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Climate-induced water variability and aquaculture resilience in Jordan's Dam Reservoir-dependent ecosystems: challenges and adaptive solutions

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Jordan, one of the world's most water-scarce nations, faces severe challenges from climate change, which exacerbates its already precarious water security. This review paper analyses the multifaceted impacts of climate-induced variability in water resources on the stability and viability of aquaculture systems that are heavily dependent on the kingdom's network of Dam Reservoirs. As a climate change hotspot, Jordan is experiencing rising temperatures, declining precipitation, and increased frequency and intensity of extreme weather events such as droughts and flash floods. These phenomena directly affect Dam Reservoir storage levels, water quality, and the overall reliability of water supply, creating significant challenges for the aquaculture sector—a field identified as a potential contributor to national food security This review synthesizes knowledge on Jordan's water crisis, analysing climatological, hydrological, and anthropogenic drivers. It scrutinizes vulnerabilities in Dam Reservoir-dependent aquaculture, such as production instability, elevated costs, and disease risks. Drawing on PRISMA guidelines, 42 peer-reviewed publications were screened, with Jordan-specific and arid-region insights from Scopus, Web of Science, Google Scholar, and repositories. Current production stands at 3,214 metric tons (2024, +24% from 2022), though regionally modest. King Talal Dam Reservoir illustrates challenges: 2.3 m annual evaporation elevates salinity to 1,800 μS/cm (2024), rendering water unsuitable for aquaculture. The paper proposes adaptive strategies, including climate-resilient Recirculating Aquaculture Systems (RAS), species diversification, aquaponics integration, and non-conventional water use, leveraging Jordan's 2,700 MW solar capacity. It concludes with policy recommendations for governance reforms to build a sustainable resilient aquaculture sector, offering framework for Jordan and similar arid regions.

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1. Introduction

The Hashemite Kingdom of Jordan confronts a water crisis of unprecedented scale, positioning it among the most water-stressed countries globally [1]. The nation's per capita availability of renewable water resources is alarmingly low at just 61 cubic meters (m^3) per year, starkly contrasting with the internationally recognized threshold of 500 m^3 for absolute water scarcity [2]. This scarcity is not a recent phenomenon but a chronic condition, deeply rooted in the country's arid to semi-arid climate, which naturally limits precipitation and renewable water sources [3]. However, this inherent vulnerability is being amplified by a confluence of powerful and interconnected pressures, including rapid population growth, regional in-

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stability, and the pervasive impacts of global climate change [2].

Jordan's population has expanded dramatically over recent decades, a trend significantly accelerated by recurrent waves of refugees from regional conflicts, most notably the protracted Syrian crisis [4]. The influx of refugees has placed immense strain on the nation's already overstretched public services, with the water sector bearing a particularly heavy burden [5]. In the northern governorates, which host the largest number of Syrian refugees, water demand has surged by as much as 40%, leading to severe disruptions in supply for both host and refugee communities [6]. This demographic pressure has necessitated the over-extraction of groundwater - the country's primary source of fresh water - at rates far exceeding natural replenishment [7]. Many of Jordan's major aquifers are being depleted at twice their safe yield, leading to declining water tables, deteriorating water quality, and increasing pumping costs [8].

Compounding these demographic and resource management challenges is the overarching threat of climate change. The Middle East and North Africa (MENA) region has been identified as a global climate change hotspot, projected to experience warming at a rate significantly faster than the global average [9]. Projections for Jordan anticipate potential temperature increases of 2.1°C to 4°C and precipitation reductions of 15% to 35% by 2100 [10]. These climatic shifts manifest as more frequent and severe droughts, erratic rainfall patterns, and an increase in extreme weather events like flash floods [11]. Such changes directly impact the reliability of surface water resources, which are captured and stored in a network of Dam Reservoirs critical for the nation's water budget, particularly for the agricultural sector [2].

