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Integrated Hydro-Economic Analysis of Water Resource Sustainability in Jordan: Systemic Trade-Offs and Institutional Constraints in the Jordan Valley

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Abstract

This research moves beyond conventional water accounting to provide a systemic diagnostic framework for the Jordan Valley, identifying the "Structural Misalignment" between economic incentives and resource sustainability. The primary contribution of this study is the development and validation of a Decision Support System (DSS) powered by two novel composite indices: the Nexus Efficiency Index (NEI) and the Composite Operational Deficit (OD). Unlike traditional reports, this analysis uncovers a critical "Governance Gap" driven by a price-incentive decoupling: a 5.7% agricultural inflation (APPI) occurring simultaneously with a 0.69% national deflation (PPI) in late 2025. By quantifying this divergence, the study provides empirical evidence of Jevons' Paradox in the Jordan Valley, where technical efficiencies (82% billing) are systematically eroded by the near-zero marginal cost of independent solar-powered pumping. The research's strategic breakthrough lies in its "Policy Localization" roadmap, designed to mitigate the 83% reduction in international technical support (USAID). Through the integration of Predictive AI (SVM) and Satellite-based Monitoring (IPADT), the study demonstrates how "Focus Metering" can capture 80% of management benefits with minimal infrastructure investment. This work transforms the Water-Energy-Food-Environment (WEFE) Nexus from a theoretical concept into an actionable, digital governance lever, providing a blueprint for achieving systemic resilience and safeguarding Jordan's "Hydrological Commons" amidst the global energy and fiscal shifts of 2026.

Keywords

Hydro-Economic Analysis (HEA), WEFE Nexus, Wicked Problem, System

Resilience, Jevons' Paradox, Nexus Efficiency Index (NEI), Operational Deficit (OD), Jordan Valley

1. Introduction

To analyze the current state of water resource management in the Hashemite Kingdom of Jordan, it is necessary to recognize that water serves as the absolute structural constraint on national planning and economic resilience. The Jordanian water sector is defined by high-level strategic challenges that necessitate continuous adaptive management and a state of "permanent hydrological alertness." Jordan is consistently positioned as the second most water-deprived nation globally [1]. While the international absolute scarcity threshold is defined at 500 m^3 of renewable water available per person per year, the average availability in Jordan declined to approximately 61 m^3 in 2021—representing less than 13% of that global benchmark [2]. This reality acts as the primary catalyst for the Kingdom's ambitious strategic projects and infrastructure modernization efforts. This status is the result of a convergence of biophysical factors, a significant humanitarian contribution to regional stability, and accelerated climate instability.

1.1. Convergent Biophysical, Climatic and Anthropogenic Drivers

Jordan is predominantly arid to semi-arid, with over 90% of its territory receiving less than 200 mm of rainfall annually [3]. In the 2023 hydrological cycle, out of a total annual rainfall volume of 8508.4 MCM, a total of 93.1% (7921.3 MCM) was lost immediately to evaporation. This leaves a restricted margin of 4.47% (380.3 MCM) for groundwater recharge and 2.39% (203.4 MCM) for surface runoff [4]. This high evaporative rate represents a fundamental physical boundary that Jordanian institutions manage through advanced storage and harvesting techniques. Potential evaporation force varies from 2000 mm/year in central northern/ highlands to 4000 mm/year in Aqaba [5].

Climate change is a measurable reality that Jordanian institutions are actively addressing through policy. In the 2024 cycle, average precipitation was 89.38 mm, representing a 38.5% decrease from the 145.37 mm recorded in 2023 [6]. Simultaneously, the average temperature in 2024 was 20.3˚C, which is 1.51˚C higher than the long-term historical mean of 18.79˚C [7]. Evaporation losses in open reservoirs are estimated at 10% to 15% of total stock annually, a figure that increases by 1.2% for every 1˚C rise in temperature. Future hydrological modeling projects a reduction in streamflow between 22.3% and 41.6%, leading to a projected structural freshwater shortage of 1521 MCM per year by 2050 [8] [9]. These projections serve as the rationale for high-priority strategic projects, such as the National Conveyor Project (NCP).

