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CASE STUDY

Interrelation of dams sustainability with the local communities and water quality

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ABSTRACT

BACKGROUND AND OBJECTIVES: Dams are vital for water management but significantly impact local communities. Striking a balance between development and sustainability demands a comprehensive understanding of these influences. The study aims to explore the complex interconnection between dam sustainability, water quality chemistry, and local communities.

METHODS: The environmental pillar for Jordanian dams was shaped by climate conditions and seismic activity, while the socioeconomic factors involved intersections density, population growth, and unemployment in the areas surrounding the dams, all of which significantly influence dam sustainability. The development of the Index of Sustainable Dams was carried out through the Wroclaw Taxonomic Method, and the Granger Causality Test was utilized to investigate the causal relationships between the different pillars of sustainability.

FINDINGS: The study classified dams performance using the Index of Sustainable Dams values. High-performance dams, with values from 0.010 to 0.299, included Kafrein, King Talal, and Wadi Shu'eib dams. Moderate performance, ranging from 0.299 to 0.528, comprised only Kufranja dam. Low-performance dams, with values from 0.528 to 0.937, included Wala, Wadi Arab, Zarqa-Main, and Mujib dams. Additionally, the results indicate that the dams were notably affected by chemical parameters, specifically electrical conductivity and the ratio of biological oxygen demand to chemical oxygen demand. An average electrical conductivity of 1116 microsiemens per centimeter negatively affects dam sustainability and community engagement, highlighting water salinity's detrimental impact. Conversely, a ratio of biological oxygen demand to chemical oxygen demand of 0.09 enhances sustainability and agricultural productivity, implying that efficient organic matter processing occurs in systems that are operating optimally. Additionally, 8.6 percent of agricultural employment and 1.4 percent of female participation play crucial roles in shaping dams sustainability.

CONCLUSION: There were notable bidirectional causal connections between the sustainability of dams and variations in job opportunities in the agricultural industry. Dam managers can use the index for Jordanian dams to pinpoint weaknesses, prioritize improvements, and track progress for enhanced sustainability.

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INTRODUCTION

Sustainability research has become increasingly important due to the mounting effects of climate change, with sustainability broadly defined as meeting current needs without compromising future generations' ability to meet theirs (Kuhlman and Farrington, 2010). This concept holds considerable significance due to its long-term approach, which combines environmental safeguarding, prudent resource management, and pollution control, all of which are vital for tackling the challenges posed by climate change. In relation to water resources, sustainable practices must prioritize both the equitable distribution of clean and safe water and the management of water infrastructure, such as dams. In Jordan, where water scarcity is a pressing issue, the sustainability of dams is of particular concern. The limited availability of water in the country, along with a rising population and the influx of refugees, has overwhelmed the existing infrastructure, highlighting the critical need for effective and sustainable water management strategies (Jamrah *et al.*, 2024). Effective dam management not only requires ensuring the structural integrity of these critical resources but also involves balancing water storage for agricultural, industrial, and domestic uses with environmental preservation efforts. The intention is to safeguard water resources for the benefit of future generations, while simultaneously enhancing the resilience of local ecosystems and the communities that depend on them (Fluixá-Sanmartín *et al.*, 2018). Additionally, the social dimension of sustainability emphasizes reducing inequalities and fostering community resilience, which is essential in regions where water shortages can significantly affect quality of life. This is especially relevant in Jordan, where sustainable dam management must also address the social impacts, such as equitable water distribution and community access to resources. Through the incorporation of these dimensions, sustainable dam practices in Jordan are designed to ensure the protection of human health and natural resources, fostering a reliable framework for economic advancement and environmental responsibility (Grasso and Tàbara, 2019). The sustainable management of dams in Jordan should not only focus on technical aspects like water storage but also incorporate broader socio-environmental considerations. o achieve long-term water security and foster sustainable development, it is vital to ensure that dams are capable of withstanding environmental challenges, including those related to climate change (Karami and Karami, 2019).

Role of sustainability indicators in water resource management.

Within sustainable development, the use of performance metrics, including sustainability indicators and indices (SIIs), has become vital for measuring progress in diverse areas, especially in the context of water management. The development of these indicators gained momentum following the 1993 United Nations Conference on Environment and Development in Rio de Janeiro (United Nations, 1993), and was further reinforced at the 2002 World Summit on Sustainable Development in Johannesburg. Since then, many organizations, government entities, and researchers have formulated a variety of sustainability indicators to focus on the environmental, social, and economic components, which constitute the three pillars of sustainability (Wu and Wu, 2011). Using too many indicators can complicate sustainability assessments, so composite indices simplify evaluation by combining them through mathematical methods. In Jordan, where water scarcity is severe due to population growth, shared water sources, and refugee influx, the SIIs are critical for effective management (Al-Weshah, 2003; Hadadin, 2015). The application of computational hydrology methods, particularly numerical modeling, plays a crucial role in the development of sustainability indices that gauge the performance of dam structures (Bahmanpouri *et al.*, 2020). Others have employed multicriteria decision analysis or life cycle assessment to evaluate various aspects of dam sustainability (Al-Weshah and Yihdego, 2018; Burgherr *et al.*, 2022; Karakuş and Yıldız, 2022). Despite these efforts, there remains a lack of a universally accepted framework for assessing the sustainability of dams. The existing gap hinders the ability to perform objective comparisons among various dams and to pinpoint particular areas that require enhancement. It is imperative to standardize these assessments in order to promote consistent evaluations and to advance the sustainable management of the critical water infrastructure in Jordan.

Bridging statistical methods in assessing sustainability

The Wroclaw Taxonomic Method (WTM), that developed by the Wroclaw Graduate School of

Economics and known as the dendric method, measures the distance from a theoretical unit that represents optimal performance across various indicators (Jain and Ganti, 2015). Senetra and Szarek-Iwaniuk (Senetra and Szarek-Iwaniuk, 2019) applied the WTM to identify and analyze problem areas in the Warmia and Mazury regions of Poland, highlighting variations in socioeconomic and demographic parameters. In addition, the research by Klóska *et al*. (2020) employed taxonomic analyses to evaluate the ranking of Poland's provinces concerning regional development, uncovering a stabilization in the highest-ranking positions and a widening gap between the most and least developed regions. Causality testing was advanced by Clive Granger in 1969 with the introduction of the Granger Causality Test (GCT). This statistical hypothesis test aims to determine if one time series can serve as a predictor for another, exploring the potential causal relationship between two variables by determining if past values of one variable contain relevant information for forecasting the future values of another (Shojaie and Fox, 2021). The GCT is a valuable tool for identifying causal relationships among key factors (Dietrich, 2011) and is widely utilized across various fields, including economics and climate change studies (Gunjal *et al.*, 2023). For example, Dörgő *et al.* (2018) used the GCT to analyze the interconnectedness of the United Nations sustainability goals, identifying causal relationships represented in a network of sustainability indicators. Similarly, Bildirici *et al.* (2023) employed the GCT to explore the impact of industry on environmental sustainability in Turkey. In addition to Agovino *et al.* (2019), a study conducted by Abu-Afifeh *et al.* (2023) applied the same methodology at King Talal Dam in Jordan. Their study examined the relationships among dam sustainability, the effects of climate change, and the various drivers that lead to dam failures. The combination of the WTM and the GCT was used to assess and test the composite indicator of dam sustainability in the context of these challenges. These two studies illustrate the successful application of WTM and GCT in the evaluation of dam sustainability amidst environmental stressors, signifying a noteworthy development in the area of study.