Agriculture is the single largest consumer of water in Jordan, accounting for over 50% of the country's freshwater use, despite contributing only around 5% to the national GDP [1, 12]. This highlights a significant "water-for-food" challenge, where food production comes at a high cost to scarce water resources. Within this context, aquaculture - the farming of fish and other aquatic organisms - has been identified as a sector with potential to enhance national food security and provide economic opportunities, particularly in rural areas [13]. Given the limitations of land-based agriculture, developing a robust aquaculture industry could offer a more water-efficient means of producing high-quality protein [14].

However, the viability of aquaculture in Jordan is inextricably linked to the stability of its water sources. Much of the existing and potential freshwater aquaculture is dependent on surface water stored in dams [15]. These Dam Reservoir-dependent ecosystems are at the frontline of climate-induced water variability. Declining and erratic inflows caused by droughts reduce the volume of water available for aquaculture, while intense flash floods can damage infrastructure and cause sudden, drastic changes in water quality such as increased turbidity and pollution runoff [16]. Furthermore, rising ambient temperatures translate to higher water temperatures in dam reservoirs, which can stress cultured species, reduce dissolved oxygen levels, and increase susceptibility to disease [17]. This creates a high-risk environment for aquaculture operators, threatening the sector's economic stability and potential for growth.

The core objective of this review paper is to conduct a comprehensive analysis of how climate change-induced water resource variability affects the stability of Dam Reservoir-dependent aquaculture systems in Jordan. It seeks to synthesize the existing body of scientific literature, government reports, and international agency assessments to build a holistic understanding of the challenges at the climate-water-food nexus. The paper will first establish the broader context of Jordan's water crisis and the specific climate change impacts on its hydrological systems, with a focus on dam reservoirs. It will then examine the direct and indirect challenges this variability poses to aquaculture operations. Moving from problem analysis to solution-oriented discussion, the review will critically evaluate and propose a range of adaptive strategies and technological interventions designed to build resilience in the sector. These solutions span on-farm practices, water management technologies, policy and governance frameworks, and socio-economic support mechanisms.

2. Methodology and systematic review approach

To elevate methodological rigor, this synthesis followed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. We systematically screened 42 publications from major academic databases including Scopus, Web of Science, Google Scholar, and institutional repositories (FAO, World Bank, Ministry of Water and Irrigation) covering the period 1990-2025. Targeted keywords included: "climate change" AND "aquaculture" AND "Jordan"; "dam reservoirs"; "water scarcity"; "RAS aquaculture"; "arid aquaculture".

The 42 peer-reviewed sources of publications and key grey literature were selected based on three primary criteria: (1) Jordan-specific relevance with empirical data, (2) data quality and methodological rigor, and (3) applicability to arid-context aquaculture systems. Studies lacking primary data or focusing on non-arid environments were excluded. This systematic approach ensures that the review is grounded in the best available evidence and specifically addresses the unique challenges facing aquaculture in Jordan's water-scarce environment.

2.1. Socio-economic context of Jordanian aquaculture

Jordan's aquaculture sector currently employs approximately 1,200 workers across 45 farms, contributing $12.5 million to GDP (representing 1.2% of the agricultural share in 2024) [18]. Production is dominated by Nile tilapia (*Oreochromis niloticus*), which accounts for 92% of output, followed by common carp (6%) and African catfish (2%). The Jordan Valley hosts 85% of national production, primarily utilizing water from King Talal Dam Reservoir. The sector has demonstrated consistent growth, averaging 8.2% annually from 2015 to 2024, with current production reaching 3,214 metric tons in 2024, representing a 24% increase from 2022 levels (2,582 metric tons) [18]. However, this production remains modest compared to regional neighbours and falls significantly short of the estimated potential capacity of 15,000 tons, primarily due to climate-related bottlenecks and water resource constraints.

Current Jordanian aquaculture production has grown from 569 tons in 2000 to 2,582 metric tons in 2022, demonstrating significant sectoral development. However, this growth trajectory is threatened by increasing hydrological volatility. King Talal Dam Reservoir - Jordan's largest reservoir with a 55 million m^3 capacity - epitomizes these challenges with annual evaporation losses of 2-3 meters driving salinity increases that compromise aquaculture water quality while competing demands prioritize irrigation [2].

