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Benchmarking Irrigation Water Delivery Performance Before and After Irrigation Modernization: A Case Study of the Uluborlu Irrigation Scheme, Türkiye

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ABSTRACT

The demand to enhance irrigation system performance through modernization and more effective water management has grown due to climate change and growing water constraint. It is necessary to use objective and standardized performance assessment techniques to evaluate the effectiveness of irrigation modernization. Using globally accepted benchmarking indicators, this study evaluated the effect of irrigation modernization on water delivery performance in the Uluborlu Irrigation Scheme, Türkiye. The project was first put into service in 1984 as a conventional open-channel, gravity-fed irrigation system. Since 2012, it has been updated and run as a pressurized, piped irrigation network. Irrigation water delivery performance was assessed using three benchmarking indicators: annual relative water supply (ARWS), annual irrigation water delivery per unit irrigated area (AIWD-IA), and annual irrigation water delivery per unit command area (AIWD-CA). Annual data from the pre-modernization (2002–2011) and post-modernization (2012–2021) periods were compared. The Shapiro-Wilk test was used to determine the normality of the data, and the non-parametric Mann-Whitney U test was used to investigate the differences between the two periods. After modernization, the benchmarking indicators steadily declined. ARWS decreased from 0.81 to 0.61, AIWD-IA from 5 913.1 to 4 472.1 m^3 ha^{-1}, and AIWD-CA from 5 345.5 to 3 740.7 m^3 ha^{-1}. Additionally, a more reliable irrigation water delivery regime was demonstrated by fewer standard deviations following modernization. Temporal trends and descriptive data consistently showed reduced water delivery levels over the post-modernization period, although these decreases were not statistically significant ($p > 0.05$). Although the anticipated benefits were only partially realized, the results show that irrigation modernization enhanced operational water conservation and contributed to a more reliable irrigation water delivery regime. This study demonstrates that benchmarking provides a robust and standardized framework for evaluating irrigation modernization outcomes and supports evidence-based decision-making for sustainable irrigation management.

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Introduction

Agriculture remains the world's largest consumer of freshwater, accounting for roughly 70% of global withdrawals (FAO 2017). In Türkiye, this figure is even higher, with approximately 77% of the nation's available water potential being allocated to agricultural irrigation (TAGEM, 2021). However, this vital resource is facing unprecedented pressure from an era marked by accelerating climate change, rapid population growth, and a soaring global food demand. It is projected that nearly one-quarter of the world's population will face water scarcity during the twenty-first century (Biswas et al., 2025; Alotaibi et al., 2023; Seckler et al., 1999). As water scarcity intensifies, optimizing the performance of existing irrigation systems has evolved from a regional concern into an urgent global priority. At the same time, agriculture offers substantial potential for improving water use efficiency and adapting to increasing water limitations (FAO, 2012). Achieving this potential requires the development and implementation of effective strategies to conserve water and enhance its efficient use in agricultural production. Consequently, maximizing water productivity stands as a cornerstone of sustainable agricultural water management (Alharbi et al., 2024; Dehghanisanij et al., 2006). Driven by these urgent needs, substantial capital has been channeled into modernizing irrigation networks globally.

This modernization goes far beyond fixing pipelines; it is a comprehensive evolution designed to elevate the technical, operational, managerial, and institutional capacity of water delivery systems (FAO, 2025). Modernization of irrigation systems substantially improves water application efficiency. In particular, replacing traditional open-channel surface irrigation systems with closed pressurized pipe distribution networks can significantly reduce conveyance losses and improve delivery control. Pressurized systems, especially drip irrigation technologies, can achieve water savings of up to 90% compared with conventional surface irrigation methods (Nikolaou et al., 2020). Modern irrigation technologies aim to provide sustainable and cost-effective solutions for agricultural water management (Askaraliev et al., 2024).

