

An Earth System Analysis of Jordanian Agriculture: From Vicious Cycles of Resource Degradation to Integrated Resilience Pathways

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Abstract

This paper applies the interdisciplinary framework of Earth System Science (ESS) to analyze the complex socio-ecological crisis facing the agricultural sector in the Hashemite Kingdom of Jordan. As one of the world's most water-scarce nations, with per capita renewable freshwater availability falling below the absolute scarcity threshold (61 m³/year), Jordan provides a critical model for understanding the detrimental impacts of anthropospheric pressures on resource systems in arid environments. The methodology employs qualitative systems analysis, integrating newly available biophysical data (2019-2023 water budgets) with a critical review of national policy documents, utilizing Causal Loop Diagrams (CLDs) to visualize systemic drivers. Key findings reveal a state of systemic overshoot driven by two dominant, interlinked, and self-reinforcing negative feedback cycles: the Water-Land Degradation Loop (R1), characterized by the "Efficiency Trap" (Jevons Paradox) where technological efficiency drives expansion rather than conservation; and the Water-Energy-Economy Drain Loop (R2), where energy-intensive deep pumping and high rates of non-revenue water (~47%) perpetuate fiscal and resource stress. These cycles persist due to a structural challenge in cross-sectoral governance, exemplified by the non-operationalization of the mandated Water-Energy-Food-Environment (WEFE) Nexus Council. The paper concludes by proposing quantifiable, integrated policy pathways—focusing on strict water demand enforcement, decoupling energy subsidies from consumption, and activating the Nexus Council—as essential structural leverage points to break these vicious cycles and shift the system from "Hard Path" dependency toward genuine Earth System stewardship.

Keywords

Earth System Science, WEFE Nexus, Jevons Paradox, Soft Path Water Management, Systems Analysis, Jordan Valley, Causal Loop Diagrams

1. Introduction

1.1. Background and Problem Statement

The Hashemite Kingdom of Jordan presents a stark and urgent case study for the application of Earth System Science (ESS) to pressing sustainability challenges. The nation is consistently ranked as one of the most water-poor countries on Earth, a condition of extreme water stress that is fundamentally shaping its development trajectory [1]-[2]. The country's per capita share of renewable freshwater has plummeted to approximately 61 m³ per year in 2023, falling far beneath the 500 m³ threshold defined as absolute water scarcity [1] [3] [4]. This natural aridity is severely compounded by a host of anthropogenic pressures, including relentless population growth exacerbated by the regional refugee crisis, which has placed unprecedented demand on the nation's finite [5] [6].

This natural aridity is severely compounded by a host of anthropogenic pressures, including relentless population growth exacerbated by the regional refugee crisis, which has placed unprecedented demand on the nation's finite resources [7] [8]. Despite efforts, the non-revenue water (NRW) rate remains just under 46% in 2024 [8], with 70% of this loss attributed to administrative causes such as illegal connections and unauthorized use [9] [10]. In the energy sector, the country has seen a 5.8% increase in electricity demand between 2023 and 2024 [4] [11], with renewable energy's contribution reaching 26% of total electricity production by the end of 2023 [12] [13]. In the food sector, reliance on imports remains high for basic commodities like wheat and grains [14], underscoring the strategic importance of protecting the Jordan Valley's productivity.

Within this context, the agricultural sector occupies a paradoxical position. It is a critical pillar for rural livelihoods and a component of the national food security strategy [4]-[6] [15]. Simultaneously, it is the primary driver of the country's water crisis, consuming over 50% of the available water supply and pushing the nation's hydrological system far beyond its limits of natural replenishment [8] [16]-[19]. This creates a state of "systemic overshoot," where the rate of consumption consistently exceeds the regenerative capacity of the natural capital base.