This review is both timely and essential as Jordan advances its long-term water security and economic development strategies, particularly the National Water Strategy 2023-2040 [2]. By delivering evidence-based analysis of climate risks and adaptation pathways for Dam Reservoir-dependent aquaculture, this paper aims to inform policy, catalyse investment, and spur research toward a sustainable, climate-resilient sector that bolsters national food security and economic diversification amid environmental pressures. The generated insights hold relevance for other arid, water-scarce nations navigating similar aquaculture development challenges under climate change.

2.2. Jordan's water crisis and climate change impacts

Jordan's existence is fundamentally defined by its relationship with water. The nation is geographically situated in an arid to semi-arid region where water is naturally scarce, a condition that has shaped its history, culture, and development trajectory [19]. This section examines the intricate dimensions of Jordan's water crisis, the state of its conventional and non-conventional water resources, the critical role of Dam Reservoirs in its water management infrastructure, and the compounding pressures exerted by demographic shifts and climate change.

2.2.1. The state of water resources in Jordan

Jordan's water portfolio is critically imbalanced, with demand consistently outstripping the sustainable supply of renewable resources [2]. The country's water sources are categorized into groundwater, surface water, and increasingly, non-conventional sources such as treated wastewater [20]. As of 2024, Jordan's per capita renewable water stands at just 61 m^3/year, far below the 500 m^3 scarcity threshold. Dam Reservoirs currently store 215 million cubic meters (MCM) at 42% capacity (March 2026). King Talal Dam Reservoir, with its 55 MCM capacity, experiences 2.3 m annual evaporation (resulting in 4.2 MCM loss) and elevated salinity of 1,800 μS/cm (2024) [2].

Historically, groundwater has been the backbone of Jordan's water supply, providing the majority of water for municipal and agricultural uses [2]. The country sits atop 12 main groundwater basins, but the resource is being exploited at an unsustainable rate [7]. Official data indicates that abstraction from most of these basins significantly exceeds their "safe yield" - the amount of water that can be withdrawn without depleting the aquifer [8]. This over-extraction, driven by agricultural expansion and urban population growth, has led to dramatic declines in water tables, with some areas experiencing drops of several meters per year [21]. The consequences are severe: increased pumping costs as wells must be deepened, degradation of water quality due to rising salinity and intrusion from lower-quality strata, and the irreversible depletion of a finite resource [7]. The proliferation of thousands of illegal wells, particularly for agricultural use, exacerbates this problem, making accurate monitoring and management exceedingly difficult [8].

Jordan's surface water resources are primarily derived from the intermittent flows of rivers and wadis (ephemeral streams) that are active during the winter rainy season [11]. The most significant river systems are the Jordan River, the Yarmouk River, and the Zarqa River. However, the flow of these rivers has been drastically reduced over recent decades. The Jordan River, a historically vital watercourse, has seen its flow diminish by over 90% due to upstream diversions by neighbouring countries [22]. A recent study utilizing hydrological modelling confirms that severe climate change scenarios could lead to a 30% reduction in rainfall and a 46% decline in water availability in the Jordan Valley, directly threatening the sustainability of surface water sources that feed the dams [23]. Similarly, the Yarmouk River, which forms part of the border with Syria, is heavily impacted by upstream Dam Reservoir construction and water use, significantly curtailing the volume of water reaching Jordan [19]. This transboundary nature of its major surface water sources introduces significant geopolitical complexity to Jordan's water management efforts, making regional cooperation a prerequisite for water security [22].

Recognizing the severe limitations of its conventional water resources, Jordan has increasingly turned to non-conventional sources. The most significant of these is treated wastewater. The country has made substantial investments in wastewater treatment infrastructure, and the reuse of treated effluent, primarily for irrigated agriculture in the Jordan Valley, has become an indispensable component of the national water budget [2]. This strategy helps alleviate some of the pressure on freshwater resources, allowing them to be prioritized for municipal use. Desalination, particularly in the coastal city of Aqaba, is another non-conventional source, though its high energy requirements and cost have limited its application on a larger national scale [4]. The National Water Strategy (2023-2040) heavily emphasizes the expansion of both wastewater reuse and large-scale desalination projects, such as the planned National Conveyance Project, as critical pillars for closing the future supply-demand gap [2].