Irrigation modernization often comprises structural and managerial interventions such as canal lining, automation of flow control structures, replacement of degraded hydraulic components, installation of flow measurement equipment, and enhanced operational management practices (Renault et al., 2007). These solutions aim to improve water delivery reliability, reduce conveyance losses, improve distribution uniformity, and increase overall irrigation efficiency. Numerous studies have shown that modernization projects can significantly improve irrigation system performance by reducing excessive water application and increasing the accuracy of water allocation (Koech & Langat, 2018; Playán & Mateos, 2006). However, some studies indicate that the expected water-saving objectives of modernization have not been fully achieved; in some cases, only slight improvements in water use efficiency have been observed, and local irrigation water consumption may have even increased at times (Soto-García et al., 2013; López-Gunn et al., 2012). This issue has been widely discussed in the literature. It has been observed that the problems of irrigation systems are related to both physical and managerial arrangements, and that the performance of these large-scale systems can only be improved through the implementation of physical changes together with institutional and managerial reforms (Plusquellec, 2009; Yaman & Güzel, 2026).

Although considerable investments have been devoted to irrigation modernization worldwide, evaluating whether these investments actually improve irrigation performance remains an important scientific and managerial challenge. Physical improvements alone cannot guarantee better system performance unless operational outcomes are quantitatively assessed using objective and standardized evaluation methods. Therefore, performance assessment has become an indispensable component of irrigation management, providing essential information for identifying operational strengths and weaknesses and supporting evidence-based management decisions.

The Food and Agriculture Organization of the United Nations (FAO), the International Water Management Institute (IWMI), the International Programme for Technology and Research in Irrigation and Drainage (IPTRID), and the International Commission on Irrigation and Drainage (ICID) have promoted benchmarking as a standard methodology for evaluating irrigation system performance.

The extent to which the operation of the irrigation distribution system is effectively managed to meet users' water requirements is an important performance indicator of irrigation projects and is defined as the service delivery performance of the irrigation project (Malano & Burton, 2001; Bos et al., 2005). In this context, among the proposed indicators, annual irrigation water delivery per unit command area, annual irrigation water delivery per unit irrigated area, and annual relative water supply are widely recognized as key indicators for evaluating water delivery performance. Şener & Abdisamad (2023) compared the irrigation performance indicators of two irrigation schemes in the Burdur Basin, one operated as a conventional open-channel system and the other as a pressurized pipe distribution network. Similarly, Kukul et al. (2008), Ünal & Kıymaz (2025), and Kirmikil (2025) assessed the performance of the Menemen Irrigation Association, the Sıddıklı Irrigation Association, and the Karacabey Water Users Association, respectively, using internationally recognized irrigation performance indicators. Comparing these indicators before and after modernization enables objective evaluation of rehabilitation effectiveness and helps identify remaining operational constraints.

In Türkiye, numerous irrigation networks constructed during the second half of the twentieth century have undergone rehabilitation and modernization to improve water management performance. However, post-rehabilitation performance assessments remain limited for many irrigation schemes, particularly with respect for long-term comparative analyses based on operational data. Evaluating changes in water distribution indicators over extended periods is essential for determining whether modernization investments achieve their intended objectives.

To address this research gap, the present study evaluates the long-term impacts of modernization on irrigation performance in the Uluborlu Irrigation Scheme, located in the Antalya River Basin of Türkiye. The scheme was modernized by converting from a conventional open-channel gravity-fed system to a closed, pressurized piped network. The analysis is based on a continuous 20-year observation period, including 10 years before and 10 years after modernization, allowing a direct comparison of irrigation system performance under two distinct operational regimes. Among the benchmarking indicators proposed by these organizations, annual irrigation water delivery per unit command area (AIWD-CA), annual irrigation water delivery per unit irrigated area (AIWD-IA), and annual relative water supply (ARWS) are widely recognized as key indicators for assessing irrigation water delivery performance. Using key irrigation performance indicators, this study aims to assess the extent to which modernization improved water management efficiency, service delivery performance, and overall system effectiveness, while also examining whether water savings achieved through modernization translated into expansion of irrigated area.

Materials and Methods

Materials

The Uluborlu Irrigation Scheme is located within the Antalya River Basin in Türkiye.

The irrigation system was commissioned in 1984 to support agricultural production in the region. The area within Türkiye and its position in the basin are shown in the study map (Figure 1). The irrigation area has an average elevation of 1 000 m above mean sea level. The study area exhibits a transitional climate between the Mediterranean and continental climate zones, characterized by semi-humid and semi-continental conditions. Annual temperatures generally range from −4°C to 30°C, with hot, dry summers and cold, rainy winters. The region is characterized by fruit orchard cultivation, particularly the locally recognized cherry variety known as the Uluborlu Cherry.

