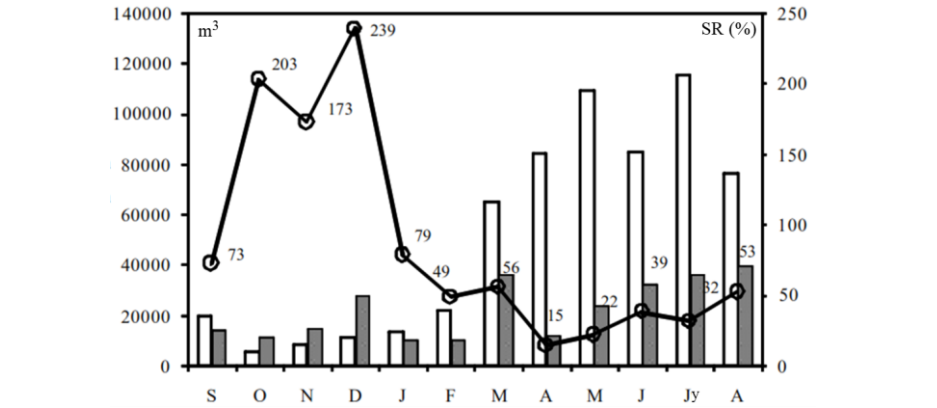


Figure 3: Monthly evolution of crop water satisfaction rates Theoretical Distributed SR

Fig. 3 indicates that the crop water satisfaction rate improved progressively following rehabilitation of the irrigation scheme. During the first years after modernization, irrigation deliveries gradually approached the theoretical crop water requirements, demonstrating a significant improvement in irrigation scheduling and water allocation. This evolution reflects the positive impact of the rehabilitation program on the capacity of the irrigation network to provide water in quantities compatible with crop demand.

The gradual increase in crop water satisfaction can be attributed to several complementary factors. Rehabilitation of the pressurized distribution network reduced hydraulic constraints, while the widespread adoption of sprinkler and drip irrigation systems facilitated more accurate irrigation scheduling. These improvements enabled farmers to apply irrigation water more efficiently according to crop requirements, thereby reducing both water deficits and excessive applications (Remini, 2020).

Experimental investigations carried out on the Zaafrana II irrigation scheme demonstrated that improved water-distribution uniformity contributes directly to better irrigation adequacy by reducing spatial variability in water application among plots (El Amri et al., 2012). Likewise, diagnostic studies on mechanized sprinkler irrigation systems have shown that regular maintenance and appropriate operation of irrigation equipment are essential for maintaining satisfactory irrigation performance throughout the irrigation season (M'Sadak et al., 2012).

The satisfactory crop water satisfaction rates obtained in the present study also indicate that the design discharge adopted during rehabilitation was generally consistent with peak irrigation demand. This observation confirms the conclusions drawn from the estimation of gross irrigation water requirements, which showed that the hydraulic capacity of the rehabilitated network was compatible with the seasonal evolution of crop water demand. Consequently, improvements in irrigation adequacy were achieved not only through modernization of the hydraulic infrastructure but also through better matching of water supply to crop requirements (Chaoui et al., 2016; Patel and Mehta, 2022; Pandey et al., 2022).

Nevertheless, irrigation adequacy should not be evaluated solely on the basis of the crop water satisfaction rate. Even when irrigation requirements are almost completely satisfied, inappropriate irrigation timing or poor irrigation uniformity may reduce water-use efficiency and crop productivity. Therefore, the interpretation of this indicator should always be associated with the agronomic water-use efficiency discussed in the following section, which evaluates the effectiveness with which irrigation water is converted into agricultural production (Pereira et al., 2012; Rezzoug et al., 2016; Zerkaoui et al., 2016; Remini, 2019; Derdour et al., 2022; Rouissat and Smail, 2022).

Recent studies dealing with irrigation management under water-scarce conditions have likewise emphasized that improving irrigation adequacy represents one of the most effective strategies for increasing water productivity while preserving groundwater resources. Investigations focusing on irrigation practices and water management in semi-arid environments have consistently highlighted the importance of combining hydraulic

modernization with continuous performance monitoring and farmer training in order to sustain high irrigation performance over time (Ouis, 2012; Kerzabi et al., 2016).