Jordan's role as a sanctuary for populations displaced by regional instability is a core component of its national resilience strategy. Between 2011 and 2025, the population increased from 7 million to 12 million [10], including more than 1.3 million Syrian refugees [11]. Approximately 89% of these refugees reside in host communities, which has required the state to increase water supply by 40% in northern governorates [8] [12]. This demographic growth coincides with a national unemployment rate for Jordanians of 21.4%, with female unemployment reaching 33.9% as of Q3 2025 [13]. Managing these variables requires the state to maintain stable water service delivery even as the government debt-to-GDP ratio reached 90.2% in December 2024 [14]. This fiscal constraint significantly limits financing options for large-scale desalination projects, making the integrated Hydro-Economic Analysis (HEA) of existing resources an indispensable necessity.

Furthermore, the structural water constraint is compounded by a long-term transition in Jordan's agricultural sector toward vertical intensification. Since the 1960s, the total agricultural area has remained relatively stagnant or even declined in certain categories, as depicted in **Figure 1**, which illustrates the stabilization of arable land and permanent crops despite surging demand. While the total harvested area for essential crops has significantly declined, the productivity per hectare has followed an aggressive upward trajectory. This transition is evidenced by a sharp increase in the consumption of chemical fertilizers, as illustrated in **Figure 2**; specifically, nitrogen consumption surged from 2100 tons in 1961 to a peak of 41,219 tons by 2022, while potash consumption saw an even more dramatic rise from just 100 tons to 32,842 tons in the same period. This "High-Input" agricultural model creates a systemic feedback loop: higher yields necessitate increased fertilizer application, which in turn requires higher water volumes for soil flushing and salinity management, thereby intensifying the pressure on the Kingdom's depleted aquifers [15].

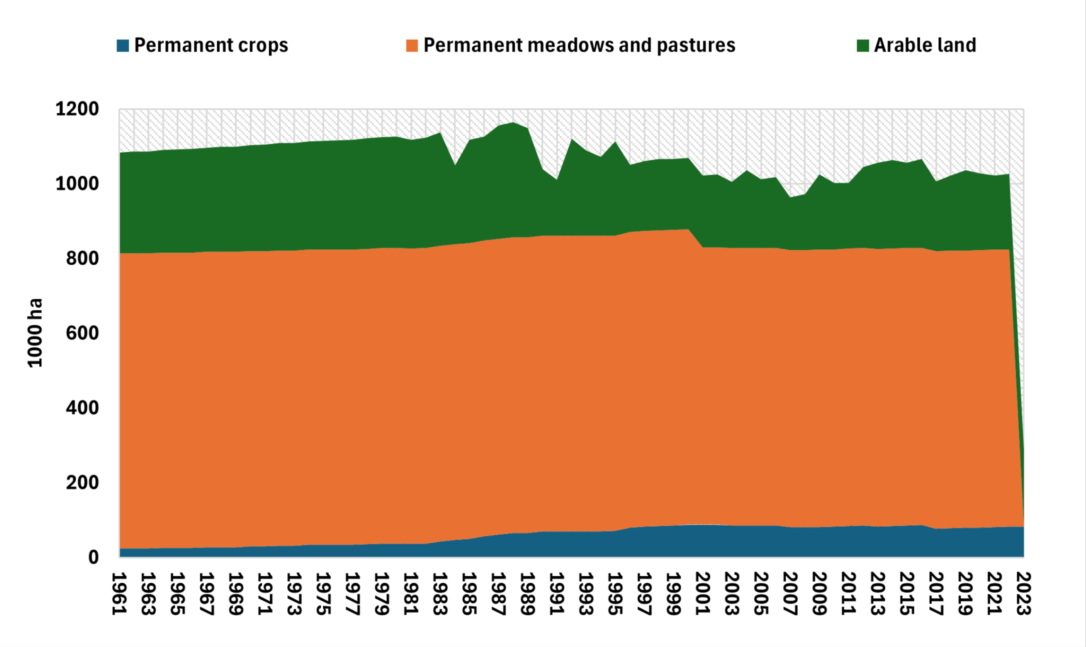

Figure 1. Agricultural area in Jordan 1960-2023.