Figure 1. Location of the Uluborlu Irrigation Scheme in Türkiye

The main water source of the irrigation scheme is the Uluborlu Dam, which has an approximate storage capacity of 21 million m³. The designed net irrigation command area of the system is 1 640 hectares. However, over time, the water resources of the Uluborlu Dam became insufficient to meet irrigation demand. Similar to many other regions in Türkiye, this limitation was mainly attributed to environmental degradation, periodic drought events, and inefficient water use, particularly resulting from the widespread reliance on traditional surface (flood) irrigation methods.

The emergence of these challenges led the General Directorate of State Hydraulic Works (DSİ) to increasingly emphasize the necessity of modern irrigation methods, particularly during the mid-2000s. Consequently, modern irrigation technologies were incorporated into newly developed irrigation projects. However, how these modern irrigation methods could be integrated into previously completed projects, and whether such integration would provide tangible benefits, became a subject of considerable debate. As a result, it was decided to implement a pilot application project. In this context, the Uluborlu Dam and Irrigation Scheme was selected as the pilot project, representing the first rehabilitation project of its kind in Türkiye.

The Uluborlu Irrigation Scheme, which was commissioned in 1984 as a traditional open-channel, gravity-fed irrigation system, underwent infrastructure modernization and has been operated as a pressurized, piped irrigation network since 2012. The objective was to modernize the irrigation infrastructure through rehabilitation. Significant improvements in water management were achieved following the rehabilitation. Since closed pressurized pipe networks are designed according to different engineering criteria than traditional open-channel systems, the network alignment was modified during modernization. To ensure uninterrupted irrigation service throughout the irrigation season, the modernization works were carefully planned and implemented in stages. The revised network layout, together with reduced conveyance and application losses, enabled the expansion of the net command area from 1 640 ha to 2 145 ha. Subsequently, minor operational adjustments were made to the service area, and the irrigation scheme has since been operated with a net command area of 2 135 ha.

With the commissioning of the closed pressurized system in 2012, modern irrigation practices became widely adopted in the region. Among these, drip irrigation systems emerged as the dominant method, replacing conventional surface irrigation practices.

This study used annual irrigation performance indicators, namely AIWD-CA, AIWD-IA, and ARWS, to evaluate the impact of irrigation system modernization in the Uluborlu Irrigation Scheme.

Methods

For analytical purposes, the dataset was divided into two periods:

- Pre-modernization period (Before, the year 2002-2011): representing the operational conditions of the classical open-channel irrigation system
- Post-modernization period (After, the year 2012-2021): representing the conditions following the conversion to a pressurized piped system in 2012

The analysis covers a continuous 20-year long-term observation period, including 10 years before and 10 years after the 2012 modernization, allowing a direct comparison of system performance between the two operational periods. To ensure consistency, annual observations were organized into a unified dataset, enabling time-series-based evaluation of irrigation performance indicators.

Irrigation system performance was evaluated using multiple quantitative indicators derived from annual operational records. These indicators represent different dimensions of system performance, including water delivery, irrigation demand fulfillment, and system efficiency. Annual irrigation water delivery data were obtained from the official operational records of DSİ. Water deliveries were measured using the standard flow measurement structures routinely operated by DSİ. The selected indicators used in this study are presented in Table 1. The data used for calculating the indicators were obtained from the official records of the General Directorate of State Hydraulic Works (DSİ, 2002–2021). Annual irrigation records for the Uluborlu Irrigation Scheme were collected from the operating authority. The dataset included irrigation water deliveries, command area, irrigated area, and crop water demand information covering both the pre-modernization and post-modernization periods. The irrigation modernization program, initiated in 2012, was used as the reference point for dividing the dataset into two distinct periods.

Following data collection, three internationally recognized benchmarking indicators were calculated: AIWD-CA, AIWD-IA, ARWS. These indicators were selected to evaluate the effectiveness of irrigation water delivery and the adequacy of water supply before and after modernization.