1.2. Problem Statement: The Failure of Linear Solutions

The central challenge facing Jordan is not simply a lack of water, but a "resilience depletion" of the entire socio-ecological system. For decades, Jordanian water policy has been characterized by a "hydraulic mission"—a state-centric engineering approach focused on mobilizing new supplies (dams, deep wells, conveyance projects) [4] [16] [20]. While these interventions staved off immediate collapse, they

demonstrated limited efficacy in arresting aquifer decline. The system is trapped in “policy rigidity,” where interventions lead to counter-intuitive outcomes; for instance, increased irrigation efficiency has not resulted in aggregate water savings but rather in agricultural expansion [21] [22].

1.3. Theoretical Foundation and Literature Review

The theoretical foundation of this paper rests on three interconnected bodies of literature: Earth System Science (ESS) [16], the Water-Energy-Food-Environment (WEFE) Nexus, and the governance of complex socio-ecological systems.

Earth System Science (ESS): ESS provides an overarching framework, moving beyond disciplinary silos to study the Earth as a single, integrated system [10]. It focuses on the interconnected components—hydrosphere, lithosphere, and atmosphere—and the feedback loops that govern their behavior. The central tenet is that human civilization is an integral, dynamic component of this system, both influencing and being influenced by the environment [15] [20].

The WEFE Nexus: Arising from this systems-thinking approach, the WEFE Nexus is a critical conceptual tool for policy analysis [1]. It recognizes that water, energy, food, and environmental security are deeply intertwined [23]. In Jordan, this nexus is particularly tight: the water sector consumes approximately 15% of the nation’s total electricity [24], meaning water scarcity is directly translatable into energy insecurity.

Governance of Complex Systems: Managing complex systems like the WEFE nexus is a profound governance challenge [4] [11]. We adopt the distinction between “Hard Path” and “Soft Path” water management [6]. The “Hard Path” relies on centralized, supply-side engineering solutions (dams, desalination, conveyance) to meet projected demand. The “Soft Path” emphasizes demand management, ecosystem restoration, and institutional reform [8] [20] [22].

1.4. Research Contribution

This paper’s primary contribution is the application of a holistic ESS framework to Jordan’s resource crisis, moving beyond a simple description of problems to a systemic diagnosis of their root causes. It moves beyond standard hydrological reporting by explicitly linking biophysical degradation (salinity, depletion) to socio-political drivers (“scarcity by design,” export incentives) through System Dynamics. It specifically addresses the “gap” in existing literature regarding why high-level strategies fail to translate into biophysical recovery [10].

2. Materials and Systems Analysis Methodology

This study employs a qualitative systems analysis methodology, specifically utilizing System Dynamics principles visualized through Causal Loop Diagrams (CLDs) [21]. This approach allows the analysis to structure complexity, synthesize diverse data streams, and diagnose structural leverage points within the socio-ecological system [25].

2.1. Integrated Data Streams

The research synthesizes data from two interconnected streams:

1) Biophysical and Hydrological Data: Updated utilizing the 2019-2023 Water Budget tables derived from Ministry of Water and Irrigation (MWI) reports [26]. This stream includes granular data on groundwater abstraction, safe yield deficits, dam storage utilization, and Non-Revenue Water (NRW) rates [1] [11] [19].

2) Governance and Policy Data: This stream consists of a critical review of the anthroposphere's response through key national strategic documents, including the National Water Strategy [4], the National Food Security Strategy [5], and the National Climate Change Policy [27]. A policy coherence matrix was developed to map synergies and conflicts across the WEFE pillars.

2.2. Qualitative Systems Analysis via Causal Loop Diagrams

Causal Loop Diagrams (CLDs) were the primary tool used for synthesis and visualization. The analysis focuses on identifying “Reinforcing Loops” (R) that drive system collapse (e.g., the Jevons Paradox) and “Balancing Loops” (B) that create stability [28] [29]. This system dynamics approach is essential for structuring complexity and identifying feedback loops in socio-ecological systems [30]. The CLDs illustrate how observed environmental degradation (biophysical result) is connected to the structure and failures of the policy system (anthropospheric cause), transcending simple data reporting and establishing the rigorous, dynamic nature of the ESS approach.