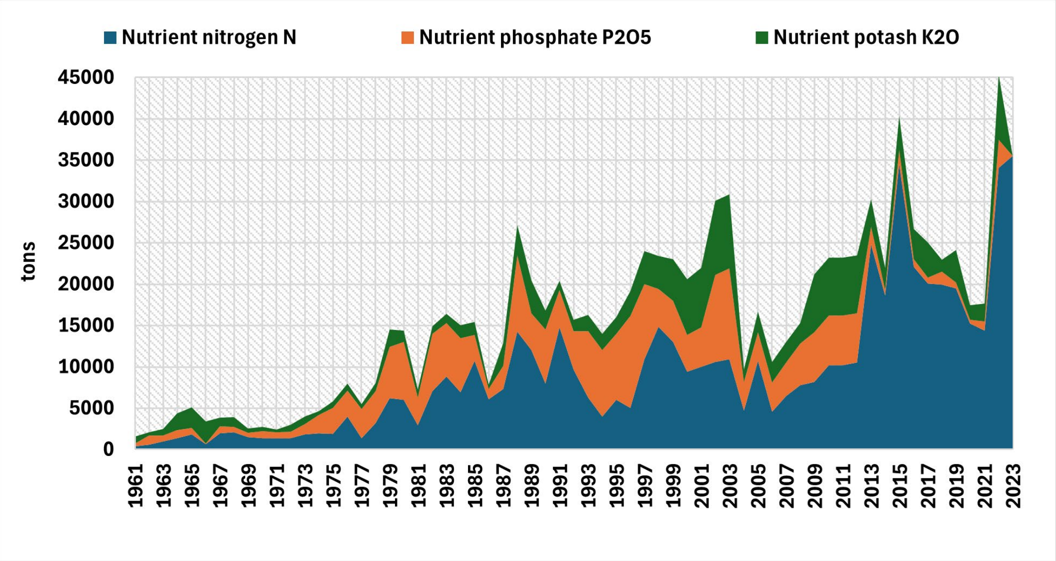

Figure 2. The fertilizers consumption in nutrients in Jordan, 1960-2023.

1.2. The Jordan Valley

The Jordan Valley Region extends along the western side of the kingdom, forming part of the Great Rift Valley. Most of the land within this depression lies below sea level, with the lowest point at the Dead Sea reaching 422 meters below sea level. Along the eastern slopes, the elevation rises sharply to approximately 700 meters above sea level, creating steep terrain intersected by side valleys. The climate ranges from arid to semi-arid, with average annual rainfall between 50 and 200 mm [16].

The Jordan Valley (JV) is Jordan's primary agricultural zone and a strategic core for national development. The Jordan Valley Authority (JVA), operating under Law No. 19 of 1988, manages the structural imperative to balance municipal water security in the Highlands with the requirements of the agricultural "food basket" [17]. The JV is recognized as a quintessential "wicked problem".

A critical "Governance Gap" has emerged within the valley regarding independent solar pumping. While the expansion of private participation in the energy sector was initially envisioned as a success in energy diversification, it has provided a technical loophole for farmers to bypass traditional energy costs. This shift has transformed a "success in energy provision" into a "challenge for water sustainability", as it effectively removes the financial "soft cap" on groundwater abstraction [18]-[21].

1.3. Literature Review

To situate the current study, a review of highly-cited academic literature focusing on water scarcity, governance, and resource modeling is conducted. While extensive literature exists that addresses the general nexus challenges, a significant gap remains in the quantitative integration of localized operational inefficiencies and specific economic value signals within a single, functional framework.

1) Hydro-Economic Modeling (HEM) and Valuation: Establishes HEM's role in assessing water allocation based on maximizing marginal economic value [22]-[24]. However, traditional HEM often struggles to integrate the disparate spatial and temporal scales of hydrological (days/basins) and economic (years/administrative boundaries) models, producing unreliable predictions on resilience and depletion rates. Even recent comprehensive work [8] [25] analyzing the hydro-political economy of Jordan establish HEM's role in assessing water allocation based on maximizing marginal economic value. They stress that HEM should inform planning by demonstrating resilience through water (re)allocation based on relative "value". However, remains at the strategic analysis level and stopping short of providing operational indices for real-time efficiency management a persistent limitation is that the most common spatial and temporal scales (basin/yearly) are "appropriate for planning but not for operational decisions".

2) Wicked Problems and Systemic Complexity: Validates that the analysis must focus on system properties rather than simple technical fixes [26] [27]. Existing participatory frameworks successfully bridge the science-policy gap but often remain conceptual, lacking the quantitative indicators required for concrete policy implementation and monitoring progress within a specific institutional context like the Jordan Valley Authority (JVA).

3) WEFE Nexus and Integrated Management: Requires a holistic approach to managing interdependencies between water, energy, food, and the environment [28] [29]. Current Jordan-specific WEFE models successfully assess high-level strategies (e.g., desalination needs) but generally lack the fine-grained, quantitative tools necessary to evaluate the financial sustainability of specific operational entities like the JVA using real-time local data.