Table 1. Performance indicators used in the study

Indicator	Indicator definition
Annual irrigation water delivery per unit command area (m^3ha^{-1}) (AIWD-CA)	Total water inflow to the irrigation system / Total command area
Annual irrigation water delivery per unit irrigated area (m^3ha^{-1}) (AIWD-IA)	Total water inflow to the irrigation system / Total irrigated crop area
Annual relative water supply	Total water inflow to the irrigation system/ Total annual volume of crop water demand

Prior to statistical comparisons, the normality of each performance indicator was assessed using the Shapiro–Wilk test. Shapiro–Wilk test results showed that AIWD-CA ($p = 0.0409$), AIWD-IA ($p = 0.0323$), and ARWS ($p = 0.0340$) did not satisfy the assumption of normality; therefore, a nonparametric approach was adopted. Since none of the variables satisfied the assumption of normality ($p<0.05$), differences between the pre-modernization and post-modernization periods were evaluated using the nonparametric Mann–Whitney U test (Wilcoxon rank-sum test). The statistical analyses were performed using JMP software (SAS Institute Inc., Cary, NC, USA), with statistical significance evaluated at the 95% confidence level ($p<0.05$).

Finally, the results obtained from the benchmarking indicators and statistical analyses were interpreted to assess the effectiveness of irrigation modernization on water delivery performance and to identify the operational improvements achieved following modernization.

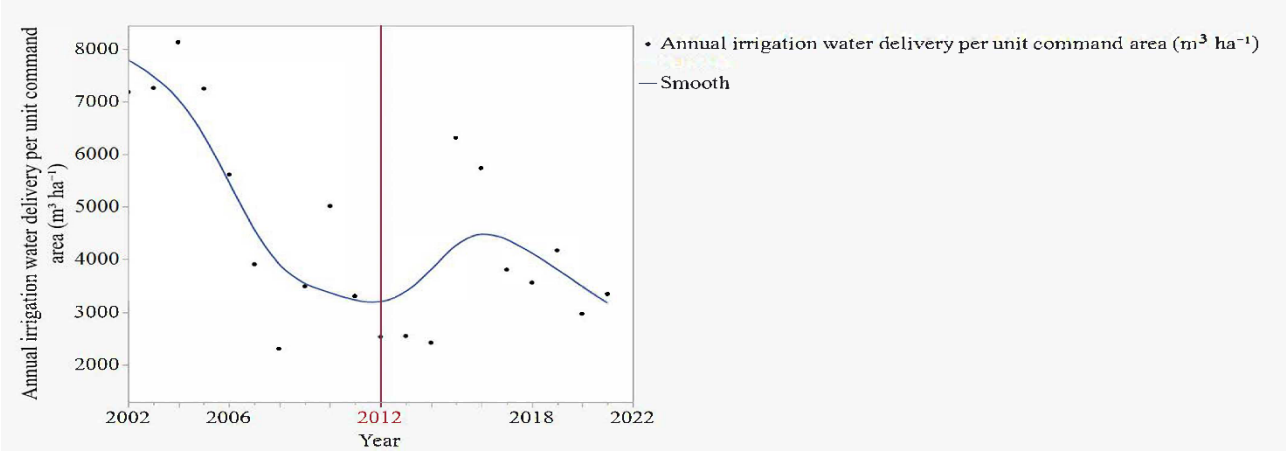
Results

Table 2 presents the descriptive statistics of the benchmarking indicators for the pre-modernization and post-modernization periods.

Table 2. Descriptive statistics of benchmarking indicators before and after irrigation modernization

Indicator	Period	Mean ± SD	Median	Minimum	Maximum	Change (%)
AIWD-CA	Before	5345.5 ± 2040.4	5316	2304	8128	
	After	3740.7 ± 1343.8	3453	2420	6316	−30.0
AIWD-IA	Before	5913.1 ± 2523.3	5685	2366	9374	
	After	4472.1 ± 1537.1	4000	3017	7530	−24.4
ARWS	Before	0.81 ± 0.35	0,78	0,32	1,28	
	After	0.61 ± 0.21	0,55	0,41	1,03	-24.7

All three indicators exhibited lower mean and median values following irrigation modernization. The mean AIWD-CA decreased from 5345.5 to 3740.7 m³ ha⁻¹, while the mean AIWD-IA declined from 5913.1 to 4472.1 m³ ha⁻¹. Similarly, the mean ARWS decreased from 0.81 to 0.61 after modernization. In addition to the reductions in the mean values, the standard deviations of all three indicators also decreased, indicating lower interannual variability and a more consistent water delivery pattern during the post-modernization period. These descriptive results suggest that the modernization of the irrigation system contributed to reduced irrigation water deliveries and improved water conservation while maintaining a more stable operational performance. The temporal variance of the three benchmarking indicators over the course of the study is shown in Figure 2.