2.3. Limitations of the Methodology

It is important to acknowledge that CLDs represent qualitative causal hypotheses derived from empirical data and theory, rather than predictive numerical models. While they excel at revealing system structure and the direction of change (e.g., collapse, oscillation), they do not provide precise quantitative predictions of timing without conversion into quantitative Stock-and-Flow models [22] [31]. Furthermore, data on illegal groundwater abstraction remains structurally opaque due to political sensitivities.

3. Results

3.1. Biophysical System Stress: A Quantitative Portrait of Overshoot

The analysis of biophysical indicators reveals an agro-ecological system under extreme and quantifiable stress [32]. New data from the 2019-2023 water budgets (Table 1) confirm a widening gap:

- Hydrosphere: The crisis is driven by groundwater abstraction at a rate approximately 200% of the safe yield. In 2023, groundwater abstraction remained at 418 MCM, far exceeding the safe yield of ~277 MCM [19]. The Net Water Balance deficit deteriorated from -139.8 MCM in 2019 to -282.2 MCM in

2023 [19].

- Lithosphere: Approximately 63% of the irrigated soils in the Jordan Valley are now saline, a direct result of long-term irrigation with lower-quality water [20] [32].
- Anthroposphere Inefficiency: Systemic inefficiencies are rampant. Non-Revenue Water (NRW) rates have stagnated at approximately 47% nationally (2023), with some regions like Yarmouk Water Company exceeding 57% [32].

Table 1. Key indicators of water resource stress in Jordan.

Indicator	Value/Rate
Per Capita Renewable Water Availability	~61 m ³ /year [1] [4]
Net Water Balance Deficit (2023)	-282.2 MCM [4]
Groundwater Abstraction vs. Safe Yield	~200% Over-abstraction [32]
Average Aquifer Level Decline (1995-2017)	~50 meters [32]
Non-Revenue Water (Losses)	~47% - 50% [3] [7]
Energy Burden (Water Pumping)	~15% of National Electricity Bill [33]

3.2. Policy Framework Analysis: An Awareness-Implementation Gap

While Jordan's national strategies demonstrate high intellectual awareness of the challenges, a persistent challenge in achieving fully integrated implementation persists. **Table 2** shows the Refined policy coherence matrix: trade-offs and governance constraints across the WEFN nexus.

WEFN Nexus Coherence: The Water Strategy's reliance on desalination (the National Conveyor Project) significantly increases energy demand, creating a direct negative trade-off with climate and energy goals [1] [20]. Similarly, the push for agricultural output can exacerbate the water crisis if not tightly coupled with water efficiency mandates.

Governance Constraints: The most significant institutional constraint is the non-operationalization of the mandated WEFN Nexus Council [28]. This demonstrates that the primary challenge is not a lack of strategy or knowledge, but persistent institutional inertia, weak enforcement of existing regulations (e.g., against illegal well drilling), and a structural barrier to horizontal collaboration and shared executive authority. This creates a structural "awareness-implementation gap." This gap allows line ministries to operate in silos, pursuing conflicting objectives (e.g., energy subsidies encouraging water depletion).

3.3. Climate Change: The Systemic Accelerator

Climate change is not merely an external variable but acts as a "systemic accelerator" for existing feedback loops. Projections indicate a 15% - 20% decrease in

Table 2. Refined policy coherence matrix: Trade-offs and governance constraints across the WEFE nexus.