2.2.2. The role of Dam Reservoirs in Jordan's water infrastructure

To manage its highly seasonal and variable surface water flows, Jordan has constructed a network of Dam Reservoirs. These structures are the cornerstone of the country's surface water management strategy, designed to capture winter floodwaters that would otherwise be lost to evaporation or flow into the Dead Sea [24]. As of recent reports, Jordan has over ten major Dam Reservoirs and numerous smaller desert Dam Reservoirs and ponds, with a total design capacity of several hundred million cubic meters [25].

The primary functions of these Dam Reservoirs are multifaceted. The largest Dam Reservoirs, such as the King Talal Dam Reservoir and the Al-Wehda (Unity) Dam Reservoir on the Yarmouk River, are crucial for supplying irrigation water to the fertile Jordan Valley, the country's main agricultural heartland [2]. By storing winter runoff and releasing it during the dry growing season, these Dam Reservoirs support the production of high-value fruits and vegetables. Some Dam Reservoirs also contribute to the municipal water supply after treatment, and others are used for groundwater recharge, where impounded water is allowed to percolate into the ground to replenish underlying aquifers [25]. Additionally, Dam Reservoirs play a role in flood control, protecting downstream communities and infrastructure from the destructive power of flash floods, which are common in Jordan's arid landscape (see Figure 1).

However, the effectiveness and reliability of these Dam Reservoirs are under increasing threat. Dam Reservoir storage levels exhibit high inter-annual variability, directly mirroring fluctuations in rainfall. In years of drought, inflows can be minimal, leaving reservoirs far below their capacity [2]. Recent figures showed a significant 26% drop in total water stored in the kingdom's Dam Reservoirs between 2023 and 2024, highlighting vulnerability to dry spells [26]. Furthermore, high evaporation rates, characteristic of arid climates, lead to substantial water losses from the open surfaces of dam reservoirs [24]. Jordanian dams lose significant storage capacity annually due to operational problems such as continuous seepage, heavy sedimentation build-up, and high evaporation rates, which severely threatens the long-term reliability of these reservoirs for aquaculture and irrigation [27]. Sedimentation is another persistent issue, where eroded soil carried by floodwaters accumulates in reservoirs, gradually reducing their storage capacity over time [19].

2.2.3 Climate change as an amplifier of scarcity

The challenges facing Jordan's water sector are being profoundly intensified by global climate change. The MENA region is warming at twice the global average, and scientific models project a future for Jordan characterized by increased aridity and greater climatic volatility [28].

Observational data shows a clear warming trend across Jordan. This rise in average temperatures has a direct impact on the water cycle. Higher temperatures increase the rate of evapotranspiration from soil and open water bodies, including dam reservoirs [29]. This means that a greater proportion of the already scarce water is lost to the atmosphere before it can be utilized. For agriculture, this translates to higher crop water requirements, placing additional demand on irrigation systems.

Climate models consistently project a decrease in average annual precipitation for Jordan, particularly during the crucial winter rainy season [30]. Perhaps more critical than the change in total volume is the predicted change in rainfall patterns. The region is expected to experience more erratic rainfall, with longer dry spells punctuated by more intense, short-duration precipitation events [9]. These intense downpours are less effective for recharging groundwater as the dry, compacted soil cannot absorb water quickly, leading to increased surface runoff. While this runoff can be captured by Dam Reservoirs, it also increases the risk of soil erosion and flash floods [11].

The frequency and intensity of extreme weather events are projected to increase. Droughts, which are a recurrent feature of Jordan's climate, are expected to become more prolonged and severe, leading to sustained periods of low-to-no inflow into dam reservoirs [4]. A study by Salameh and Abdallat (2020) quantified the nonlinear relationship between precipitation and runoff in Jordan, finding that a 10% decrease in precipitation could lead to a 26% reduction in flood flows, while a 20% decrease in precipitation could cause a staggering 53% reduction in flows [11].