Environmental and socioeconomic dimensions of dams

Dams are influenced by several climatic and geological factors, such as the amount of precipitation, the number of rainy days, temperature fluctuations, and seismic activity. Elevated rainfall contributes to an increased water supply, while a reduction in rainy days may result in water scarcity. Higher temperatures increase evaporation and promote algal blooms, degrading ecosystems (Abu-Afifeh *et al.*, 2023; Al-Afeshat, 2024). Dams, in turn, influence the environment by modifying flow patterns and stabilizing water levels to buffer against climatic variations. The western side of Jordan is a tectonically active region influenced by the Dead Sea Transform Fault (DSTF), which extends approximately 1,100 kilometer (km) and formed during the Miocene period. The Arabian and African Plates are separated by the DSTF, which features several segments. Notably, the Jordan Valley Fault runs from the southern part of the Dead Sea to Lake Tiberias, while the Wadi Araba Fault extends from the Dead Sea to the Gulf of Aqaba (Abu Ghazaleh, 2011). The ongoing movement along this fault has generated macro-faults like the Karak Al-Faiha Fault and the Swaqa Fault, and geophysical studies confirm continuous tectonic activity (El-Issa and Mustafa, 1986; Amaireh, 2017; Qutishat, 2022). In recent decades, seismic events have been recorded, including a significant 7.3 moment magnitude (Mw) earthquake in the Gulf of Aqaba in 1995 and a 6.2 Local magnitude (ML) earthquake near Jericho in 1927, alongside numerous smaller quakes (Ambraseys, 2009; Qutishat, 2022). The region's history of seismic activity create potential hazards for infrastructure, especially for dams that are primarily located on the western side of Jordan near the DSTF. The sediments in this vicinity are delicate and vulnerable to liquefaction. Geological investigations, including the study of soft sediment deformations known as "Seismites" (Seilacher, 1969, 1984), have provided insights into the area's seismic history. In water-saturated, unconsolidated sediments, seismites are created when seismic waves of magnitude Mw ≥ 5.5 trigger liquefaction, resulting in the distortion of sedimentary layers (Seilacher, 1969). In Jordan, these layers have been detected in the Lisan Formation and Holocene deposits, indicating past seismic events linked to the DSTF's movement (Amaireh, 2017; Qutishat, 2022). Measurements of fault dip and strike in the Lisan layers align with the DSTF's direction, further supporting evidence of ongoing tectonic activity. In addition, the sensitive characteristics of the sediments in the area increase

their risk of liquefaction, especially close to dams, where seismic vibrations could threaten their structural integrity. Addressing these risks is crucial for long-term infrastructure resilience, as dam failures could result in catastrophic consequences (Abu-Afifeh *et al.*, 2023; Al-Afeshat, 2024). In response, Jordan has created seismic monitoring networks, notably the Jordan Seismological Observatory, to observe seismic events and deliver timely alerts (Zardari *et al.*, 2017; Utete *et al.*, 2022). These efforts, coupled with resilient engineering practices, are vital for enhancing the safety and sustainability of dams in a region prone to seismic hazards. Dams also have significant impacts on socioeconomic development, particularly in areas adjacent to their structures. Infrastructure growth, measured by intersections density as intersections per squared kilometers (intersections/km^2), often accelerates around dams due to improved transportation networks and economic opportunities they create (Pekel *et al.*, 2016). This advancement fosters agriculture, industry, and tourism, leading to better living standards for nearby residents. Population growth rates in these areas further reflect the economic attractiveness of dam-adjacent regions, as people migrate to access the resources and jobs created by the dam (Rui and Othengrafen, 2023). Nevertheless, a fast-growing population can challenge water resources and infrastructure, highlighting the need for strategic planning to avert overexploitation. The unemployment rate is another key socioeconomic indicator, as dams generate direct and indirect jobs (Rahbeh *et al.*, 2019). Elevated unemployment rates can signify an uneven distribution of economic advantages. The unemployment figures for women particularly underscore the gender inequalities present in employment opportunities. While dams promote regional development, challenges persist in equitably sharing economic benefits, particularly for women. Balancing economic growth with social equity is vital for maximizing dams' positive impact on local communities. (Schmitt *et al.*, 2022).

Significance and implications

Across the globe, the sustainability of dams is confronted with a complicated issue: finding a balance between maintaining water quality and addressing the socio-economic demands of local populations. As dams regulate water resources for agricultural, industrial, and domestic use, issues such as increasing salinity, measured by electrical conductivity (EC) and the presence of organic pollutants reflected by the biochemical oxygen demand to chemical oxygen demand ratio (BOD/COD) threaten the usability of these water bodies. The selection of EC as a primary water quality metric is based on its ability to reflect water salinity, an important aspect for effective irrigation in Jordan. Monitoring EC is essential for sustainable agriculture in Jordan, addressing soil salinization from climate change. The BOD to COD ratio evaluates organic matter biodegradability, assessing wastewater treatment effectiveness and dam effluent impacts. These water quality indicators affect ecosystems and agriculture, particularly vulnerable female workers, amid scarce resources (Winton *et al.*, 2019). This study offers a fresh perspective on the social, economic, and environmental factors that affect the sustainability of dams in Jordan, thereby addressing a critical gap in research. It underscores the interplay between water quality, the well-being of local communities, and the sustainability of dams, especially concerning agricultural laborers and women. By exploring challenges including water scarcity and climate change, this research encourages the adoption of sustainable practices aimed at strengthening dam resilience. It aims to develop a decision-making framework prioritizing environmental integrity and community well-being, providing actionable recommendations for policymakers to improve water resource management and support local development, assessing water availability and quality concerning community livelihoods. This study has been carried out in Jordan, specifically examining nine major dams: King Talal Dam (KTD), Wadi Arab Dam (WAD), Wadi Shu'eib Dam (WSD), Kafrein Dam (KAD), Wala Dam (WD), Mujib Dam (MD), Kufranja Dam (KUD), and Zarq Ma'in Dam (ZMD) in 2017 to 2024.

MATERIALS AND METHODS

Study sites description

The study identifies several significant dams in Jordan, including the KTD, WAD, WSD, KAD, WD, MD, KUD, and ZMD. Among these, the KTD, located in Jerash, is a non-homogeneous earthfill dam constructed in 1978. It stands 108 meters (m) high and spans 350 m, with a storage capacity of 83 million cubic meters (MCM), including 8 MCM of dead

storage. The dam's spillway has a design flow of 4,500 cubic meters per second (m³/s), and it serves crucial purposes for water supply and irrigation (Abu-Afifeh *et al.*, 2023; MWI, 2024). Similarly, the WAD, completed in 1986, is a 435-meter-long heterogeneous earthen dam, standing 82.5 m high with a storage capacity of 16.8 MCM. Serving a crucial function in the management of water resources in northern Jordan, this dam boasts a drainage capacity of 840 m³/s and covers a catchment area of 262 squared kilometers (km²) (Hadadin and Al-Adwan, 2020; Al-Afeshat, 2024; MWI, 2024). The WSD, completed in 1969, is 730 m long and 32 m high, with a storage capacity of 1.4 MCM. The dam irrigates 10,000 dunums of land and replenishes groundwater in the historic Shouna farms (AlSmadi, 2022; Al-Afeshat, 2024; MWI, 2024). The KAD, completed in 1997, has a capacity of 8.5 MCM and is 37 m high and 552 m long. It supports irrigation of 16,000 dunums in Al-Rama and Al-Kafrain and plays a key role in groundwater recharge (Al-Afeshat, 2024; Al-Nawaiseh, 2024; MWI, 2024). Constructed between 1999 and 2003, the WD features a storage capacity of 25 MCM and is instrumental in enhancing groundwater recharge, particularly for the drinking water supplies in Amman. It is 52 m high and 380 m long, with a catchment area of 1,770 km² (Abu-Afifeh *et al.*, 2023; MWI, 2024). The MD, completed in 2004, is a rolled concrete dam with a capacity of 35 MCM. It combines water from the Mujib basin and desalinated water from the Dead Sea region, helping to supply water to Amman and ease the national water shortage (Abu-Afifeh *et al.*, 2023; MWI, 2024). The KUD, located in Ajloun and completed in 2017, stands 80.5 m high and has a capacity of 7.8 MCM. It supports irrigation, drinking water, and flood prevention in the Kufranja Valley (Al-Kloub, 2023; MWI, 2024). Finally, the ZMD, built in 2017 with a 2 MCM capacity, is located 5 km south of Ma'in. It manages floodwaters from Wadi Ma'in, protects the Hammamet Ma'in resort, and supports local irrigation and underground water recharge (MWI, 2024). The geographic location of the study area, along with historical seismic events affecting Jordanian dams, is depicted in Fig. 1. This information underscores the risks to dam sustainability and structural integrity, especially concerning older dam structures.