Overall, the results demonstrate that rehabilitation substantially improved the crop water satisfaction rate within the Zaafrana II irrigation scheme. The close correspondence between irrigation water deliveries and theoretical crop water requirements confirms that the modernization program significantly enhanced irrigation adequacy and created favorable conditions for improving agricultural production while supporting sustainable management of limited groundwater resources (Paulo Monteiro and Costa Manuel, 2004; Zegait et al., 2021; Rajput et al., 2023; Lachache et al., 2023; Remini, 2025; Subhadarsini et al., 2026).

Agronomic water-use efficiency (WE)

Agronomic water-use efficiency represents the final performance indicator used in the present study because it integrates the combined effects of water allocation, irrigation adequacy, agricultural intensification and crop management. Unlike the previous indicators, which evaluate specific components of irrigation performance, agronomic water-use efficiency reflects the capacity of the irrigation scheme to convert irrigation water into agricultural production. Consequently, it provides an integrated assessment of the overall effectiveness of the rehabilitation program.

The evolution of agronomic water-use efficiency during the study period is presented in Fig. 4.

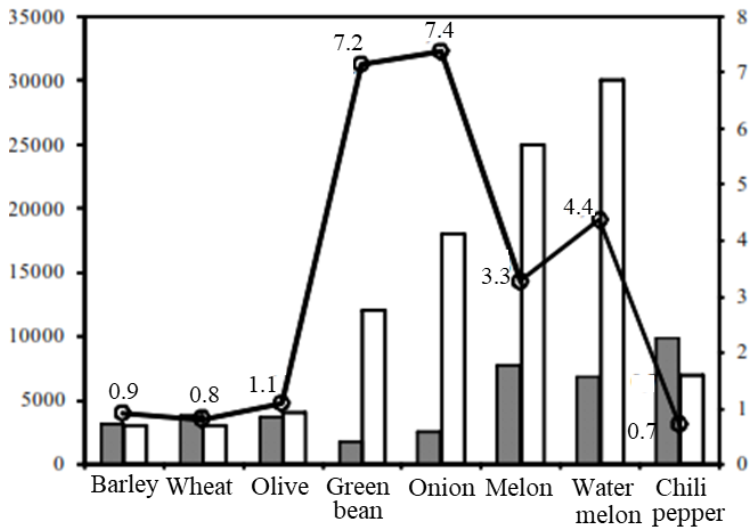


Figure 4: Evolution of agronomic water-use efficiency in the Zaafrana II irrigation scheme. ■ Volume m³/ha ■ Yield T/ha —○— WE kg/m³

The results presented in Fig. 4 indicate that agronomic water-use efficiency improved progressively following rehabilitation of the irrigation scheme. The increase observed throughout the monitoring period demonstrates that the improvements achieved in water distribution and irrigation management were progressively translated into higher agricultural productivity per unit volume of irrigation water. This evolution confirms that rehabilitation not only enhanced the hydraulic performance of the irrigation network but also improved the productive use of groundwater resources (Khemmoudj et al., 2016; El Fellah Idrissi et al., 2017).

The progressive increase in agronomic water-use efficiency may be explained by the combined effects of several complementary factors. Modernization of the irrigation infrastructure improved the reliability of water delivery, while the widespread adoption of sprinkler and drip irrigation systems facilitated better irrigation scheduling and reduced application losses. At the same time, the increase in agricultural intensification enabled farmers to optimize land utilization and improve crop productivity. The combination of these factors contributed to increasing the quantity of agricultural production obtained for each cubic meter of irrigation water applied.

Similar conclusions have been reported in studies devoted to the evaluation of irrigation-system performance, where improvements in hydraulic efficiency alone were considered insufficient unless accompanied by increases in water productivity. Bhouri Khila et al. (2015) emphasized that irrigation-performance assessment should integrate both hydraulic and agronomic indicators because efficient water conveyance does not necessarily guarantee efficient agricultural production.