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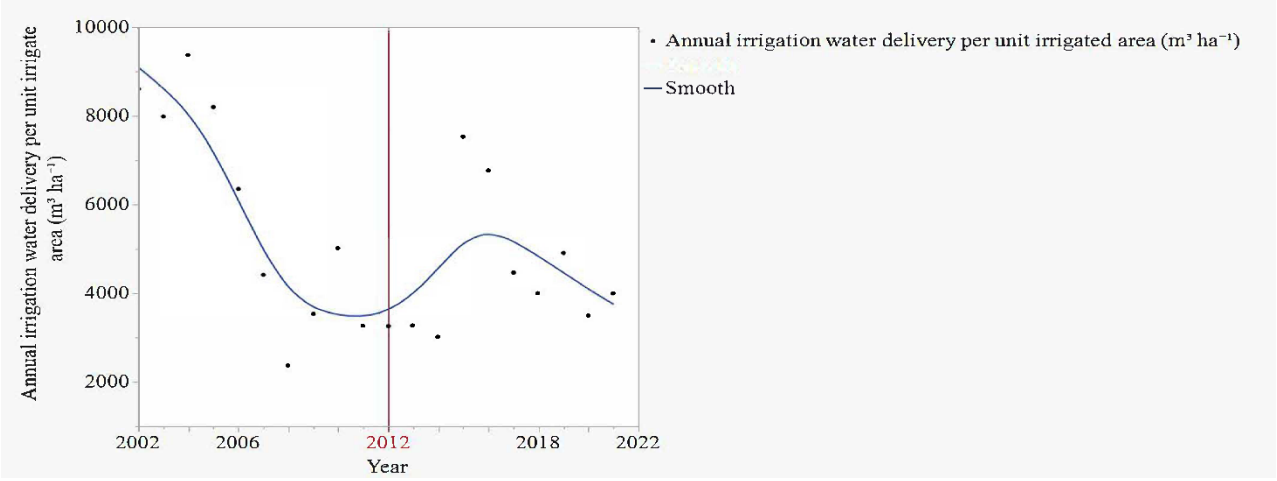

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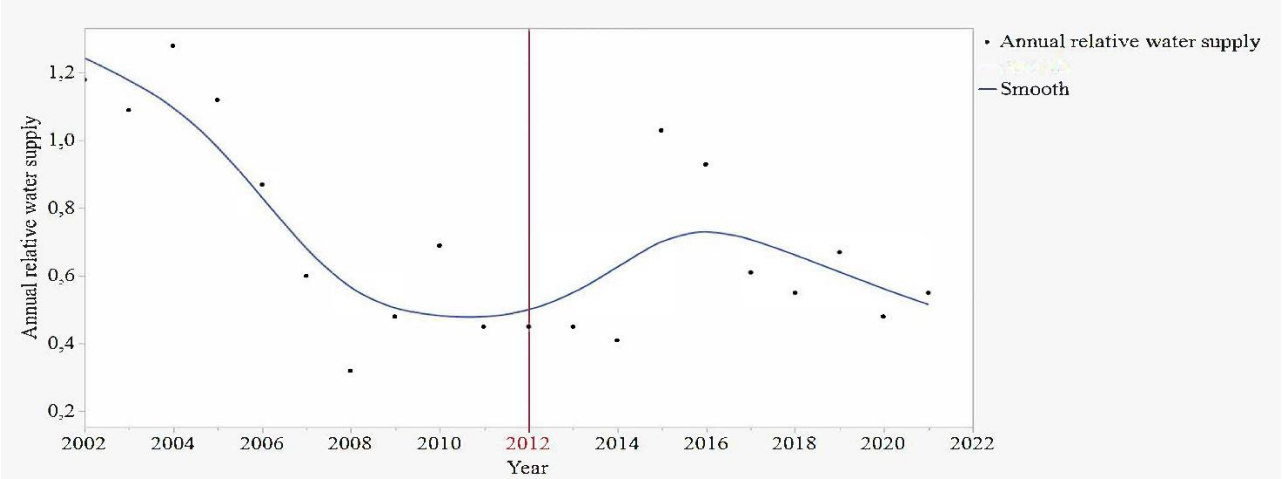