Estimation of the index of sustainable dam

The sustainability index for Jordanian dams (ISD) was determined using data gathered from various indicators, which were aggregated through the WTM. This approach assigns weights to the indicators based on their significance. This strategy assigns importance-based weights to the indicators. Numerous methodologies have been introduced for merging several pillars into a single composite index (OECD, 2008; Chudy-Laskowska *et al.*, 2020) with WTM being applied in this analysis. Originally developed by Polish mathematicians from the Wroclaw Graduate School of Economics in the 1950s (Jain and Ganti, 2015), WTM calculates a composite indicator using the sum of Euclidean distances between each dam and an "ideal dam". By normalizing these distances with a variability measure, it becomes possible to rank the dams according to how closely they align with the optimal scenario. A composite indicator was created for each pillar using Wroclaw taxonomy, followed by an overall sustainability index derived by applying the same method to all pillars. For the mathematical formulation, let $x_{ij}^{\ t}$ be the value of the jth indicator (for $j \in \{1, \ldots, 8\}$, $K = 8$) across the ith Jordanian dam ($i \in \{1, \ldots, 8\}$, $N = 8$) at time $t \in \{2017, \ldots, 2023\}$. In addition, the generic 2-dimensional matrix is denoted by $X \in R^{N,K,t}$ representing the distribution of the indicators for the 8 Jordanian dams over time. For a fixed year t, the normalized matrix is calculated and denoted as Z ($+z_{ij}^{t}$ for the positively corrected with the indicator and $-z_{ij}^{t}$ for the negatively corrected with the indicator), using Eq. 1 (Agovino *et al.*, 2019):

$$z_{ij}^{t} = \pm \frac{x_{ij}^{t} - \overline{x}_{j}^{t}}{\sigma_{j}^{t}} \quad (1)$$

Where, $\overline{x}_{j}^{t}$ and σ_{j}^{t} are the mean and the standard deviation of the jth indicator, such that $\overline{x}_{j}^{t} = \frac{1}{N}\sum_{i=1}^{N} x_{ij}^{t}$ and $\sigma_{j}^{t} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(x_{ij}^{t} - \overline{x}_{j}^{t}\right)^{2}}$. Thus, for all the indicators in each year, the maximum value m_{j}^{t} is computed as a benchmark for the indicator. Then, for each dam for each year, the Euclidean distance (e_{i}^{t}) between all the normalized values and such maximum reads is calculated using Eq. 2 (Agovino *et al.*, 2019):

$$e_{i}^{t} = \sqrt{\sum_{j=1}^{K}\left(z_{ij}^{t} - m_{j}^{t}\right)^{2}} \quad (2)$$

Thus, with the mean and the standard deviation denoted by $\overline{e^{t}} = \frac{1}{N}\sum_{i=1}^{N} e_{i}^{t}$ and $\sigma\left(\overline{e^{t}}\right) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(e_{i}^{t} - \overline{e^{t}}\right)^{2}}$, respectively,

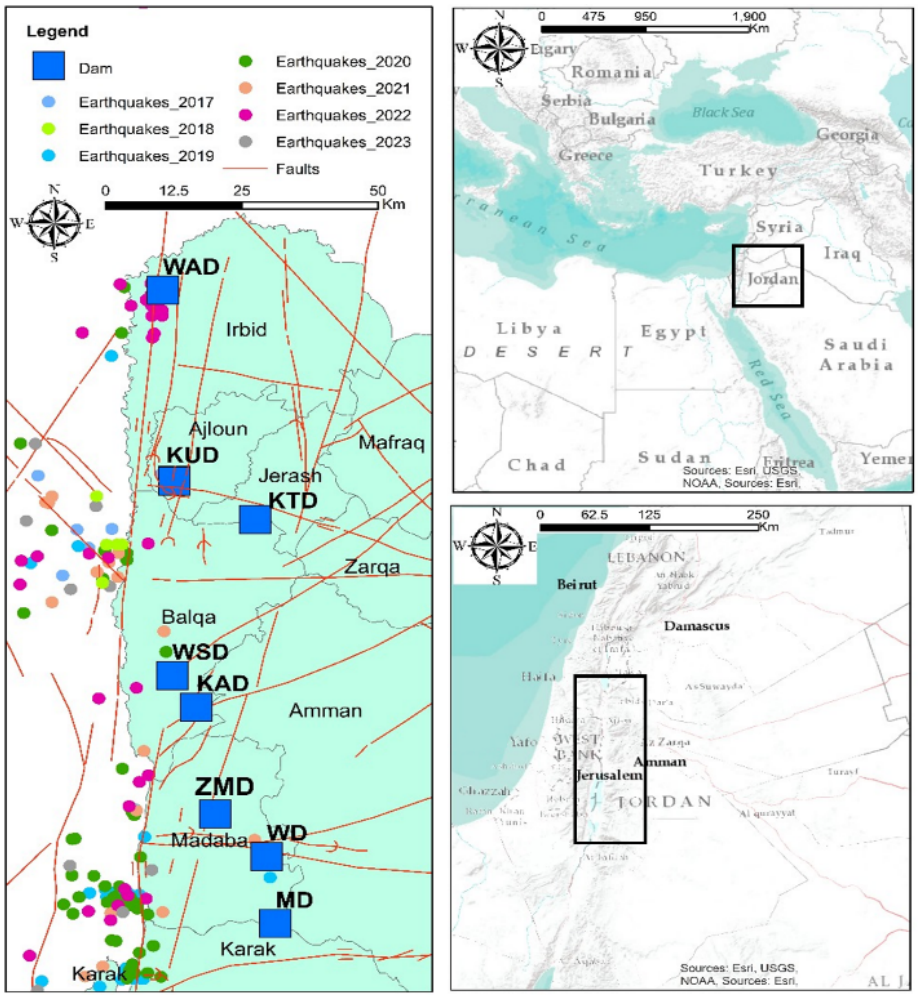

Fig. 1: Geographic location of the study area and historical seismic events near Jordanian dams that affects dam sustainability by threatening structural integrity, especially in older dams. Even moderate events can cause damage, making seismic monitoring crucial for the long-term safety of Jordanian dams (MWI, 2024; MEMR, 2024)

the Wroclaw index at time *t* is calculated using Eq. 3 (Agovino *et al.,* 2019):

$$W_i^t = \frac{e_i^t}{\overline{e}^t - 2\sigma\left(\overline{e}^t\right)} \tag{3}$$

A value of 0 is assigned to the index when the distance between a particular dam and the reference is nonexistent, indicating that the dam attains the maximum value in all pillars. The index, however, increases when the dam is far from the reference. However, this definition of W_i^t seems counterintuitive because as the index increased, in far-from-optimal situations all dams showed better performances. Thus, the complement to the maximum achieved in each year of the indicator is computed using Eq. 4 (Agovino *et al.,* 2019):

$$ISD_i^t = \max W^t - W_i^t \tag{4}$$

The choice of the WTM for determining the ISD significantly impacted the weighting of individual indicators due to its systematic approach to evaluating multiple criteria based on their contributions to overall sustainability. The WTM operated on a multi-dimensional scaling framework that facilitated the

normalization of data and the consolidation of different indicators into one comprehensive index. A key aspect of the WTM process was the normalization of indicators, which guaranteed that comparisons could be made across different scales and units. This transformation allowed for a fair assessment of each indicator's contribution to the ISD, ultimately influencing how these indicators were perceived within the broader sustainability framework. It is important to note that the normalized values showed a mix of positive and negative signs, which illustrates the diverse effects that individual indicators contributed to the overall sustainability index. This duality allowed for the precise representation of the extreme impacts of specific indicators—both advantageous and harmful—in the final ISD score, thereby enhancing the understanding of sustainability in relation to Jordanian dams.