Likewise, investigations carried out on mechanized irrigation systems in central Tunisia demonstrated that maintaining high irrigation performance depends not only on the quality of the hydraulic infrastructure but also on regular maintenance of irrigation equipment, appropriate operating conditions and continuous technical monitoring of irrigation practices (Douh et al., 2012; M'Sadak et al., 2012; Hamimed et al., 2017).

Recent studies devoted to groundwater management in semi-arid environments have further shown that improving water productivity constitutes one of the most effective strategies for adapting irrigated agriculture to increasing water scarcity. Rather than increasing groundwater abstraction, sustainable agricultural development should primarily rely on improving the economic and agronomic value generated by each unit of water consumed. This approach is fully consistent with the objectives of integrated water-resources management and climate-change adaptation (Kerzabi et al., 2016; Ouis, 2012).

The results obtained in the Zaafrana II irrigation scheme clearly demonstrate that rehabilitation successfully improved the productive use of irrigation water. Nevertheless, further improvements remain possible through optimization of irrigation scheduling, continuous technical support for farmers, periodic evaluation of irrigation-system performance and adoption of crop-management practices capable of increasing crop productivity without increasing irrigation-water consumption.

Overall, agronomic water-use efficiency provides the most comprehensive indicator of the success of the rehabilitation program because it synthesizes the cumulative effects of all the performance indicators analyzed previously. The observed improvement confirms that modernization of the irrigation scheme contributed not only to improving hydraulic performance but also to enhancing the economic and agronomic value of the limited groundwater resources available under the semi-arid conditions of central Tunisia.

Overall assessment of irrigation scheme performance

The integrated assessment of the six performance indicators provides a comprehensive evaluation of the rehabilitation program implemented in the Zaafrana II public irrigation scheme. Rather than analyzing each indicator separately, the combined interpretation of hydraulic, agronomic and management indicators makes it possible to identify the strengths and remaining limitations of the irrigation system. Such an integrated approach is now widely recognized as the most appropriate framework for evaluating irrigation projects because no single indicator is able to characterize the overall performance of an irrigation scheme (Bhouri Khila et al., 2015; Pereira et al., 2012).

The results obtained in the present study indicate that rehabilitation considerably improved the technical functioning of the irrigation scheme. The increase in the water resource utilization rate demonstrates that groundwater resources allocated to irrigation were more effectively mobilized after modernization, whereas the high distribution efficiency confirms the satisfactory hydraulic behavior of the pressurized distribution network. Similar observations concerning the importance of efficient water-resource planning and hydraulic management have been reported by Argaz (2018), who emphasized that integrated planning considerably improves the allocation and utilization of available water resources in semi-arid basins. Likewise, Aroua (2022) showed that long-term water-management strategies must combine hydraulic efficiency with sustainable resource planning in order to respond to increasing water scarcity.

The widespread adoption of sprinkler and drip irrigation systems further confirms the success of the rehabilitation program. Modern irrigation equipment improves not only water application efficiency but also the reliability of irrigation scheduling and the spatial uniformity of water distribution. Nevertheless, technological modernization alone cannot ensure sustainable irrigation performance unless accompanied by appropriate governance and continuous technical support for farmers. Similar conclusions were reached by Ayari and Ayari (2017), who stressed the importance of strengthening institutional governance for improving water management, and by Faye (2016), who highlighted the decisive role of local management institutions in maintaining irrigation performance over the long term.

The improvement in agricultural intensification and crop water satisfaction demonstrates that the technical rehabilitation of the irrigation network generated significant agronomic benefits. Better reliability of water delivery encouraged farmers to expand irrigated cropping activities while ensuring closer correspondence between irrigation supply and crop water requirements. These observations are consistent with the findings of Hamimed

et al. (2017), who demonstrated the usefulness of evapotranspiration monitoring for improving irrigation management in agricultural areas, and with those of Jelisavka and Goran (2018), who emphasized that modernization of irrigation practices constitutes a prerequisite for sustainable agricultural development under conditions of increasing water scarcity.