4) Groundwater Governance Gaps: Research identifies the inadequacies of managerial-focused approaches to control over-abstraction, often driven by distorted price signals [30] [31]. This literature highlights the symptoms of inadequate governance but rarely provides the specific, formulaic tools needed to quantify the resulting operational deficits and nexus inefficiencies at the utility level.

1.4. Research Gap and Unique Contribution

The primary research gap is not a lack of data, but rather the profound misalignment of price incentives that current models inadequately address. While the national economy experienced a producer price deflation (PPI) of 0.69% [32], the agricultural sector faced an inflationary bias (APPI) of 5.7% in the first eleven months of 2025 [33]. This divergence is the core of the "Governance Gap" addressed by this research.

This study contributes uniquely by providing the first application of an integrated framework utilizing two novel, composite quantitative indices—the Nexus **Efficiency Index (NEI)** and the **Composite Operational Deficit (OD)**—to bridge the gap between abstract WEFE theory and practical policy implementation. This study contributes uniquely by:

1) **Empirical Validation of the Decoupling Effect**: Utilizing granular 2025-2026 data to empirically contrast national PPI deflation with sharp agricultural price inflation, revealing how market volatility directly drives resource depletion (e.g., a 68.3% collapse in tomato prices versus a 23.2% surge in banana prices in late 2025 dictates irrigation intensity) [34].

2) **Value-Based Resilience Modeling**: The innovative **NEI** is used to quantify the economic value generated per unit of resource input ($water\ (\times)\ energy$), providing a novel, unified metric that allows policymakers to directly evaluate the economic resilience of different cropping patterns under acute scarcity —an analytical step missing in prior literature.

3) **Integrated Governance Solutions**: Proposing specific, data-driven policy levers that leverage the energy component (e.g., solar monitoring) to enforce water sustainability, thereby translating the conceptual WEFE Nexus into actionable, quantitative governance solutions embedded within the operational reality of the JVA.

2. Methodology

The analysis employs an integrated Hydro-Economic Analysis (HEA) methodology, designed to identify optimal water management strategies by characterizing and valuing water demands against biophysical and institutional constraints. This framework informs strategic plans to improve the economic performance of water systems through integrated modeling, culminating in the development of novel composite indices for operational deficit and nexus efficiency.

2.1. Data Acquisition, and Strategic Benchmarks

The study is based on official records from the Ministry of Water and Irrigation (MWI) and the Jordan Valley Authority (JVA) for the period 2018-2024, supplemented by real-time macroeconomic data from 2025. The analytical structure adheres to the conceptual flow presented in **Figure 3**, which integrates the HEA process with the Water-Energy-Food-Environment (WEFE) Nexus components.

Figure 3 serves as a dynamic roadmap to model the complex interactions within the Jordan Valley. This framework is operationalized across four critical dimensions:

- System Boundaries and HEA Domain: The HEA domain is represented by the dashed boundary, defining the administrative control zone. Within these boundaries, the four components—Water, Energy, Food, and the Environment—are mathematically integrated to ensure that no resource is managed in isolation.
- External Pressures: Red arrows entering the system represent macro-variables that impose constraints, including Climate Change, evidenced by the 38.5% decrease in rainfall in 2024 [6]; Population Growth, with the national population reaching 12 million by 2025 [9]; and Institutional Constraints, such as the 90.2% debt-to-GDP ratio recorded in December 2024 [14].

- The "Wicked Problem" Core: At the convergence of the four Nexus circles lies "Trade-off Management," designated as the Wicked Problem. This core is where **the study's novel research equations (*NEI* and *OD*)** are applied to manage the conflict to manage the conflict between agricultural production needs (e.g., the 23.2% surge in banana prices [34]) and the imperative of resource conservation under acute scarcity.
- Inputs vs. Outputs: Inputs consist of high-resolution hydrologic and economic data, such as the 2023 total managed water inflow of 462 MCM [25]. Outputs are the "Policy Scenarios" generated by the system, which propose solutions like digital solar-pumping monitoring to address price decoupling.

The HEA framework requires the operationalization of three main elements: the physical flow network, economic valuation functions, and system constraints.