Comparative analysis of causal relationships

In order to discern trends, patterns, and areas needing enhancement, a comparative analysis of the sustainability indices of Jordanian dams was performed. The GCT was used to examine the causal relationships between ISD, local communities, and water quality indicators, focusing on the direction of the influence rather than the extent of the impact (Dietrich, 2011; Olabi *et al.*, 2022). The local communities' indicators are centered on the agricultural workforce present in the regions near the dams. The percentage of workers aged 15 and over in the agricultural sector (WASPOP) provides insight into the reliance of the local population on agriculture as a livelihood, reflecting the socio-economic importance of the dam for irrigation. Another critical indicator is the percentage of female workers aged 15 and over in the agricultural sector (FWAGRS), which highlights the role of women in the local agricultural economy, offering a perspective on gender equality and employment opportunities in these areas. In the study, the assessment of the sustainability of Jordanian dams was conducted using water quality indicators derived from the Environmental Indicators framework, as adapted by the Organisation of Economic Co-operation and Development (OECD) (OECD, 2008). These indicators aligned with international standards, enhancing the credibility of the findings. Ensuring high water quality is vital for the long-term sustainability of dams, significantly influencing both ecosystem health and the livelihoods of local communities. Utilizing these indicators allowed for reliable comparisons with other studies, ensuring the conclusions were based on sound evidence and strengthening the study's relevance in sustainable water management practices in Jordan. Measured in microsiemens per centimeter (µS/cm), electrical conductivity (EC) indicates the concentration of dissolved salts in water. This information is vital for evaluating salinity levels and the water's viability for agricultural purposes. The BOD to COD ratio (BCREFF, unitless) indicates the presence of organic pollutants in the dam effluent, with lower ratios suggesting better water quality. These indicators deliver critical data for analyzing the influence of the dam on environmental conditions and local water supplies (Winton *et al.*, 2019; MWI, 2024). The GCT is used to evaluate whether one variable can predict another (Dumitrescu and Hurlin, 2012). Specifically, it examines whether variable *y* is Granger-caused by variable *x*, meaning that *y* is regressed on its own past values as well as those of *x*. The test checks whether the coefficients related to *x* are significantly different from zero (Agovino *et al.*, 2016; Saidi and Ben Mbarek, 2016). The general formula for conducting the GCT in panel data using Eq. 5 (Dumitrescu and Hurlin, 2012):

$$y_i^t = \alpha_0 + \sum_{j=1}^{K} \alpha_j y_{i-j}^t + \sum_{j=1}^{K} \delta_j x_{i-j}^t + f_i + u_i^t \quad (5)$$

Where, i = 1, …, N are the Jordanian dams and t = 1, …, n represents the time index. The model in-differences eliminates the fixed effects (f_i), using Eq. 6 (Dumitrescu and Hurlin, 2012):

$$y_i^t - y_{i-1}^t = \alpha_0 + \sum_{j=1}^{K} \alpha_j \left(y_{i-j}^t - y_{i-j-1}^t \right) + \sum_{j=1}^{K} \delta_j \left(x_{i-j}^t - x_{i-j-1}^t \right) + \left(u_i^t - u_{i-j-1}^t \right) \quad (6)$$

This specification introduces a simultaneity bias because the error term is correlated with $y_i^t - y_{i-1}^t$. In this case, it is possible to produce a consistent estimate by applying the Two-Stage Least Squares (2SLS) regression analysis. To verify whether x causes y, it is necessary to test the joint hypothesis H_0: $\delta_1 = \delta_2 = \ldots = \delta_n = 0$. If the null hypothesis is rejected, then x Granger causes y. The GCT was performed using *R* programming language studio (RStudio, 2024.08.0

Table 1: List of variables for environmental and socioeconomic pillars (including climate conditions, seismic activity, infrastructure, population and unemployment) that were normalized according to Eq. 1

Pillar	Description of the indicator	Unit
Environmental	Mean annual precipitation (MAP)	Millimeter (mm)
	Annual rainy days (ARD)	day
	Mean annual temperatura (MAT)	Degree Celsius (°C)
	Maximum seismic magnitude affected the dam (SEIMAG)	Unitless
Socioeconomic	Intersections density at the area adjacent to the dam (INTDEN)	Intersections/km^2
	Population growth rate in the area adjacent to the dam (POPGRW)	Percent (%)
	Unemployed individuals aged 15 and over as a percentage of the population in the area adjacent to the dam (UINPOP)	%
	Unemployed females aged 15 and over as a percentage of the total unemployed population in the area adjacent to the dam (UFUPOP)	%

Build 463© 2009-2024 Posit Software, Public Benefit Corporation: PBC). The sensitivity analysis was conducted for the GCT by varying the lag lengths to 1, 2, and 3 lags. This strategy was implemented to analyze the reliability of the causal links identified between the sustainability index, local communities, and water quality indicators. The findings revealed uniform results across multiple lag settings, which bolstered the trustworthiness of the conclusions. By systematically altering the lags, the analysis ensured that the causal interpretations were not unduly influenced by a specific lag arrangement, effectively addressing potential ambiguities in the model.

Indicators of the environmental and Socioeconomic pillars

In this analysis, the selected indicators were based on the accessibility of data and their importance concerning the eight dams under investigation. These indicators are commonly featured in the literature as important factors influencing dam sustainability and were chosen to ensure consistency in data collection and comparison. The selected indicators—such as mean annual precipitation, annual rainy days, mean annual temperature, maximum seismic magnitude, intersections density, population growth rate, and unemployment rates, represent essential environmental, social, and economic factors that are commonly acknowledged in studies related to dam management. Table 1 presents the indicators chosen for constructing the ISD and conducting the causality tests.

Climate conditions and seismic activity have a substantial effect on the operations of Jordanian dams, thereby significantly influencing their environmental sustainability. Variability in precipitation plays a crucial role in water availability for dam reservoirs; lower precipitation can strain resources for irrigation and domestic use (Rahbeh *et al.*, 2019; MWI, 2024). While greater rainfall improves water storage, it also raises the potential for overflow. Furthermore, alterations in rainfall patterns combined with rising temperatures lead to increased evaporation, thereby affecting the ability of dams to retain water. Variability leads to fluctuating levels, sediment buildup, and lower water quality. Thermal stratification reduces oxygen in deeper layers, harming aquatic life. The implementation of adaptive management strategies is crucial for the preservation of dams as climate conditions shift (Abu-Afifeh *et al.*, 2023; Al-Afeshat, 2024; MWI, 2024; MEMR, 2024). Seismic activity is another critical factor influencing the environmental sustainability of dams. Higher seismic events threaten the structural integrity of Jordan's dams, especially older ones, potentially causing cracks and compromising safety (Ambraseys, 2009; Zardari *et al.*, 2017; Qutishat, 2022; Al-Afeshat, 2024). These environmental challenges emphasize the importance of adaptive management, which must consider socioeconomic influences, including the development of surrounding urban areas (Rui and Othengrafen, 2023). This increase in intersections suggests a growing infrastructure network, possibly driven by population growth (DOS, 2024). The increase in local populations underscores the potential strain on water resources, infrastructure, and job opportunities in the vicinity of the dams. Unemployment in the area also displayed notable patterns. The overall unemployment rate and unemployed females suggest persistent challenges in the labor market, especially for women. Elevated unemployment levels, combined with the expanding population in the region, point to possible

Table 2: Summary statistics (mean ± standard deviation) of environmental and socioeconomic variables for the Jordanian dams (KTD, WAD, WD, MD, WSD, KAD, KUD and ZMD) used in the analysis through 2017-2023

Dam	MAP mm	ARD day	MAT °C	SEIMAG Unitless	INTDEN Inters./km²	POPGRW %	UINPOP %	UFUPOP %
KTD	6.9 ± 1.6	54 ± 8	22 ± 2	2 ± 0.8	5.3 ± 0.1	2.4 ± 0.1	3.5 ± 0.2	4 ± 0.3
WAD	10.1 ± 1.2	41 ± 6	20.2 ± 0.5	1.3 ± 1.7	8.5 ± 0.2	2.3 ± 0.1	18.8 ± 2	22.1 ± 2
WD	6.1 ± 1	15 ± 3	22.7 ± 2.1	1.8 ± 0.8	4.2 ± 0.2	2.3 ± 0.1	2.2 ± 0.3	2.1 ± 0.3
MD	5.5 ± 0.9	12 ± 3	22.7 ± 2.1	1.7 ± 1.1	2 ± 0.1	2.3 ± 0.6	2.9 ± 0.4	4.3 ± 0.5
WSD	8.4 ± 2.3	33 ± 4	22.3 ± 0.7	2.2 ± 1	5.1 ± 0.2	3.7 ± 2.1	5.1 ± 0.4	5.1 ± 0.6
KAD	8.4 ± 2.3	33 ± 4	22.3 ± 0.7	1.7 ± 1.1	7 ± 0.2	7 ± 0.2	5.1 ± 0.4	5.1 ± 0.6
KUD	6.7 ± 1.8	27 ± 3	20.1 ± 0.6	2.7 ± 0.4	4.5 ± 0.1	2.8 ± 1.6	5.6 ± 0.5	5.7 ± 0.7
ZMD	6.8 ± 1.1	33 ± 4	20.4 ± 1.9	2.2 ± 1.4	1.9 ± 0.1	0.7 ± 0	3 ± 0.5	3.3 ± 0.7

socioeconomic challenges that could jeopardize the sustainability of the communities adjacent to the dams. Addressing these issues requires a balanced approach to economic development, water resource management, and community support (Filipović *et al.*, 2022).