Policy Instrument/Goal	Water Sector Impact	Energy Sector Impact	Food/Agriculture Impact	Governance Trade-Off
Desalination (NCP) [1]	+ Supply Security	- High Energy Demand (R2)	0/+ Urban Food Support	Hard Path dependency; increases fiscal strain on MWI
Agricultural Export Subsidies	- Increased Abstraction (R1)	0 (Indirect)	+ Rural Livelihoods/GDP	Jevons Paradox; institutional silo between MWI and MoA
Energy Subsidies on Deep Pumping	- Encourages Overdraft (R2)	- Fiscal Burden (Utility Debt)	0/+ Short-term Farmer Profit	Blocks Soft Path; politically entrenched resistance
National Water Strategy 2023-2040	+ Sustainability goals	+/- Reliance on NCP energy	+ Focus on TWW reuse	Policy-practice gap; fragmented authority [17]

(+) Synergy, (-) Trade-off, (0) Neutral/Mixed Impact.

precipitation by 2050 [28] [34]. Rising temperatures increase evapotranspiration, simultaneously increasing crop water demand while reducing groundwater recharge by up to 30% [21] [31]. This effectively shrinks the “safe yield” target annually, making historical abstraction rates increasingly unsustainable.

4. Discussion

The biophysical degradation and policy incoherence are dynamically linked through two dominant, self-reinforcing feedback loops that drive the Jordanian system toward collapse.

4.1. The Water-Land Degradation Loop (R1)

The dynamics of agricultural expansion are visualized in **Figure 1** (see attached images). This cycle, known as the “Efficiency Trap” or Jevons Paradox [8], begins with “Intense Agricultural Production Demand.”

Mechanism: To address scarcity, policies promote water-saving technologies (e.g., drip irrigation). However, improved efficiency reduces the effective cost of water per crop unit. Driven by socio-economic policies incentivizing high-value export crops (Virtual Water Trade Paradox) [32], farmers reinvest savings to expand cultivated land (Rebound Effect) rather than conserving water [30] [35].

Result: Aggregate water consumption rises (Agricultural consumption reached 623.4 MCM in 2023), accelerating Severe Aquifer Depletion and Soil Salinization, closing the vicious cycle.

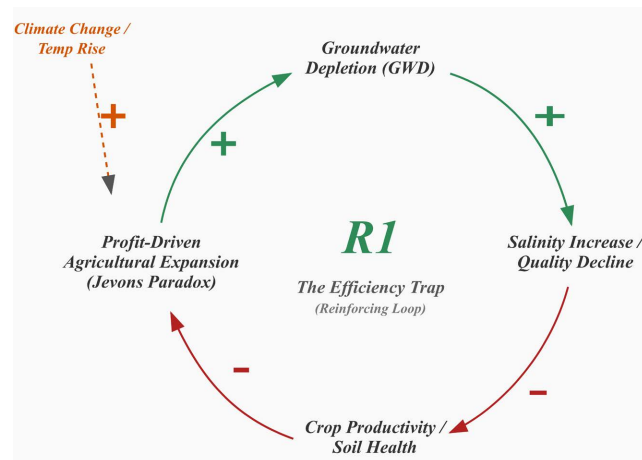


Figure 1. Causal loop diagram of the water-land degradation cycle (R1).

4.2. The Water-Energy-Economy Drain Loop (R2)

The systemic link between water depletion and economic strain is illustrated in Figure 2.

Mechanism: Severe “Groundwater Depletion” leads to dropping water tables (~50 m historically) [11]. This physically increases the “Pumping Depth,” requiring significantly more “Energy.”

Feedback: High energy costs, coupled with energy subsidies, strain utility budgets. This leads to reduced financial capacity for infrastructure investment, keeping NRW rates high (~47%). High NRW forces utilities to pump even more water to meet demand, further draining aquifers and energy resources [1] [32].