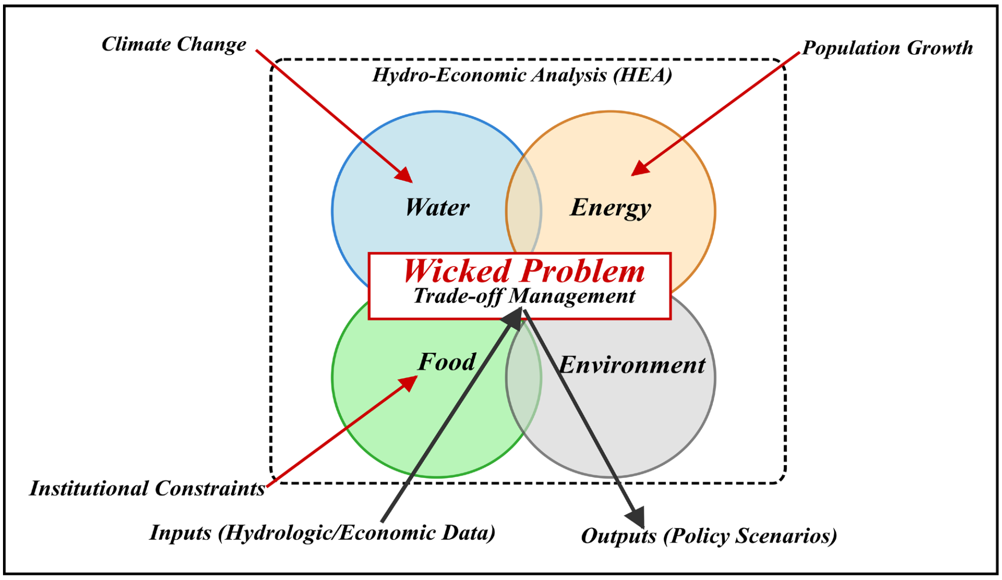

Figure 3. The Integrated Conceptual Framework for Hydro-Economic Analysis (HEA) and the Water-Energy-Food-Environment (WEFE Nexus).

2.2. Operationalizing the HEA Framework: The Three Pillars

To translate this conceptual framework into a quantitative model, the HEA framework activates three essential elements:

- Physical Flow Network: Based on the comprehensive water balance, the model tracks the 210 MCM allocated to irrigation from source to farmgate [25].
- Economic Valuation Functions: These functions bridge the gap between resource costs and market signals, such as the 5.7% cumulative inflation in agricultural producer prices during 2025 [33].
- System Constraints: The model is bounded by operational inefficiencies, primarily the 18% commercial water loss (reflecting 82% JVA Billing Efficiency [35] [36]) and physical losses which contribute to a total of 27% Non-Revenue Water (NRW) loss (125 MCM) [25]. This loss acts as a major barrier to systemic resilience and is integrated into the model's constraints.

2.3. Model Parameterization and Construction

2.3.1. Data Inputs

The physical system was parameterized by aggregating regional data spatially and temporally, focusing on key hydrological and geophysical inputs necessary for flow simulation (**Table 1**).

Table 1. Key Hydro-Economic Model Parameters (Physical and Geophysical Constraints).

Parameter	Model Significance	Estimation Method
Aggregated Climatic Inputs	Simulates surface runoff and evapotranspiration	based on MWI climate data
Available Soil Water Capacity	Triggers percolation and determines irrigation requirements	based on soil characteristics.
Groundwater Recession	Controls the rate of groundwater flow from the saturated storage	using hydrograph separation.
Geophysical Classification	Determines partitioning of rainfall	using land use data from MWI/JVA reports.

The economic component characterizes water demands using marginal economic value, operationalizing the allocation priority observed in the system. The systemic constraints define the boundaries of the optimization problem (**Table 2**).

Table 2. Synthesized Data Inputs for Hydro-Economic Analysis (Based on 2023 Baseline).

Input Category	Data Point	Value	Context/Rationale
Structural Allocation	Domestic Water Use (Actual 2023)	526.4 MCM/year [4]	Reflects population growth and priority
Structural Allocation	Agricultural Water Use (Actual 2023)	623.4 MCM/year [4]	Reflects mandated stabilization
Sustainability Constraint	Amman-Zarqa Abstraction Surplus	−93.5 MCM	Critical groundwater depletion rate
Sustainability Constraint	Total Groundwater Share (2023)	263.4 [4]	Reflects high dependency on aquifer storage
Operational Efficiency	JVA Billing Efficiency	82% [35] [36]	Technical billing ratio in the Jordan Valley

A critical constraint in the HEA framework is the inclusion of the Amman-Zarqa Over-abstraction deficit (−93.5 MCM). This basin, which produced 181 MCM in 2023 against a safe yield of only 87.5 MCM, serves as a primary source for municipal water in Jordan. The massive over-abstraction underscores the structural pressure on the entire water grid, necessitating the diversion of surface water from the Jordan Valley to meet urban needs.