The progressive increase in agronomic water-use efficiency constitutes the most convincing evidence of the effectiveness of the rehabilitation program because it integrates the cumulative effects of all the previous indicators. Improved water productivity indicates that the additional volumes of groundwater mobilized after rehabilitation were effectively transformed into agricultural production. This observation agrees with the conceptual framework proposed by Bhouri Khila et al. (2015), according to which irrigation performance should always be evaluated through the combined analysis of hydraulic efficiency, irrigation adequacy and agronomic productivity rather than through isolated indicators.

Despite these encouraging results, long-term sustainability will depend on maintaining the hydraulic infrastructure in good operating condition and preserving groundwater resources. Hydrogeological studies conducted in semi-arid environments have shown that excessive groundwater abstraction, declining recharge and climatic variability may progressively reduce the sustainability of irrigation development if water withdrawals are not continuously monitored (Bahir et al., 2015; Chibane and Ali-Rahmani, 2015; Bemmoussat et al., 2017). Furthermore, recent investigations devoted to drought evolution and climate variability have confirmed that increasing climatic uncertainty will require more adaptive irrigation-management strategies in the future (Choukrani et al., 2018; Doumounia et al., 2020; Benali Khodja and Ferdjouni, 2024).

Overall, the integrated interpretation of the six performance indicators demonstrates that the rehabilitation program successfully achieved its principal objectives. The simultaneous improvement of water-resource utilization, distribution efficiency, irrigation modernization, agricultural intensification, crop water satisfaction and agronomic water-use efficiency confirms that modernization generated substantial technical and agronomic benefits. These results support the view that sustainable irrigation development in semi-arid regions should rely not only on rehabilitation of hydraulic infrastructure but also on continuous performance assessment, integrated water-resources management and adaptive irrigation strategies capable of responding to future climatic and hydrological challenges (Keddar and Souar, 2024; Khemmoudj et al., 2016).

CONCLUSION

The present study evaluated the performance of the rehabilitated Zaafrana II public irrigation scheme in central Tunisia using six complementary performance indicators describing the hydraulic, agronomic and managerial dimensions of irrigation. This integrated evaluation made it possible to assess not only the technical functioning of the irrigation network but also its contribution to the efficient utilization of groundwater resources and the development of irrigated agriculture. The selected indicators provided

a comprehensive framework for analyzing the effectiveness of the rehabilitation program and identifying its principal achievements.

The results demonstrated that rehabilitation substantially improved the overall performance of the irrigation scheme. The modernization of the pressurized distribution network considerably increased the utilization of the allocated groundwater resources while maintaining a high distribution efficiency. At the farm level, the rehabilitation program encouraged the widespread adoption of sprinkler and drip irrigation systems, thereby facilitating more reliable water delivery and improving irrigation management. These technical improvements were accompanied by a progressive increase in agricultural intensification, satisfactory crop water supply and enhanced agronomic water-use efficiency, indicating that the modernization program successfully translated hydraulic improvements into agricultural benefits. These findings are fully consistent with the objectives of the Tunisian National Irrigation Water Saving Strategy and with previous evaluations of the Zaafrana II irrigation scheme.

The combined interpretation of the six performance indicators confirms that irrigation-system performance cannot be adequately described by a single hydraulic indicator. Rather, effective evaluation requires simultaneous consideration of water-resource utilization, distribution efficiency, irrigation equipment, agricultural intensification, crop water satisfaction and water productivity. This integrated approach provides a more realistic assessment of irrigation-system performance and facilitates the identification of priorities for future management interventions, as emphasized in recent syntheses devoted to irrigation-performance assessment.

Despite the encouraging results obtained after rehabilitation, several challenges remain. The sustainability of the irrigation scheme will depend on continuous maintenance of the hydraulic infrastructure, periodic evaluation of irrigation performance, optimization of irrigation scheduling and long-term preservation of groundwater resources. Under the expected effects of climate change and increasing water scarcity, future improvements should focus primarily on increasing water productivity rather than expanding groundwater abstraction. Strengthening technical support to farmers, promoting continuous monitoring of irrigation-system performance and integrating climate-adaptation measures into irrigation management will further enhance the sustainability of public irrigation schemes operating under semi-arid conditions.