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Figure 2. Temporal variations in benchmarking indicators before and after irrigation modernization in the Uluborlu Irrigation Scheme
(a) AIWD-CA, (b) AIWD-IA, and (c) ARWS.

Even before the updated irrigation system was put into service in 2012, there was a noticeable slowdown in the delivery of irrigation water. After commissioning, there was a brief rise in the indicators during the first few years of operation. Following this, all indicators started to decline again and stayed below the levels noted in the early years of the research period. This temporal pattern indicates that the modernization helped to maintain reduced irrigation water supply levels and a more stable operational regime over time, even though it did not result in an immediate and persistent decrease in water delivery.

Before comparing the pre-modernization and post-modernization periods, the normality of each benchmarking indicator was evaluated using the Shapiro–Wilk test (Table 3).

Table 3. Normality test results of the benchmarking indicators

Indicator	Shapiro–Wilk (W)	p-value	Distribution
AIWD-CA	0.8998	0.0409	Non-normal
AIWD-IA	0.8943	0.0323	Non-normal
ARWS	0.8955	0.0340	Non-normal

As shown in Table 3, all three indicators deviated significantly from a normal distribution ($p<0.05$). Therefore, the nonparametric Mann–Whitney U test (Wilcoxon rank-sum test) was selected to evaluate differences between the two periods (Table 4).

Table 4. Mann–Whitney U test results for benchmarking indicators

Indicator	Mean rank (Before)	Mean rank (After)	Z	p-value
AIWD-CA	12.70	8.30	1.625	0.104
AIWD-IA	12.30	8.70	1.323	0.186
ARWS	12.25	8.75	1.288	0.198

The Mann–Whitney U test results are presented in Table 4. Although all benchmarking indicators exhibited lower mean ranks during the post-modernization period, none of the differences between the pre-modernization and post-modernization periods were statistically significant ($p > 0.05$). Specifically, the mean ranks of AIWD-CA, AIWD-IA, and ARWS decreased from 12.70 to 8.30, from 12.30 to 8.70, and from 12.25 to 8.75, respectively. These findings indicate a consistent reduction in irrigation water delivery following modernization, suggesting improved water conservation. However, the magnitude of these reductions was insufficient to reach statistical significance at the 95% confidence level.

The distribution of the three benchmarking indicators prior to and during irrigation modernization is shown in Figure 3. Box plots show the distribution of annual values and enable a visual comparison of median values, variability, and interannual changes between the pre-modernization and post-modernization periods. The box plots (Figure 3) and temporal trends (Figure 2) continuously show reduced irrigation water delivery levels following modernization, even though the Mann–Whitney U test did not find statistically significant differences between the two eras.