RESULTS AND DISCUSSION

Environmental and socioeconomic indicators among Jordanian dams

The environmental and socioeconomic indicators surrounding the dams play a crucial role in determining the availability and sustainability of water resources. Factors such as precipitation, temperature, seismic activity, population growth, unemployment rates, and infrastructure development, as detailed in Table 2, influence the structural stability, water retention capacity, and community reliance on the dams. T The pressures indicated by these factors highlight the difficulties encountered in these areas, affecting both the sustainable management of water in the long term and the viability of the dams (Fan *et al.*, 2022). The MAP varies across the dams, with the WAD receiving the highest precipitation at 10.1 ± 1.2 mm, while the MD has the lowest at 5.5 ± 0.9 mm. This changes in precipitation are a significant element affecting the water inflow into dams, thereby influencing the sustainability and management of water resources. Dams experiencing reduced precipitation may encounter difficulties in sustaining adequate water levels, particularly during periods of drought. When looking at the ARD, the KTD experiences the highest number of rainy days, averaging 54 ± 8 days per year. In contrast, the MD and WD have significantly fewer rainy days, with only 12 ± 3 and 15 ± 3 days, respectively. The disparity in rainfall frequency is an essential consideration in water storage planning. With fewer days of precipitation, there may be times of diminished water availability, which calls for enhanced water management practices to guarantee a steady supply (Chow *et al.*, 1988; White *et al.*, 2019). The MAT ranges from 20.2 ± 0.5°C at the WAD to 22.7 ± 2.1°C at both the WD and MD. Higher temperatures can contribute to increased evaporation rates, which may impact water retention in these dams, particularly in warmer regions. This could necessitate strategies to mitigate water loss, such as enhanced dam infrastructure or water conservation measures, as explained by McKee *et al.* (1993) and Vicente-Serrano *et al.* (2010). Regarding the SEIMAG, the dams are exposed to seismic magnitudes ranging from 1.3 ± 1.7 at WAD to 2.2 ± 1.0 at WSD. Even though the recorded magnitudes are not extreme, they stress the importance of safeguarding the structural integrity of dams against potential earthquakes, particularly in regions that are at risk of seismic events (Qutishat, 2022; Chen *et al.*, 2023; Pang *et al.*, 2024). In terms of infrastructure development, the INTDEN at the areas adjacent to the dams reveals that the WAD has the highest density, with 8.5 ± 0.2 intersections/km², indicating a more developed transportation and connectivity network. In contrast, the MD and WD show reduced intersection densities of 2 ± 0.1 and 4.2 ± 0.2, respectively. This suggests that these regions might experience restricted access to road networks, which could influence local economic activities and accessibility. The POPGRW shows notable differences across the regions surrounding the dams. The WSD has the highest population growth rate at 3.7 ± 2.1%, reflecting rapid demographic changes that could place additional demand on water resources for agricultural, industrial, and domestic use. Other dams, such as the KTD and WAD, exhibit more moderate growth rates around

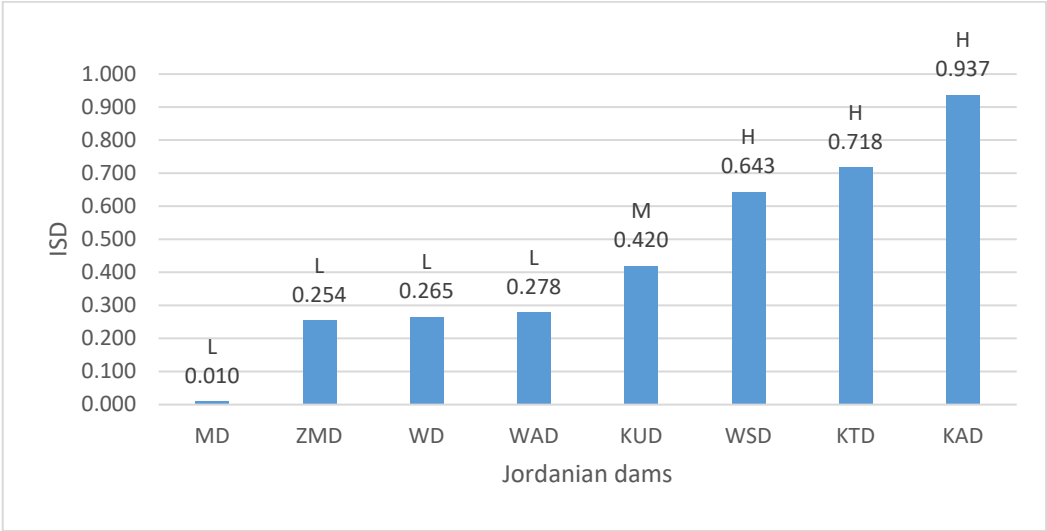

Fig. 2: Ranks of the Jordanian dams (KTD, WAD, WD, MD, WSD, KAD, KUD and ZMD) with respect to the average ISD through 2017-2023 and performance categories (L: Low-performance dams, M: Moderate-performance dams and H: High-performance dams)

2.3–2.4%, which might still impact water demand but to a lesser extent. The UINPOP in the regions adjacent to the dams also varies significantly. With an unemployment rate of 18.8 ± 2%, the WAD faces considerable socioeconomic hurdles. This elevated rate may drive a greater reliance on dam resources for economic sustenance, particularly in agriculture. In contrast, other dams such as the MD and WD report relatively low unemployment rates, between 2.2 ± 0.3% and 5.1 ± 0.4%, suggesting more stable economic conditions in those areas. There are notable variations in the percentage of the UFUPOP aged 15 and above compared to the overall unemployed population. The WAD has the highest rate at 22.1 ± 2%, indicating significant gender disparities in employment opportunities. Conversely, dams like the MD and WD show much lower female unemployment rates, between 2.1 ± 0.3% and 5.1 ± 0.6%, reflecting potential improvements in gender equality in these regions. Closing the gender employment gaps is essential for bolstering the socioeconomic resilience of communities residing near the dams, as indicated by previous studies (Langill, 2020; Zhang *et al.*, 2021; Tandon *et al.*, 2022).

The performance of Jordanian dams according to the ISD

The initial phase of the analysis provided an overview of the performance rankings of Jordanian dams based on the average ISD from 2017 to 2023 (Fig. 2). In order to present the findings on sustainable dam performance more clearly, the ISD index has been classified into three levels: high (H), moderate (M), and low (L). This classification is established through the analysis of the index's mean and standard deviation (Agovino *et al.*, 2019; Abu-Afifeh *et al.*, 2023). The years with values between the minimum (which by definition is 0) and $m_{ISD} - 0.5\sigma_{ISD}$ were categorized as Low. Years with values in the interval $[m_{ISD} - 0.5\sigma_{ISD}, m_{ISD} + 0.5\sigma_{ISD})$ were classified as moderate, while years with values in the interval $[m_{ISD} + 0.5\sigma_{ISD}, ISD_{max}]$ were classified as High, where ISD_{max} is the maximum of the ISD:

- The high-performance dams, with ISD values from 0.010 to 0.299, included KAD, KTD and WSD.
- The moderate-performance dam, with ISD values from 0.299 to 0.528, included KUD.
- The low-performance dams, with ISD values from 0.528 to 0.937, included WAD, WD, ZMD and MD.