The methodological approach adopted in the present study may also be extended to other rehabilitated irrigation schemes in Tunisia and similar Mediterranean environments. The use of standardized performance indicators facilitates comparisons among irrigation schemes, supports decision-making for rehabilitation programs and contributes to improving the allocation and management of increasingly scarce water resources. Consequently, the proposed evaluation framework represents a useful decision-support tool for irrigation managers, water authorities and policy-makers involved in the modernization of irrigated agriculture.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could influence the work reported in this article.

REFERENCES

- ADJA M.G., ASSANDE A.A., DJEMIN E.J., SORO S.I., JOURDA J.P. (2021). Contribution of a GIS to mapping and spatial-temporal characterization of rainfall variability: case of the northern part of Ivory Coast, *Larhyss Journal*, No 47, pp. 119-132.
- AL ATIRI R. (2004). Modernization Efforts in Irrigated Agriculture in Tunisia, INCO-WADEMED Project, Proceedings of the Seminar on the Modernization of Irrigated Agriculture, Rabat, April 19-23, Morocco.
- ALLEN R.G., SMITH M., PERRIERA L.S., PERRIER A. (1994). An update of the calculation of reference evapotranspiration, *International Commission on Irrigation and Drainage (ICID) Bulletin*, Vol. 43, No 2, pp. 35-92.
- ARGAZ A. (2018). 1D model application for integrated water resources planning and evaluation: case study of Souss River Basin, Morocco, *Larhyss Journal*, No 36, pp. 217-229.
- AROUA N. (2018). Water resources in SNAT 2030. between economic needs and ecological requirements, *Larhyss Journal*, No 35, pp. 153-168. (In French)
- AROUA N. (2022). Long term city development versus water strategy in Al-Maghreb, *Larhyss Journal*, No 50, pp. 173-197.
- ASSEMIAN A.E., DJE BI DOUTIN S., SAMAKÉ Y. (2021). Consequences of the effects of climate change on water resources in a humid tropical zone of central eastern Côte d'Ivoire, *Larhyss Journal*, No 45, pp. 95-105.
- AYARI K., AYARI A. (2017). For better governance of drinking water in Tunisian rural areas, *Larhyss Journal*, No 29, pp. 7-21.
- BAHIR M., EL MOUKHAYAR R., CARREIRA P., SOUHEL A. (2015). Isotopic tools for groundwater management in semi-arid area: case of the Wadi Ouazzi Basin, Morocco, *Larhyss Journal*, No 23, pp. 23-39.
- BAICHE A., SIDI MOHAMED H., ABLAOUI H. (2015). Overexploitation of water resources of the Mostaganem Plateau aquifer, *Larhyss Journal*, No 22, pp. 153-165.
- BEKHIRA A., HABI M., MORSLI B. (2019). The management of flood risk and development of watercourses in urban areas: case of the town of Bechar, *Larhyss Journal*, No 37, pp. 75-92. (In French)