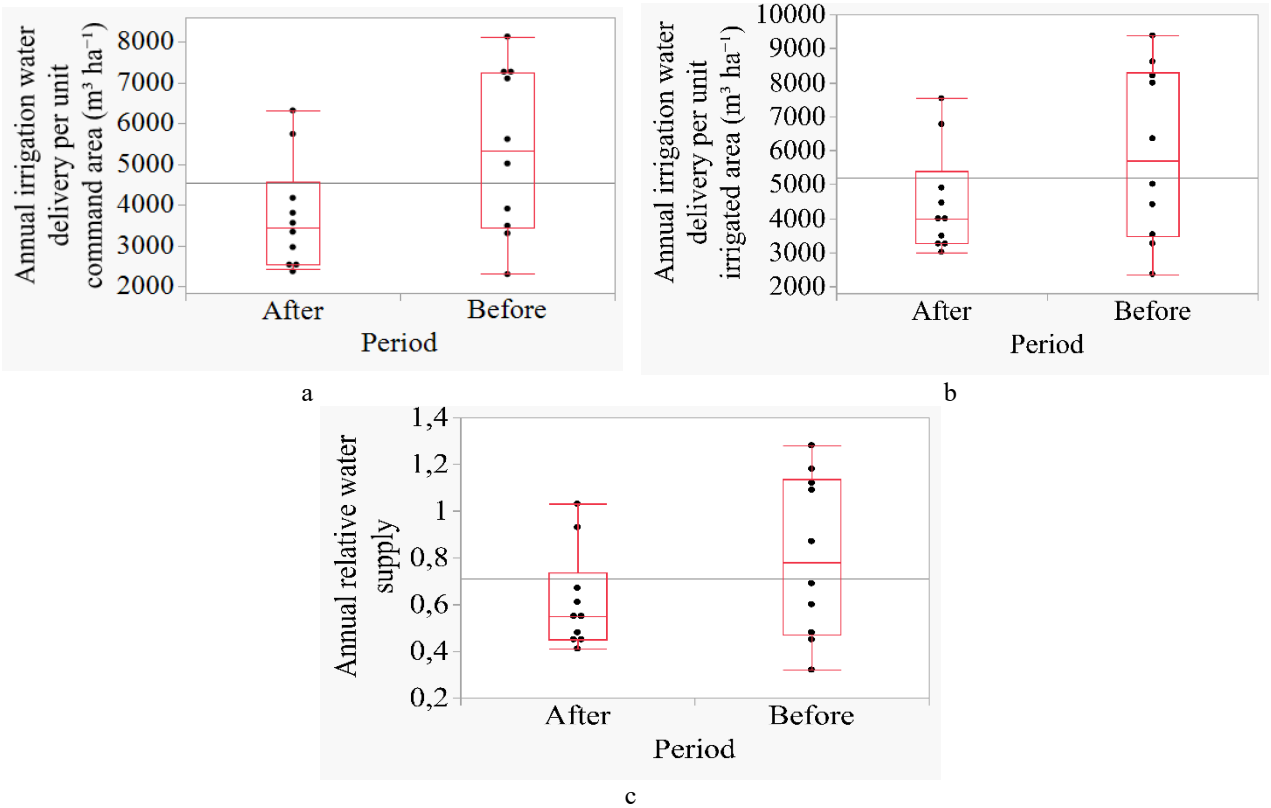

Figure 3. Box plots with individual annual observations comparing
(a) AIWD-CA, (b) AIWD-IA, and (c) ARWS before and after irrigation modernization in the Uluborlu Irrigation Scheme

Although the observed reductions were not statistically significant at the 95% confidence level, this indicates that modernization enhanced water saving.

Discussion

According to numerous prior studies Irrigation modernization reduces needless water deliveries while increasing conveyance efficiency, operational flexibility, and overall irrigation effectiveness (Koech & Langat, 2018; Playán & Mateos, 2006). Since all benchmarking indicators (AIWD-CA, AIWD-IA, & ARWS) showed lower values after the modernized irrigation system was put into service, the results of this study largely align with these observations. These findings support the view that modernization contributes not only to physical system improvement but also to more effective operational control, as emphasized by Price (1999), who defined modernization as the process of upgrading irrigation systems to meet new performance criteria through improvements in infrastructure, operational procedures, and management practices. Similarly, Çetin et al. (2024) compared the irrigation performance of the Devegeçidi and Ergani irrigation schemes and reported that the modernization of irrigation systems plays a significant role in reducing irrigation water use. Similarly, Şener & Abdisamad (2023) compared the performance of the Karataş Irrigation Association, which operates a predominantly open-channel irrigation system, and the Karaçal Irrigation Association, which uses a pressurized pipe irrigation system. They reported ARWS values ranging from 0.53 to 0.73 for the Karataş scheme and 0.47 to 0.96 for the Karaçal scheme.

In particular, the reduction in ARWS from 0.81 to 0.61 indicates that the annual volume of irrigation water delivered relative to the estimated crop water requirement decreased following modernization. However, an ARWS value below 1 does not necessarily imply inadequate irrigation or reduced crop productivity, as actual irrigation requirements may differ from estimated crop water requirements due to factors such as effective rainfall, improved irrigation efficiency, and on-farm irrigation management. It should also be noted that the present study focused exclusively on benchmarking indicators related to irrigation water delivery performance. Agronomic and economic outcomes, such as crop yield and water productivity, were beyond the scope of this study. Therefore, the potential impact of the observed reduction in ARWS on crop productivity could not be directly evaluated. Future studies integrating irrigation water delivery, crop yield, and water productivity indicators would provide a more comprehensive assessment of the benefits of irrigation modernization.