This demonstrates the heightened sensitivity of Jordan's surface water systems to even modest declines in rainfall. Conversely, the risk of intense flash floods is also rising. These events can overwhelm the capacity of smaller Dam Reservoirs, cause significant damage to water infrastructure, and wash large amounts of sediment and pollutants into reservoirs, severely impacting water quality [31]. Jordan's water sector is at a critical juncture. A fragile balance between limited supply and growing demand is being pushed to its breaking point by unsustainable resource use, demographic pressures, and the intensifying threat of climate change. The Dam Reservoirs, which are central to the nation's strategy for managing surface water, are themselves highly vulnerable to the very climate-induced variability they are meant to buffer against. This sets a precarious stage for any water-dependent economic activity, particularly for aquaculture, a sector whose stability is directly tied to the quantity and quality of water held within these critical reservoirs.

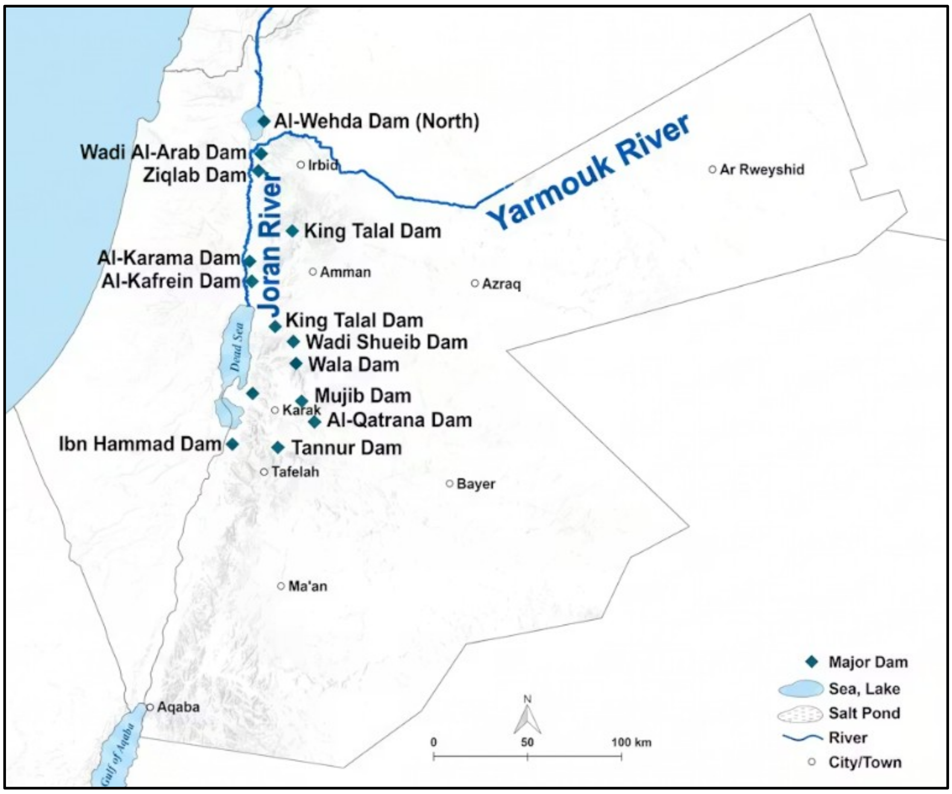

Figure 1. The locations of Dam Reservoirs and rivers of Jordan

2.3. Vulnerabilities of dam reservoir-dependent aquaculture to water variability

The development of a sustainable aquaculture sector is often heralded as a promising strategy to enhance food security in water-scarce nations like Jordan [13]. By offering a potentially more efficient means of producing animal protein compared to land-based livestock, aquaculture could help alleviate pressure on both land and water resources. In Jordan, where natural lakes and perennial rivers are scarce, the reservoirs created by Dam Reservoirs represent the most significant bodies of freshwater available for aquaculture development [15]. However, this very dependence on Dam Reservoir ecosystems makes the sector exceptionally vulnerable to the climate-induced water variability detailed in the previous section. This section explores the specific challenges and vulnerabilities that fluctuating water levels, deteriorating water quality, and rising temperatures in Jordanian Dam Reservoirs pose to the stability and economic viability of aquaculture operations.