- BEMMOUSSAT A., ADJIM M., BENSAOULA F. (2017). Use of the ZYGOS model for the estimation of groundwater recharge in Sikkak watershed (Northwestern Algeria), *Larhyss Journal*, No 30, pp. 105-119.
- BENALI KHODJA M., FERDJOUNI N. (2024). Assessment of the meteorological drought in the northern part of Algeria: case of the Isser Wadi watershed, *Larhyss Journal*, No 58, pp. 39-54.
- BEN MECHLIA N. (2004). Prospects for Enhancing the Value of Irrigation Water in the Maghreb Countries, *Options Méditerranéennes, Series B.*, No 47, pp. 169-185.
- BENSLIMANE M., HAMIMED A., KHALDI A. EL ZERAY W. (2011). Methodological approach to evaluating wetland water management policy in the case of Chott Chergui (southwest Algeria), *Larhyss Journal*, No 22, pp. 167-181.
- BERREZEL Y.A., ABDELBAKI C., ROUISSAT B., BOUMAAZA T., KHALDOON A.M. (2023). Decision support system for the management of water distribution networks: a case study of Tourville, Algeria, *Larhyss Journal*, No 54, pp. 7-24.
- BHOURI KHILA S., DOUH B., MGUIDICHE A., BOUJELBEN A. (2015). Summary of the main performance indicators of irrigated systems, *Larhyss Journal*, No 24, pp. 263-279. (In French)
- BOS M.G. (1997). Performance indicators for irrigation and drainage, *Irrigation and Drainage Systems*, Vol. 11, No 2, pp. 119-137.
- BOS M.G., BURT C.M., MOLDEN D.J. (2005). *Irrigation and Drainage Performance Assessment: Practical Guidelines*, CABI Publishing, Wallingford, United Kingdom.
- BOULY S., CISSE A., FAYE C. (2019). Problematic of storm water management in cities in developing countries: case of Santhiaba and Belfort district (commune of Ziguinchor, Senegal), *Larhyss Journal*, No 39, pp. 313-331.
- CHAOUI S., HOUICHI L., TEBBI F.Z. (2016). Numerical simulation using characteristics method of pressurized transient flow in a water supply gravity pipe, *Larhyss Journal*, No 25, pp. 83-99. (In French)
- CHIBANE B., ALI-RAHMANI S.E. (2015). Hydrological based model to estimate groundwater recharge, real evapotranspiration and runoff in semi-arid area, *Larhyss Journal*, No 23, pp. 231-242.
- CHOUKRANI G., HAMIMSA A., SAIDI M.E., BABQIQI A. (2018). Diagnosis and future projection of climate change in arid zone: case of Marrakech-Safi region (Morocco), *Larhyss Journal*, No 36, pp. 49-63.
- CHOWGULE V., KULKARNI K.H. (2026). Cost overrun analysis of water resources projects, *Larhyss Journal*, No 65, pp. 27-47.
- DERDOUR A., BELAM N., CHEBAB W. (2022). Traditional irrigation system and methods of water harvesting in the oasis of Sfisifa, Ksour Mountains, Algeria, *Larhyss Journal*, No 49, pp. 17-35.

- DOORENBOS J., PRUITT W.O. (1977). Crop Water Requirements, FAO Irrigation and Drainage, Paper No 24, Food and Agriculture Organization (FAO), Rome, Italia, 176p.
- DOUH B., CHEHAIBI S., ZOUAGHI M. (2012). Diagnostic analysis of the maintenance of operational condition of mechanized sprinkler irrigation systems, Larhyss Journal, No 11, pp. 47-61. (In French)
- DOUH B., BOUJELBEN A., KHILA S., BEL HAJ MGUIDICHE A. (2013). Effect of subsurface drip irrigation system depth on soil water content distribution at different depths and different times after irrigation, Larhyss Journal, No 13, pp. 7-16.
- DOUMOUNIA A., ZEBE A., DAMIBA L., ZOUGMORE F., NIKIEMA M. (2020). Climate variability analysis in the Nouhao sub-basin in eastern center of Burkina Faso, Larhyss Journal, No 41, pp. 57-69.
- EL AMRI A., MAJDOUB R., M'SADAK Y., AOUICHAOU G. (2012). Experimental assessment of the uniformity of water distribution in the irrigated perimeter Zaafrana II (Central Tunisia), Larhyss Journal, No 11, pp. 37-45.
- EL FELLAH IDRISSE B., CHERAI B., HINAJE S., MEHDI K. (2017). Climatic variability and its influence on water resources in the northern part of the middle atlas Moroccan: the case of the Sefrou and the Anoceur causses, Larhyss Journal, No 32, pp. 155-179. (In French)
- EL MOUKHAYAR R., BAHIR M., CARREIRA P. (2015). Estimation of groundwater recharge in arid region through hydrochemistry and isotope: a case study of the Kourimat Basin, Morocco, Larhyss Journal, No 23, pp. 87-104.
- FAYE C. (2016). Management of water resources in the locality of Ndondol: community management of water resources and water-use conflicts in the villages of Mbomboye, Senegal, Larhyss Journal, No 25, pp. 219-240.
- GHARBI N. (2007). National Irrigation Water Saving Program: The Tunisian Experience, Ministry of Agriculture and Water Resources, Tunis, Tunisia, 20 p. (In French)
- HAMIMED A., ZAAGANE M., OUALID A.T., TEFFAHI M., BAKHTIAR D. (2017). Monitoring daily actual evapotranspiration and surface water status over an agricultural area in western Algeria using remote sensing data, Larhyss Journal, No 29, pp. 45-59.
- JAYASENA H.A.H., RATHNAYAKE R.D.D.P., CHANDRASENA M.G.P.N., RANATHUNGA B.P.D.W. (2021). A classic example of urban-rural linkages through the ancient Voda Ela in Sri Lanka: symbiosis of the total environment for efficient water management, Larhyss Journal, No 47, pp. 59-82.
- JELISAVKA B., GORAN R. (2018). Irrigation of agricultural land in Montenegro: overview, Larhyss Journal, No 33, pp. 7-24.