The data on ISD from 2017 to 2023 provides important insights into the sustainability trends of Jordanian dams (Table 3). Given that a greater ISD signifies improved sustainability, the effectiveness of the dams can be measured by their average ISD values, enabling classification into high, medium,

Table 3: Environmental and socioeconomic sustainability indicators of the high-performance dams (KAD, KTD and WSD) for the years 2017 and 2023

Dam	Year	MAP (mm)	ARD (day)	MAT (°C)	SEIMAG (Unitless)	INTDEN (Inters./km^2)	POPGRW (%)	UINPOP (%)	UFUPOP (%)
KAD	2017	13.5	24	22.7	0.0	6.7	6.7	5.5	5.6
	2023	6.3	38	21.5	2.4	7.4	7.4	4.4	4.5
KTD	2017	5.3	39	18.4	2.4	5.2	2.6	3.8	4.4
	2023	8.6	62	24.4	2.5	5.5	2.2	3.3	3.6
WSD	2017	13.5	24	22.7	0.0	4.8	2.4	5.5	5.6
	2023	6.3	38	21.5	2.8	5.4	7.2	4.4	4.5

and low-sustainability categories. High-sustainability dams include KTD, WSD, and KAD. The KTD shows a consistent improvement in sustainability over the years, with its ISD increasing from 0.432 in 2017 to 1.111 in 2023, yielding a mean ISD of 0.718. This increasing trend implies that the KTD has achieved greater sustainability over time, possibly owing to advancements in management strategies or favorable environmental conditions, aligning with the conclusions drawn in the previous study conducted by Abu-Afifeh *et al.* (2023). The high ISD value for KTD in 2023 can be attributed to several key changes in both environmental and socioeconomic indicators between 2017 and 2023. Starting with the environmental indicators, the MAP increased from 5.3 mm in 2017 to 8.6 mm in 2023, reflecting an overall improvement in water availability for the dam, which likely contributed to its enhanced performance and sustainability. Similarly, there was a significant rise in the ARD, which grew from 39 days in 2017 to 62 days in 2023, thereby ensuring a more consistent supply of rainfall to the dam's catchment region. This increase in the ARD, combined with higher MAP, would have improved water inflows, allowing the KTD to better sustain water resources over time, as addressed by Ta'any *et al.* (2013) and Karami and Karami (2019). The SEIMAG exhibited a stable trend, showing a minor rise from 2.4 to 2.5. This indicates that seismic activity had a limited impact on the dam's sustainability. However, it is likely that KTD continued to demonstrate resilience to such seismic events, as noted by Abu-Afifeh *et al.* (2023). In terms of socioeconomic indicators, the INTDEN increased slightly from 5.2 intersections/km² in 2017 to 5.5 intersections/km² in 2023, indicating modest infrastructure development around the dam. The improved accessibility may have supported more effective maintenance and operational oversight of the dam, leading to its enhanced sustainability (Llamosas and Sovacool, 2021). The POPGRW in the area surrounding KTD decreased from 2.6% to 2.2% during this period, reducing pressure on the dam's water resources, which could explain the improvements in sustainability as there was less demand on the dam's capacity. Lastly, both the UINPOP and UFUPOP showed a positive trend, with UINPOP decreasing from 3.8% to 3.3% and UFUPOP from 4.4% to 3.6%. This decline in unemployment, notably among female workers, suggests a more favorable socioeconomic environment, which may be attributed to expanded employment opportunities or development projects associated with the dam and its neighboring regions. These changes would have indirectly supported the dam's sustainability, as stronger economic conditions tend to align with better resource management and investment in infrastructure (Fan *et al.*, 2022). The WSD follows a similar trend, with its ISD rising steadily from 0.379 in 2017 to 1.157 in 2023, resulting in a mean ISD of 0.643. This indicates a marked increase in sustainability, with WSD showing continuous enhancement in its performance. The high ISD value for WSD in 2023 can be explained by significant shifts in both environmental and socioeconomic indicators between 2017 and 2023. Regarding the environmental indicators, the ARD increased notably from 24 days in 2017 to 38 days in 2023, suggesting that although there was less overall precipitation, rainfall events were spread over more days. This could have contributed to a more frequent replenishment of the dam, helping to lessen the consequences of diminished total rainfall. The MAT decreased slightly from 22.7°C to 21.5°C, which may have contributed to reduced evaporation, thus aiding in water retention despite the lower MAP (Ta'any *et al.*, 2013; Karami and Karami, 2019; Abu-Afifeh *et al.*, 2023). On the socioeconomic side, INTDEN increased from 4.8

intersections/km² in 2017 to 5.4 intersections/km² in 2023, indicating that infrastructure around the dam became more developed over this period. This likely improved access and maintenance, contributing to the dam's high ISD. However, a dramatic change occurred in the POPGRW, which jumped from 2.4% to 7.2% between 2017 and 2023. This indicates a rapid population expansion in the area adjacent to the dam, which would normally increase pressure on water resources. The significant ISD implies that WSD was able to satisfy the rising demand through proficient management and strategic allocation of resources. Lastly, both the UINPOP and UFUPOP improved during this period, with UINPOP decreasing from 5.5% to 4.4% and UFUPOP from 5.6% to 4.5%. The enhancement in job opportunities, particularly for women, reflects encouraging socioeconomic circumstances in the neighboring region. The correlation between economic stability and lower unemployment rates likely facilitated improved dam management, as local communities may have had greater financial resources to dedicate to dam infrastructure and upkeep, which in turn supported WSD's commendable sustainability performance (Adjei *et al.*, 2022; Fan *et al.*, 2022; Kamara *et al.*, 2022). The KAD, with the highest mean ISD of 0.937, demonstrates the most significant improvements in sustainability. Starting at 0.654 in 2017, KAD's ISD rose to 1.538 by 2022 and 1.429 by 2023, signaling substantial efforts in maintaining or improving the dam's sustainability. In terms of environmental indicators, the ARD increased from 24 days in 2017 to 38 days in 2023, implying that although there was less overall precipitation, rainfall was more evenly distributed across the year. This approach could have ensured that water levels remained more consistent, even in light of the lower total precipitation. The MAT decreased slightly from 22.7°C to 21.5°C, which might have contributed to lower evaporation rates, thus assisting in the dam's water conservation efforts despite the lower precipitation (Ta'any *et al.*, 2013; Karami and Karami, 2019; Abu-Afifeh *et al.*, 2023). Regarding socioeconomic indicators, INTDEN increased from 6.7 intersections/km² in 2017 to 7.4 intersections/km² in 2023, suggesting enhanced infrastructure development around the dam. This upgrade to the infrastructure is expected to have enhanced access and maintenance capabilities, which would help in maintaining the dam's performance. The POPGRW also rose from 6.7% in 2017 to 7.4% in 2023, reflecting a growing population in the vicinity of the dam. While a growing population could have led to greater demand for the dam's resources, the high ISD reflects KAD's ability to effectively manage these pressures through strategic resource management and operational practices. Improvements were also seen in the unemployment indicators, with the UINPOP dropping from 5.5% to 4.4%, and the UFUPOP decreasing from 5.6% to 4.5% between 2017 and 2023. The drop in unemployment, particularly for women, suggests that economic conditions in the area have improved, potentially resulting in greater local backing for the dam's operations and sustainability programs. The positive economic trend likely facilitated investments in infrastructure and enhanced dam management practices, these results agreed with litrautre findings (Adjei *et al.*, 2022; Fan *et al.*, 2022; Kamara *et al.*, 2022).