2.3.2. Formulation Steps

The formulation of the Decision Support System (DSS) followed a multi-stage analytical process to ensure that the mathematical model accurately reflects the biophysical and economic realities of the Jordan Valley:

- **Step 1**: Mass Balance Normalization: The physical flow data for the period 2018-2023 was normalized to establish a baseline for "Normal Operating Conditions". This involved reconciling the 526.4 MCM municipal use against the 623.4 MCM agricultural peak observed in 2023 to identify the "Systemic Over-abstraction Gap" [4].
- **Step 2**: Constraint Integration (The Penalty Function): The Amman-Zarqa deficit (−93.5 MCM) was integrated as a negative scalar in the surface water availability function. This step ensures that the model "penalizes" agricultural allocations when highland groundwater levels drop, simulating the real-world diversion of Yarmouk and Al-Adasiyah waters to urban centers [4].
- **Step 3**: Economic Weighting and PPI/APPI Decoupling: To account for the 5.7% agricultural inflation (APPI) [33] versus the −0.69% national deflation (PPI) recorded in 2025 [32], a sensitivity coefficient was added to the "Net Economic Value" component. This allows the model to detect when high crop prices (e.g., Bananas at +23.2%) [33] trigger a surge in energy-intensive pumping.
- **Step** 4: Final Composite Index Derivation: By synthesizing the results from the previous steps, the two primary indices were formulated to measure fiscal sustainability and nexus efficiency.

2.3.3. Decision Support System (DSS) Formulation

The HEA framework utilizes a basin-scale mass balance model to track water capital ($Actual\ storage_t = Actual\ storage_{t-1} + Inflows - Outflows$) [25]. To evaluate Policy shifts, the study utilizes two composite indices:

- Composite Operational Deficit (**OD**):

$$\mathrm{OD} = \sum (C_e + C_o + C_m) - (R_i + G_s)$$

where:

C_e is energy cost, C_o is operation, C_m is maintenance, R_i is revenue, G_s is government subsidy

$$R_i = (Total\ water\ distributed \times Tariff) \times 0.82.$$

- NEI:

$$\mathrm{NEI} = \frac{\mathrm{NetEconomicValue}(\mathrm{JD})}{\mathrm{Water\ Used}(\mathrm{m}^3) \times \mathrm{Energy\ Intensity}(\mathrm{kWh} \mid \mathrm{m}^3)}$$

2.4. Data Quality and Limitations

Empirical approaches based on observational data face limitations due to simplifying assumptions; results should be treated as indicative of potential impacts. Crucially, the reliance on annual/basin-scale data is inappropriate for operational decision-making, potentially underestimating impacts from extreme, short-term events [28]. Future model refinement requires investment in advanced techniques, such as the Support Vector Machine (SVM) algorithm [1].

3. Results

3.1. Longitudinal Water Budget and Aquifer Trends (2018-2023)

The longitudinal analysis identifies 2023 as a pivotal fiscal year, characterized by an unprecedented convergence of sectoral demands that pushed Jordan's water infrastructure to its operational limits. Municipal demand escalated to 526.4 MCM, a trajectory driven by sustained population growth and systemic hosting responsibilities. Simultaneously, the agricultural sector experienced an aggressive surge, reaching a historic peak of 623.4 MCM—a significant departure from the relative stabilization observed during the 2021-2022 period. Table 3 illustrates the shift in sectoral allocations alongside the specific pressures on the Amman-Zarqa aquifer [4].

Table 3. Longitudinal trends in water sector allocations and groundwater dependency (2018-2023).

Year	Municipal/Drinking (MCM)	Agricultural/Irrigation (MCM)	Groundwater Share (MCM)	Amman-Zarqa Extraction
2018	479.5	555.3	245	177.81
2019	497.37	560.54	219	163.59
2020	517.63	566.94	199.69	159.4
2021	519.84	531.1	209.75	166.01
2022	517.65	517.71	246.73	162.4
2023	526.4	623.4	263.4	181

This dual-sector expansion intensified the reliance on groundwater, which provided 263.4 MCM as a primary strategic buffer. The structural stress is most acute within the Amman-Zarqa Groundwater Basin, where 2023 production reached 181 MCM. When measured against a safe yield of 87.5 MCM, this represents a staggering 93.5 MCM operational deficit, threatening the long-term hydraulic integrity of the aquifer. The necessity of diverting surface water for urban use underscores the importance of a unified management framework.