- KERZABI R., MANSOUR H., YOUSFI S., MUDRY J., BENCHAI B. A. (2016). Factors for assessment of groundwater vulnerability in semi-arid and arid zones, *Larhyss Journal*, No 27, pp. 187-203.
- KEZZAR M., SOUAR A. (2024). The water management system in the village of Menades in Algeria between past and present, *Larhyss Journal*, No 57, pp. 55-79.
- KHEMMOUDJ K., BENDADOUCHE H., MERABET S. (2016). Water resources in semi-arid and sustainable development, case Djemila northeast Algerian region, *Larhyss Journal*, No 26, pp. 249-258. (In French)
- LACHACHE S., DERDOUR A., MAAZOUZI I., AMROUNE A., GUASTALDI E. (2023). Statistical approach of groundwater quality assessment at Naama region, South-West Algeria, *Larhyss Journal*, No 55, pp. 125-144.
- LOUATI M.H. (2008). Mediterranean Strategy for Sustainable Development, Water Use Efficiency, National Study of Tunisia, Plan Bleu., 17p. (In French)
- LOUHICHI K. (1999). Improving irrigation efficiency for water conservation: the case of an irrigated area in Tunisia, Mediterranean Action Plan, CIHEAM-IAMM, 59p. (In French)
- MEZENNER N., BENKACI T., BERMAD A., DECHEMI N. (2022). Dam reservoir operation optimization using genetic algorithm and principal component analysis simulation model - case of dam Ghrib, *Larhyss Journal*, No 51, pp. 145-160.
- MOLDEN D.J., SAKTHIVADIVEL R., PERRY C.J., DE FRAITURE C., KLOEZEN W.H. (1998). Indicators for Comparing Performance of Irrigated Agricultural Systems, IWMI Research Report No. 20, International Water Management Institute, Colombo, Sri Lanka.
- MORSLI S., HABI M. (2026). Performance and assessment of future water management using the WEAP and RRV indicators in Maghnia municipality, northwestern Algeria, *Larhyss Journal*, No 66, pp. 265-295.
- M'SADAK Y., DOUH B., HAMZA M.E. (2012). Diagnosis of system operation pivot sprayers used in large irrigated exploitation of central Tunisia, *Larhyss Journal*, No 11, pp. 97-107. (In French)
- NAKOU T.R., SENOU L., ELEGBEDE B., CODO F.P. (2023). Climate variability and its impact on water resources in the lower mono river valley in Benin from 1960 to 2018, *Larhyss Journal*, No 56, pp. 215-234.
- NICHANE M., KHELIL M.A. (2015). Climate change and water resources in Algeria - vulnerability, impact and adaptation strategy, *Larhyss Journal*, No 21, pp. 25-33. (In French)
- OUIS S. (2012). Impact of climatic fluctuations on the quantity and quality of groundwater in a semi-arid region: case of the Ghriss plain (northwest Algeria), *Larhyss Journal*, No 11, pp. 119-131. (In French)