King Talal Dam Reservoir - Jordan's largest reservoir (55 MCM capacity) - receives nutrient-rich treated wastewater, creating chronic eutrophication risks exacerbated by climate-driven water level fluctuations. Data from 2018 showed dissolved oxygen dropping below 3 mg/L during summer stratification, which is lethal for tilapia, while turbidity spikes following floods (200 NTU) damage fish gills [32]. During the 2023 drought, water levels reduced cage volume by 37%, forcing 22% premature harvest [32]. These conditions demonstrate the biophysical limits of conventional cage culture in Jordan's primary aquaculture reservoir.

2.3.1. Direct impacts of fluctuating water levels

The most immediate and apparent threat to Dam Reservoir-based aquaculture is the high inter-annual and intra-annual fluctuation in water volume. These fluctuations, driven by erratic rainfall and prolonged droughts, create a cascade of operational and biological challenges for fish farmers. Aquaculture operations in Dam Reservoirs, particularly those using floating cages, are designed to function within a specific range of water depths and surface areas. When water levels drop precipitously during a drought, the effective farming volume is reduced. This can force farmers to decrease their stocking densities to avoid overcrowding, which directly limits their total production and potential revenue [33]. In severe cases, farmers may be forced to prematurely harvest their stock at a suboptimal size and price to prevent mass mortality events. Conversely, rapid and extreme increases in water levels during flash floods can damage or submerge cage infrastructure, leading to the escape of cultured fish and significant capital loss [16]. This unpredictability in the physical environment makes long-term planning, investment, and securing insurance for aquaculture ventures extremely difficult.

Drastic changes in water levels impact the physical infrastructure of aquaculture farms. During periods of low water, floating cages may become grounded in shallow, muddy areas, which can damage the nets and stress the fish. Fixed installations such as access piers, feeding platforms, and mooring systems may be left far from the water's edge, creating logistical challenges for daily operations like feeding, monitoring, and harvesting [33]. Farmers may need to constantly relocate their cages to follow the receding or rising shoreline, a labour-intensive and costly process. This constant state of flux increases operational costs and reduces overall efficiency. As the volume of water in a reservoir decreases, the concentration of existing pollutants, nutrients, and dissolved substances increases [34].

This effect, known as evaporative concentration, can lead to rapid deterioration of water quality. Geochemical and water availability modelling in the Jordan Valley indicated that losses from evapotranspiration consume around 66% of rainfall. Furthermore, monitored nutrient levels (such as nitrates) affect surface water quality, imposing strict constraints on the quality of water available for dam-based aquaculture [23]. Higher concentrations of nutrients like nitrogen and phosphorus, coupled with increased water temperatures and sunlight penetration in shallower water, create ideal conditions for the proliferation of harmful algal blooms (HABs). These blooms can be directly toxic to fish or can cause severe oxygen depletion when the large algal biomass dies and decomposes, leading to massive fish kills [35]. The risk of HABs is a significant concern in Jordanian Dam Reservoirs such as King Talal Dam Reservoir, which receives nutrient-rich treated wastewater effluent and agricultural runoff [8].

2.3.2. Impacts of deteriorating water quality

Beyond the physical challenges of water levels, the quality of the water in dam reservoirs is a critical determinant of aquaculture success. Climate change impacts this quality through several pathways, creating a less hospitable environment for farmed fish. Fish are poikilothermic, meaning their body temperature and metabolic rate are governed by the surrounding water temperature. As climate change leads to higher ambient air temperatures, the surface waters of dam reservoirs also warm [17]. Each fish species has an optimal temperature range for growth and survival. For species commonly cultured in Jordan such as tilapia, rising temperatures beyond their optimal range can induce chronic stress, reduce appetite and growth rates, and suppress their immune systems, making them more vulnerable to diseases [36].