The dynamics of groundwater extraction are further evidenced by the proliferation of active infrastructure, with the total number of wells in the Amman-Zarqa basin reaching 1043 in 2023. A critical breakdown of these extraction patterns reveals a near-parity between competing demands: private agricultural wells accounted for 73.6 MCM, while municipal wells contributed 72.1 MCM.

3.2. Nexus Interaction: Decoupling and Economic Volatility in 2025

By integrating the 2023 baseline with real-time economic indicators from 2025, the research identifies a significant decoupling between national fiscal trends and agricultural market signals.

1) Price Incentives: While the national PPI showed a deflationary trend of -0.69% [32], the Agricultural Producers Price Index (APPI) surged by 5.7% [33].

This rise is particularly visible in high-value crops like bananas (+23.2%) and lemons (+202.4%) [33].

2) Energy Dynamics: The 2.43% decrease in electricity prices [34], combined with the successful expansion of solar energy initiatives, has effectively lowered the operational costs of pumping. This creates a scenario where the economic return of high-value crops encourages further resource use—a technical validation of Jevons' Paradox [37] within the Jordan Valley.

3.3. Key Index Results: OD and NEI

The application of the novel Composite **OD** and **NEI** within the Decision Support System (DSS) yielded the following key insights:

1) **OD Analysis**: The **OD** analysis suggests that current water management structures are facing significant financial stress. The existing tariff and subsidy structures G_s are misaligned with 2025 market realities, contributing to a "Wicked Problem" where financial viability **OD** clashes with resource sustainability (aquifer depletion).

2) **NEI Analysis**: In the context of the **NEI**, lower energy input costs are being reinvested into intensification. The **NEI** highlighted stark contrasts: market shocks (like the −68.3% drop in tomato prices [33]) can lead to sudden shifts in farming behaviors, whereas high-value, high-water crops (like bananas at +23.2%) show a higher **NEI** but pose a greater risk to the physical water balance.

3) **Systemic Efficiency**: The analysis confirms that while the JVA possesses a solid 82% billing efficiency foundation [35] [36], technical efficiency alone cannot manage the demand surge to 623.4 MCM agricultural consumption [4]. The **NEI** and **OD** results collectively point towards the necessity of digital governance solutions to align green energy transition with conservation goals.

The outcomes of these policy evaluations were synthesized into a comprehensive matrix, illustrating the critical trade-offs inherent in current management strategies and highlighting scenarios with the highest economic viability (Table 4).

Table 4. Longitudinal trends in water sector allocations and groundwater dependency (2018-2023).

Policy Shift	Impact on Water (**W**)	Impact on Food (**F**)	Impact on Energy (**E**)	Economic **ROI**
Irrigation Industry	Reduced dam pressure.	Decreased low-value production.	Reduced pumping loads.	Very High: Return rises to 15 - 20 (JD/m^3).
Solar Expansion	22% depletion risk.	Improved food security.	National grid relief.	Medium: Operational savings vs capital loss.
Digitalization	70% loss recovery.	Improved supply regularity.	Reduced energy waste.	High: Payback of 3.5 years.

4. Discussion

4.1. The Nexus Feedbacks

The study's results, when contextualized against the historical data presented in

Figure 1 and **Figure 2**, reveal a critical "Nexus Feedback Loop". The transition toward vertical intensification—marked by a surge in potash and nitrogen consumption from 1961 to 2022—has institutionalized a high-input dependency. While this model successfully increased yields despite a stagnant agricultural land area, it has also increased the "Resource Resistance."

The 2025 data analysis confirms Jevons' Paradox [37]: technical gains and lower input costs (energy) are being reinvested into further intensification to capitalize on surging agricultural prices. The **NEI** results indicate that total water consumption did not drop despite the 2.43% decrease in electricity prices [34], confirming that efficiency gains were consumed by increased demand.

4.2. Governance and Decoupling Risks

A primary risk identified in the Composite OD analysis is the decoupling between national deflationary trends (−0.69% PPI) [32] and sectoral inflation (+5.7% APPI) [33]. This gap suggests that current subsidy structures are misaligned with the market realities of 2025. Without the proposed Decision Support System (DSS) and "Focus Metering" for solar-pumping, the agricultural sector remains vulnerable to "Market Shocks", where price collapses could lead to sudden farm abandonments and further ecological degradation [34].