The KUD is classified as having moderate sustainability, with a mean ISD of 0.420. Although its ISD fluctuates over the years, from a low of 0.098 in 2018 to a high of 0.861 in 2022, the overall trend points toward moderate improvements in sustainability. The observed variability implies that KUD has taken significant steps toward sustainability; however, its performance may still be impacted by external factors, such as environmental conditions or modifications in operational practices (Table 4). Low-sustainability dams include WAD, WD, MD, and ZMD. The WAD exhibits a low mean ISD of 0.278, although it shows some improvement in 2023 with an ISD of 0.648. The WAD's sustainability has generally remained low, the MAP declined from 9.8 mm in 2017 to 7.9 mm in 2023. Accordingly, the dam's sustainability did not improve, as indicated by the lower ISD. The slight rise in MAT from 20.1°C to 20.3°C, coupled with an increase in SEIMAG from 0.0 to 1.8, suggests some environmental stress. There was a notable increase in the UINPOP, which rose from 16.4% to 20.0%, and the UFUPOP also increased from 18.4% to 24.1%. These changes suggest that the local resources and management capabilities may be under strain due to economic conditions. Similarly, the WD has a low mean ISD of 0.265, with slight improvements over the years, culminating in a higher ISD of 0.577 in 2023. The WD experienced a reduction in the MAP from 7.0 mm in 2017 to 6.5 mm in 2023 and a slight decrease in ARD from

Table 4: Environmental and socioeconomic sustainability indicators of the moderate-performance dam (KUD) and low-performance dams (MD, WAD, WD and ZMD) for the years 2017 and 2023

Dam	Year	MAP (mm)	ARD (day)	MAT (°C)	SEIMAG (Unitless)	INTDEN (Inters./km^2)	POPGRW (%)	UINPOP (%)	UFUPOP (%)
KUD	2017	10.8	19	20.4	2.1	4.3	1.9	6.1	6.2
	2023	5.0	30	19.3	3.2	4.8	5.6	4.9	4.9
MD	2017	5.7	13	18.2	0.0	1.9	1.4	3.1	4.8
	2023	5.1	9	24.8	3.1	2.1	2.7	3.2	4.4
WAD	2017	9.8	30	20.1	0.0	8.2	2.4	16.4	18.4
	2023	7.9	48	20.3	1.8	8.8	2.1	20.0	24.1
WD	2017	7.0	16	18.2	2.5	4.0	2.4	2.6	2.7
	2023	6.5	13	24.8	2.1	4.5	2.2	1.8	1.8
ZMD	2017	7.9	24	16.4	0.0	1.8	0.8	3.7	4.4
	2023	6.4	37	22.1	3.0	2.1	0.7	2.2	1.8

16 to 13 days, indicating less water availability. The MAT rose significantly from 18.2°C to 24.8°C, likely increasing water loss through evaporation. Although the SEIMAG decreased from 2.5 to 2.1, the minor improvement in seismic conditions did not lead to significant sustainability gains. The socioeconomic factors represented by POPGRW, UINPOP, and UFUPOP displayed a combination of trends, indicating an overall reduction in general unemployment, yet highlighting continued issues regarding female unemployment. The MD consistently shows very low sustainability, with a mean ISD of just 0.010, as its ISD remains at 0 for most of the years, indicating minimal or no significant improvements. The environmental conditions saw a reduction in MAP from 5.7 mm in 2017 to 5.1 mm in 2023, alongside a decrease in ARD from 13 days to 9 days, which could have negatively impacted water availability. The MAT increased sharply from 18.2°C to 24.8°C, which may have led to higher evaporation rates, further straining the dam's water resources. The SEIMAG value experienced a substantial increase from 0.0 to 3.1, potentially reflecting an elevated level of exposure to seismic risk. Socioeconomically, there was a modest increase in the POPGRW, UINPOP and UFUPOP rates, indicating potential socioeconomic pressures that may have affected the dam's management and sustainability efforts. Finally, the ZMD, with a mean ISD of 0.254, follows a similar pattern to WAD and WD, displaying gradual improvement in sustainability, particularly in 2022 when its ISD rose to 0.615. The MAP dropped from 7.9 mm in 2017 to 6.4 mm in 2023, while the ARD increased from 24 to 37 days, potentially reflecting a shift towards less intense but more frequent rainfall. There was a considerable rise in the MAT, climbing from 16.4°C to 22.1°C, which intensified worries regarding evaporation. Furthermore, the SEIMAG value increased from 0.0 to 3.0, reflecting a greater seismic risk. The POPGRW remained nearly stagnant, while the UINPOP and UFUPOP decreased slightly, yet not enough to suggest substantial socioeconomic progress. Involving community feedback contributes to the long-term viability of dams by taking into account regional water demands, agricultural techniques, and the implications of their operations. It provides information on maintenance, promotes ownership, and weaves in cultural practices. Community involvement facilitates adaptive management, strengthening resilience against climate change.

Causality and dependency concerning local communities and water quality indicators

The analysis of the ISD causality highlights how local community indicators (WASPOP and FWAGRS), along with water quality indicators (ECDEFF and BCREFF), impact the sustainability performance of Jordanian dams. The results obtained from the causality test executed in RStudio demonstrate several noteworthy relationships (Table 5 and Table 6).

With an average value of 8.6%, WASPOP reflects a moderate level of agricultural engagement in the regions surrounding the dams. However, the elevated standard deviation of 6.2% and a coefficient of variation of 71% reflect notable variations across different locations and years. These distinctions point to a considerable variation in agricultural dependency, which can impact water resource usage and may have consequences for sustainability efforts. Positive significant relationships with ISD are observed at

Table 5: Summary statistics (mean ± standard deviation, minimum, maximum and coefficient of variation) of the local communities and water quality measures used in the analysis through 2017-2023

Year	ISD	WASPOP (%)	FWAGRS (%)	ECDEFF (µS/cm)	BCREFF Unitless
Observations	56	56	56	56	56
$\mu \pm \sigma$	0.44 ± 0.38	8.6 ± 6.2	1.4 ± 1.0	1116 ± 534	0.09 ± 0.04
Minimum	0.00	2.3	0.0	304	0.03
Maximum	1.54	23.1	3.1	2263	0.20
Coefficient of variation (%)	87	71	73	48	41

Table 6: Summary of Granger-causality test conducted among the ISD, WASPOP, FWAGRS, ECDEFF and BCREFF including significancy, confidence level and sensitivity through 2017-2023

X-variables	*y*-variables				
	ISD	WASPOP (%)	FWAGRS (%)	ECDEFF (µS/cm)	BCREFF Unitless
ISD	-	Yes [+b1, +c2, +b3]	Yes [+c1, +c2, +c3]	No	No
WASPOP	Yes [+a1, +a2, +a3]	-	No	No	No
FWAGRS	Yes [+a1, +b2, +a3]	No	-	No	No
ECDEFF	Yes [-a1, -a2, -b3]	Yes [-a1, -a2, -b3]	Yes [-b1, -c2]	-	No
BCREFF	Yes [+d1]	No	Yes [+d1]	No	-

Note: *x* granger causes *y*; Yes : dependent; No : independent; – : not applicable) in addition to the significant empirical results of the causality test obtained by RStudio. (+ and – are positive and negative significant relationships, respectively; a, b, c and d are 0.1%, 1%, 5% and 10% confidence, respectively; 1, 2 and 3 are first, second and third lag order.

the first (b1), second (c2), and third (b3) lag orders, indicating that an increase in agricultural workforce percentages is associated with improvements in dam sustainability over time. Areas characterized by increased agricultural activity may exert greater pressure on water resources, which could have both beneficial and detrimental effects on ISD, contingent upon the effectiveness of resource management strategies (Adjei *et al.*, 2022; Abu-Afifeh *et al.*, 2023).