The Mann–Whitney U test revealed that the observed decreases were not statistically significant, although all benchmarking indicators consistently showed lower values following irrigation modernization. This may partly be explained by the limited number of annual observations (10 years before and 10 years after modernization), which may have reduced the statistical power of the analysis and the ability to detect moderate differences between the two periods. Therefore, the observed downward trends should be interpreted with appropriate caution, while recognizing their practical relevance in the context of long-term irrigation management. The comparatively modest improvement implies that infrastructure modernization alone may not be sufficient to achieve the anticipated improvements in irrigation performance. These findings are consistent with the observations of Plusquellec (2002), who emphasized that physical rehabilitation alone is often insufficient to achieve sustainable performance improvements unless accompanied by managerial and institutional adjustments. The potential benefits of modernization may have been influenced by drought conditions associated with climate change, increasing uncertainty in water availability, operational constraints in water distribution, and possible limitations in irrigation management. Lakshmi et al. (2025) identified 2008 as a severe drought year in the Antalya Basin, where the Uluborlu Irrigation Scheme is located, based on their analysis covering the 2001–2023 period. Consistent with this finding, the ARWS value in the Uluborlu Irrigation Scheme declined to 0.32 in 2008, which was well below the pre-modernization average of 0.81 ± 0.35. Nevertheless, although severe drought conditions during the pre-modernization period reduced the ARWS below its average level, the declining trend continued after modernization, with the mean ARWS further decreasing to 0.61 ± 0.21.

As a result, the anticipated decrease in irrigation water use was only partially realized, even if the modernization project seems to have improved water conservation and better controlled water distribution. These results demonstrate that adaptable operational management in the face of changing climate conditions is just as important to the success of irrigation modernization as improvements in physical infrastructure.

Overall, the findings imply that modernization should not be viewed as a one-time engineering intervention but rather as a long-term management process. Irrigation managers can differentiate infrastructure-related gains from operational and climatic factors by using benchmarking indicators, which offer a standardized and globally comparable framework for assessing this process. To promote adaptive irrigation management and future investment choices, benchmarking should be included in regular post-modernization performance evaluations.

Conclusion

Using internationally accepted benchmarking indicators—AIWD-CA, AIWD-IA, and ARWS—this study assessed the impact of irrigation modernization on irrigation water delivery performance in the Uluborlu Irrigation Scheme. After the modernized irrigation system was put into service in 2012, a comparison of the pre-modernization and post-modernization periods revealed consistent decreases in all three indicators, suggesting a trend toward reduced irrigation water deliveries and enhanced operational water conservation.

Descriptive statistics and graphical analysis consistently showed lower median values and reduced interannual variability following modernization, even if the observed reductions were not statistically significant according to the Mann-Whitney U test. These results imply that the modernization project enabled a more reliable and

regulated irrigation water supply system. However, the comparatively little improvement shows that infrastructure repair is not enough to completely realize the anticipated improvements in irrigation performance.

The findings also show that external factors like drought conditions, water supply, climatic unpredictability, and operational management techniques have a significant impact on the effectiveness of irrigation modernization. As a result, modernization ought to be viewed as an ongoing management process that incorporates adaptive water allocation techniques, efficient system operation, and infrastructure enhancement.

Finally, this study shows that benchmarking offers a useful and consistent framework for evaluating the results of irrigation modernization. Regular use of benchmarking indicators support adaptive irrigation management, enable evidence-based performance evaluation, and improve decision-making for future modernization investments in the face of growing water scarcity and climate change.

Declarations

Ethical Approval Certificate

This study did not involve human participants or animals. Therefore, ethical approval was not required.

Author Contribution Statement

The author solely conducted all aspects of this study, including conceptualization, methodology, data collection, formal analysis, interpretation of the results, and manuscript preparation.

Fund Statement

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Conflict of Interest

The author declares no conflict of interest.

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Not applicable.

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