- PANDEY P., MISHRA R., CHAUHAN R.K. (2022). Future prospects in the implementation of a real-time smart water supply management and water quality monitoring system, *Larhyss Journal*, No 51, pp. 237-252.
- PATEL K., MEHTA D. (2022). Design of the continuous water supply system using Watergems software: a case study of Surat city, *Larhyss Journal*, No 50, pp. 125-136.
- PAULO MONTEIRO J., COSTA MANUEL S. (2004). Dams' groundwater modelling and water management at the regional scale in a coastal mediterranean area (the southern Portugal region – Algarve), *Larhyss Journal*, No 3, pp. 157-169.
- PEREIRA L.S., CORDERY I., IACOVIDES I. (2012). Improved indicators of water use performance and productivity for sustainable water conservation and saving, *Agricultural Water Management*, Vol. 108, pp. 39-51.
- PLAYÁN E., MATEOS L. (2006). Modernization and optimization of irrigation systems to increase water productivity, *Agricultural Water Management*, Vol. 80, No 1-3, pp. 100-116.
- QURESHI H.U., ABBAS I., SHAH S.M.H., TEO F.Y. (2024). Hydrologic evaluation of monthly and annual groundwater recharge dynamics for a sustainable groundwater resources management in Quetta city, Pakistan, *Larhyss Journal*, No 60, pp. 27-53.
- RAJPUT D.C., MISTRY K.P., BHORANIYA J.K., UMRIGAR J.N., WAIKHOM S.I. (2023). Assessing the decadal groundwater level fluctuation-a case study of Gujarat, India, *Larhyss Journal*, No 54, pp. 175-191.
- REMINI B. (2019). The Oasis of El Guerrara (Algeria): irrigation and recharge of the aquifers ensured by the floods, *Larhyss Journal*, No 40, pp. 135-163. (In French)
- REMINI B. (2020). Oued M'Zab's I.R.S development population and floods, life in harmony Part 1: hydraulic structures, *Larhyss Journal*, No 42, pp. 63-95.
- REMINI B. (2025). Algeria's groundwater: an untapped strategic resource for water security, *Larhyss Journal*, No 61, pp. 401-431.
- REZZOUG C., REMINI B., HAMOUDI S. (2016). Modern irrigation in oasis of Lahmar (Bechar, Algeria): problems and consequences, *Larhyss Journal*, No 25, pp. 259-267. (In French)
- ROUISSAT B., SMAIL N. (2022). Contribution of water resource systems analysis for the dynamics of territorial rebalancing, case of Tafna system, Algeria, *Larhyss Journal*, No 50, pp. 69-94.
- SAIDI S., AMMAR S., Jlassi F., BOURI S. (2016). Urban expansion and its impact on water resources using remote sensing and GIS: Case of great Tunis, *Larhyss Journal*, No 28, pp. 87-101. (In French)
- SHAIKH A.F., BHIRUD Y.L., MORE S.B., PAWAR A.D., VAIDYA O.V. (2024). Comparative analysis of optimization algorithms for reservoir operations: a case study on Ukai dam, *Larhyss Journal*, No 58, pp. 179-196.

- SUBHADARSINI J., JHARIYA D.C., VIDYARTHI V.K., SAHU M. (2026). Assessment and validation of groundwater potential zones using analytical hierarchy process (AHP) and observed yield data in the central Kharun river basin, Chhattisgarh, India, *Larhyss Journal*, No 66, pp. 127-156.
- TRIVEDI M., SURYANARAYANA T.M.V. (2023). An assessment of optimal operation policies for a reservoir using particle swarm optimization, *Larhyss Journal*, No 56, pp. 107-121.
- VERMA S., SAHU R.T., PRASAD A.D., VERMA M.K. (2023). Reservoir operation optimization using ant colony optimization a case study of Mahanadi reservoir project complex Chhattisgarh - India, *Larhyss Journal*, No 53, pp. 73-93.
- ZEGAIT R., REMINI B., BENSAHA H. (2021). Groundwater vulnerability assessment in the M'Zab valley - southern Algeria, *Larhyss Journal*, No 48, pp. 211-234.
- ZELLA L., SMADHI D. (2007). Evolution of Irrigation, *Larhyss Journal*, No 6, pp. 65-80. (In French)
- ZERKAOUI L., BENSLIMANE M., HAMIMED A., KHALDI A. (2016). Land development issues and water use conflict in mountain areas, case of the Beni Chougrane mountains (northwestern Algeria), *Larhyss Journal*, No 26, pp. 209-223. (In French)