The average participation of female workers in agriculture is low at 1.4%, with a high coefficient of variation (73%) indicating inconsistent participation levels, which range from no involvement to a maximum of 3.1%. Cultural, social, or economic factors that impact women's roles in agriculture may contribute to these discrepancies, ultimately influencing the social sustainability dimension of the ISD. The positive significant relationships observed at all three lag orders (c1, c2, c3) suggest that higher female participation in agriculture has a favorable effect on the ISD, emphasizing the importance of gender inclusion in agricultural activities to enhance sustainability outcomes (Langill, 2020; Tandon *et al.*, 2022; Abu-Afifeh *et al.*, 2023). Rola-Rubzen *et al.* (2020) highlighted barriers like gender roles and lack of resources that limit women's agricultural technology adoption. Glazebrook *et al.* (2020) noted gender bias impacts on productivity, advocating for policy reforms. Memon *et al.* (2020) emphasized female participation in microfinance, while Mashapure *et al.* (2022) addressed entrepreneurship challenges. The average electrical conductivity of dam effluent is 1,116 µS/cm, with values ranging from 304 to 2,263 µS/cm, indicating considerable variability in salinity across different dam sites. With a coefficient of variation of 48%, there are evident differences in water quality, potentially driven by agricultural runoff or the natural mineral content present in the water. Negative significant relationships with ISD are noted at the first (a1), second (a2), and third (b3) lag orders, suggesting that higher electrical conductivity levels—indicative of poorer water quality—may negatively impact dam sustainability. Proper management of water salinity is essential for sustaining a conducive ISD (Santos *et al.*, 2017; Bor and Elçi, 2022). The BOD to COD ratio averages 0.09, with values ranging from 0.03 to 0.20, and a coefficient of variation of 41%. This variability points to discrepancies in the biodegradability of organic matter among various dam locations, which may be attributed to differing degrees of

pollution management and treatment efficacy. A positive significant relationship with ISD at the first lag order (d1) suggests that higher BCREFF values, indicating better biodegradability of organic matter, contribute positively to water treatment processes and the overall sustainability of the dams (Winton *et al.*, 2019; Alrbaihat and Abu-Afifeh, 2023). An overview of the causal relationships observed among the variables in the second phase of the analysis is presented, summarizing the econometric results while highlighting both the direction and statistical significance of these relationships. Specifically, Table 6 offers a comprehensive summary of the cause-and-effect connections, including the polarity of these relationships, between the ISD and the indicators for local communities (Abu-Afifeh *et al.*, 2023) and water quality (Santos *et al.*, 2017; Bor and Elçi, 2022). The analysis of the impact of local communities and water quality measures on the sustainability of Jordanian dams revealed the following relationships:

WASPOP causality

• ISD: Strong positive relationships at all lag orders (a1, a2, a3) indicate that higher ISD values can predict increased WASPOP in subsequent periods.

• No significant causal relationships were found between WASPOP and FWAGRS, ECDEFF, or BCREFF.

FWAGRS causality

• ISD: Positive causality at all lag orders (a1, b2, a3), suggesting that higher female participation in agriculture may lead to improvements in dam sustainability.

• No significant causality was identified between FWAGRS and WASPOP, ECDEFF, or BCREFF.

ECDEFF causality

• ISD and WASPOP

• Across all lag orders (a1, a2, b3), negative relationships were identified, indicating that higher levels of electrical conductivity correspond to a reduction in both dam sustainability and the percentage of the agricultural workforce.

FWAGRS

• Shows negative relationships at the first (b1) and second (c2) lag orders, suggesting a negative impact of higher salinity on female agricultural participation.

BCREFF causality

• ISD and FWAGRS: Positive relationships at the first lag order (d1), indicating that better biodegradability (higher BOD to COD ratio) is associated with improvements in both dam sustainability and female participation in agriculture.

Jordan's path to sustainable water resource and dam management

Jordan's sustainability efforts focus on water resilience, particularly dams (MWI, 2024). To combat water scarcity, the National Water Strategy (2023-2040) focuses on enhancing water security, encouraging the reuse of wastewater, and modernizing governance frameworks. Regulatory frameworks, such as the Water Authority Law No. 18 (1988) and Water Use Regulation No. 85 (2013), guide sustainable water management. The Wastewater Treatment and Reuse Regulation No. 65 (2004) supports safe wastewater reuse, while energy laws promote renewable projects and efficiency (Energy Law No. 13, 1999; Renewable Energy Law No. 2, 2012). Land and agricultural sustainability are addressed by the Land Law No. 13 (2015) and Agricultural Law No. 44 (2002). Biodiversity is safeguarded through the Nature Reserves Law No. 47 (2006) and Wildlife Protection Law No. 12 (1995). Waste policies, like the Waste Management Law No. 27 (2007), aim to protect water quality. The National Food Security Strategy (2021-2030) and the Comprehensive Energy Sector Strategy (2020-2030) underscore the necessity of resource conservation in their strategic frameworks (MOE, 2024). To strengthen resilience against climate change, Jordan implements these policies, which are designed to ensure the sustainable availability and quality of water resources over the long term.

CONCLUSION

This study explores the interplay between social, economic, and environmental factors affecting Jordanian dams' sustainability, addressing a significant research gap. The statement draws attention to the interconnectedness of dam sustainability, community involvement, and water quality, stressing the importance of a unified approach that aligns socioeconomic factors with environmental management practices. The study's indicators reflect local context, accounting for regional

differences in environmental, social, and economic conditions, allowing customization to address unique challenges. Significant findings highlight the connections that affect dam sustainability. The WASPOP exhibits a positive link with the ISD, implying that heightened agricultural participation can contribute to enhanced sustainability. Female participation in agriculture also positively impacts ISD, underscoring social inclusivity's importance. Conversely, water quality issues, like higher ECDEFF, negatively affect ISD and community involvement, while better biodegradability (higher BOD to COD ratio) improves sustainability. The insights reveal the importance of implementing specific strategies to enhance water quality while also promoting gender inclusion. The study demonstrates the utility of the WTM and GCT for evaluating dam performance, adaptable across different contexts. Broadening research to encompass various environmental, social, and economic elements can lead to better dam management practices. Incorporating statistical models and qualitative insights provides a more comprehensive understanding of sustainability challenges. Jordan's National Water Strategy (2023-2040) addresses severe water scarcity through wastewater reuse, rainwater harvesting, and governance modernization. Sustainable water management is directed by regulatory laws, and policies concerning energy, agriculture, biodiversity, and waste management are vital for safeguarding resources and fostering efficiency. Dam managers can use ISD scores to identify weak points and prioritize interventions, track performance, and guide policy, fostering long-term sustainability and resilience.

AUTHOR CONTRIBUTIONS

A. Al-Afeshat contributed to the conceptualization and methodology of the study. M.M. Zoubi was involved in the investigation and original draft preparation. Q.Y. Abu-Afifeh provided resources and was responsible for data curation. H. Al-Jawaldeh performed formal analysis and validation. T.A. Qutishat handled the software and visualization aspects of the research. A.M.N. Masoud was in charge of reviewing and editing the manuscript. M. Rahbeh managed the project administration and provided supervision throughout the study.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
$\mu \pm \sigma$	Mean ± standard deviation
µS/cm	Micro-siemens per centimeter
σ_j^t	Standard deviation of the jth indicator
°C	Degree Celsius
2SLS	Two-stage least squares
ARD	Annual rainy days
BCREFF	The BOD to COD ratio of dam effluent
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand

DSTF	Dead sea transform fault
e_i^t	The euclidean distance
ECDEFF	Electrical conductivity of dam effluent
f_i	Fixed effects
FWAGRS	Percentage of female workers aged 15 and over in the agricultural sector
GCT	Granger causality test
H	High-performance dams
H_0	Joint hypothesis
i	Denotes Jordanian dams {1, …, 8}
INTDEN	Intersections density at the area adjacent to the dam
ISD	Index of sustainable dams
ISD_{max}	Maximum index of sustainable dams
j	Denotes indicator {1, …,8}
KAD	Kafrein dam
km	Kilometer
km²	Squared kilometer
KTD	King Talal dam
KUD	Kufranja dam
L	Low-performance dams
M	Moderate-performance dams
m_j^t	Maximum value of indicator
MAP	Mean annual precipitation
MAT	Mean annual temperature
MCM	Million cubic meters
MD	Mujib dam
ML	Local magnitude
mm	Milimeter
Mw	Moment magnitude
PBC	Public Benefit Corporation
POPGRW	Population growth rate in the area adjacent to the dam
RStudio	R programming language studio
SEIMAG	Maximum seismic magnitude affected the dam
SIIs	Sustainability indicators and indices
t	Denotes time period {2017, …, 2023}
UFUPOP	Unemployed females aged 15 and over as a percentage of the total unemployed population in the area adjacent to the dam
UINPOP	Unemployed individuals aged 15 and over as a percentage of the population in the area adjacent to the dam
W_i^t	Wroclaw index
WAD	Wadi Arab dam
WASPOP	Percentage of workers aged 15 and over in the agricultural sector
WD	Wala dam
WSD	Wadi Shu'eib dam
wt	Weight
WTM	Wroclaw taxonomic method
X	Generic 2-dimensional matrix
x	Independent granger variable
$\overline{x}_j^t$	Mean of the jth indicator
y	Dependent granger variable
Z	Normalized matrix
ZMD	Zarq-Main dam

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