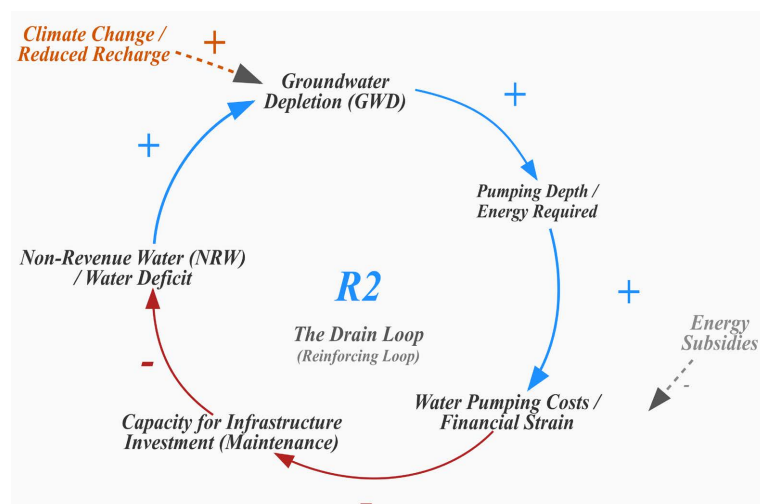


Figure 2. Causal loop diagram of the water-energy-economy drain cycle (R2).

4.3. Structural Constraints and Institutional Dynamics of the Anthroposphere

Both R1 and R2 are enabled and strengthened by the underlying siloed governance structure. The non-operationalization of the WEFE Nexus Council confirms that

institutional inertia and structural barriers to horizontal coordination are the primary challenges to sustainability [10] [21] [28].

These structural constraints manifest in three critical ways:

1) The Political Economy of Sectoral Silos: Ministries (Water, Agriculture, Energy) operate with conflicting mandates and compete for donor funding [28]. The Ministry of Agriculture aims to maximize production (driving R1), while the Ministry of Water struggles to conserve resources. The current framework lacks an empowered coordinating authority to enforce cross-sectoral trade-offs.

2) Territoriality and Coordination Constraints: Establishment of the Council implies a cession of sovereignty from line ministries to a central body. Administrative constraints related to jurisdictional authority limit the full operationalization of the Nexus [32] [36] [37].

3) Resource Management and Social Stability: Management of abstraction limits (breaking R1) is politically costly as it confronts influential tribal and agricultural constituencies. The state often tolerates illegal wells and high NRW as a form of social stability maintenance [11] [20].

This context drives a persistent bias toward “technocratic fixes” (Hard Path), which address the symptoms of scarcity without tackling the root causes of unsustainable demand and governance constraints.

5. Conclusion and Integrated Policy Recommendations

Table 3. Actionable policy recommendations for systemic intervention.

Strategic Axis	Systemic Intervention	Quantifiable Target	Mechanism & Systemic Impact
1) Governance & Coordination	Activate and empower the WEFE Nexus Council [20]	Operational < 12 months	Mechanism: Establish under Prime Ministry. Impact: Breaks “Siloed Policy” driver. [36] [37]
2) Demand Management (R1 Attack)	Enforce groundwater abstraction limits [8] [17]	Reduce overdraft by 50% (5 yrs)	Mechanism: Smart meters & strict fines. Impact: Slows aquifer depletion [33] [38]
3) Agricultural Transformation	Mandate Climate-Smart Agriculture (CSA) with Caps	Convert 25% of land	Mechanism: Link subsidies to legal caps to prevent Jevons Paradox [33] [39]
4) Energy-Water Decoupling (R2 Attack)	Decouple energy subsidies from consumption	Reduce pumping energy 20%	Mechanism: Replace cheap electricity with direct income support. Impact: Removes pumping incentive
5) Non-Conventional Water	Scale up the use of treated wastewater in agriculture	Reduce NRW to 30%	Mechanism: Invest in “last mile” infrastructure Impact: Substitutes freshwater in agriculture (R1 substitution)

The comprehensive Earth System Analysis confirms that Jordan’s agricultural unsustainability is a systemic crisis of coupled human and natural systems. The reli-

ance on “Technocratic Fixes” (Hard Path) without addressing the underlying feedback loops (Soft Path) will only delay and deepen the eventual collapse (Actionable Policy Recommendations in **Table 3**).

Conflicts of Interest

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

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