The January 2025 shift in cooperation cancelled 83% of global USAID programs [38] [39]. This necessitates the "Localization of National Technical Teams" to ensure strategic projects like the National Conveyor Project (NCP) remain sustainable beyond 2025, reducing reliance on external operational support.

4.3. Digital Governance as a Decision-Support Lever

Jordan is a leader in digital water governance pilot projects, such as those in Amman that reduced energy consumption by 54% [40]. The DSS framework proposed leverages existing advanced techniques:

- Predictive AI: SVM algorithms already predict dam water quality with 99.8% accuracy [1].
- IPADT Integration: The IPADT tool, based on WaPOR satellite data, is slated for JVA integration by late 2025 to enable real-time productivity monitoring [41].

4.4. The Added Value and Innovation of the Proposed Framework

The innovation in this research does not lie in the complexity of the mathematical formulas themselves, but rather in the conceptual framework and practical application that links the water, energy, and economic sectors within a specific context (Jordan). The added value of the proposed framework is highlighted through the following points:

1) Innovation in "Integration" and Nexus Thinking: While many Hydro-Economic Models (HEMs) focus on improving water allocation based solely on marginal economic value, or energy models focus solely on grid efficiency; the inno-

vation in this research lies in linking these sectors quantitatively and directly in a single index **NEI**. The index connects the economic value (JD), water consumption (m^3), and energy intensity (kWh/m^3) in a common denominator to create a unified efficiency metric. This "integration" is an innovation in the applied methodology that many theoretical WEFE Nexus frameworks lack.

2) Innovation in "Tailoring" to Local Conditions (Tailor-made metrics): Standard metrics (such as general environmental performance indicators) are often too generic. In contrast, the Deficit **OD** index is specifically designed to reflect the institutional and financial reality of a specific entity (the Jordan Valley Authority JVA), including unique variables such as government subsidies $\boldsymbol{G_s}$ and revenues $\boldsymbol{R_i}$ which are impacted by the 82% billing efficiency. This specificity makes the index a powerful tool for decision support in this specific context, adding immediate applied value.

3) Innovation in Bridging the Gap Between Theory and Practice: Academic literature is full of concepts, but there is a continuous challenge in translating them into practical, measurable field tools. These indicators provide quantitative tools to bridge the gap between the "Wicked Problem" of managing trade-offs and tangible policy solutions. The model's ability to justify a $92.2 million investment in smart meters [42] based on the results of these relatively simple equations is evidence of their practical innovation and importance.

The equations are not intuitive in the context of their innovative use for linking water, energy, and finance challenges within a coherent analytical framework. The innovation lies in the "methodology" that allows these simple equations to produce complex, actionable insights to address the critical water scarcity problem in the region.

5. Conclusion

Jordan's water sector faces unique challenges where high efficiency exists alongside a widening structural gap. Resilience by 2050 requires maximizing economic returns, the localization of technical expertise, and the adoption of digital governance tools to protect the "hydrological commons" for future generations.

National planning must bridge the digital investment gap and transition toward value-based management. Achieving systemic resilience by 2050 requires bridging an unsustainable **1521 MCM structural gap** [8] [9].

Strategic Roadmap:

- Institutionalize EIWP Benchmarks: Transition support programs to rewarding Economic Irrigation Water Productivity, specifically for crops like Medjool dates (2500 - 3500) JD/ton [43] [44].
- Centralized IoT Governance: Mandate IoT-based metering for all solar wells to restore financial and monitoring control [31].
- Implement the "Focus Metering" Strategy: Prioritize the $92.2 million investment to digitize 15% - 20% of high-flow nodes to capture 80% of management benefits [42].

Recommendations for Future Research

The results of this study call for a transition from theoretical analysis and modeling to the empirical validation of the developed tools and indicators. The study recommends focusing on the following future research areas:

- Field Validation of NEI: This study recommends that the National Agricultural Research Center (NCAR), Faculties of Agriculture, and research entities in Jordan conduct controlled field experiments. The objective is to apply the NEI index to specific irrigation scenarios (e.g., comparing traditional versus modern solar-powered irrigation techniques) to document the actual efficiency of water and energy resources and their impact on net economic returns.
- Utilizing Data from Solar Energy and Digital Monitoring: Future research should focus on analyzing the precise data resulting from the proposed digital monitoring systems ("Focus Metering") once they are installed. This allows for a continuous evaluation of how reduced solar energy costs (C_e) impact groundwater consumption patterns, providing real-world data to verify Jevons' Paradox within the Jordanian context.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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