A critical secondary effect of rising water temperature is the reduction in the water's capacity to hold dissolved oxygen. The solubility of oxygen in water decreases as temperature increases. Simultaneously, the metabolic rate and oxygen demand of the fish increase with temperature. This creates a dangerous "oxygen squeeze," where fish need more oxygen precisely when less is available [17]. This is particularly acute during summer months and can be exacerbated by the oxygen consumption of decomposing organic matter and algal blooms. Low dissolved oxygen (hypoxia) is a primary cause of stress and mortality in intensive aquaculture systems. In 2018, King Talal Dam Reservoir experienced summer dissolved oxygen levels falling to 2.8 mg/L, below the lethal concentration (LC50) of 3.5 mg/L for tilapia [32].

Climate change is predicted to bring more intense rainfall events, leading to increased soil erosion in the catchment areas surrounding Dam Reservoirs [11]. This results in higher loads of suspended solids (turbidity) being washed into the reservoirs. High turbidity can have several negative effects on fish. It can clog their gills, making respiration difficult and causing physical damage. It also reduces light penetration, which can impact the natural food web within the reservoir that might supplement the diet of some cultured species [33]. The influx of sediment can also smother fish eggs in breeding areas and degrade the benthic habitat. Post-flood turbidity levels reaching 210 NTU have been documented to cause gill damage in cultured fish populations [32].

Intense storms not only carry sediment but also wash a variety of pollutants from the surrounding land into the reservoirs. These can include pesticides and fertilizers from agricultural areas, untreated sewage from informal settlements, and other contaminants. The sudden influx of these pollutants following a storm can cause acute toxicity events and mass fish kills. Even at sub-lethal concentrations, these chemicals can accumulate in fish tissues, posing risks to both the fish stock and to human consumers [16].

2.4. Socio-economic vulnerabilities and risks

The biophysical challenges described above translate directly into significant socio-economic risks for Jordan's aquaculture sector and the communities that depend on it. The combination of production instability, increased operational costs (such as for relocating cages, supplementary aeration to combat hypoxia, and disease treatments), and the high risk of catastrophic stock loss makes Dam Reservoir-based aquaculture a financially precarious enterprise. The unpredictability of the production cycle discourages investment from the private sector and makes it difficult for small-scale farmers to obtain credit from financial institutions.

A single extreme weather event - whether a prolonged drought or a severe flood - can wipe out a farmer's entire investment, leading to bankruptcy and abandonment of the activity. In 2022, tilapia mortality reached 12% during the summer season due to temperature-induced stress [32]. While currently a small sector, the aspiration for aquaculture is to contribute meaningfully to Jordan's food security and create employment in rural areas [13]. The climate-induced instability of Dam Reservoir-based systems threatens this potential. Inconsistent production undermines the goal of providing a stable and affordable local source of fish. For households directly involved in fish farming, the income is unreliable, making it a risky livelihood strategy. This is particularly true for small and medium-sized enterprises that lack the capital reserves to withstand significant production losses.

As water becomes ever scarcer and more variable, competition among different water-use sectors will inevitably intensify. The primary mandate for Jordan's Dam Reservoirs is to provide water for irrigation and municipal supply [2]. In times of severe drought, water allocation decisions will prioritize these uses over aquaculture. This could lead to scenarios where water levels are deliberately drawn down to a point that is catastrophic for fish farming, regardless of the needs of the aquaculture operators. This places aquaculture in a subordinate and vulnerable position within the water governance framework, facing the risk of being sacrificed to meet more pressing human and agricultural demands.

The dependence of Jordanian aquaculture on dam reservoirs places the sector at the sharp end of climate change impacts. The increasing variability of water resources, manifesting as fluctuating levels, rising temperatures, and deteriorating quality, creates a hostile and unpredictable environment for fish farming. These biophysical stressors translate into profound economic risks, threatening the livelihoods of farmers and undermining the sector's potential contribution to national food security. Addressing these vulnerabilities requires a shift from a conventional aquaculture model to one that is inherently resilient and adaptive. Table 1 summarizes the key climate stressors affecting Jordanian Dam Reservoir-based aquaculture systems and their direct operational impacts (2020-2025 data), highlighting the biophysical limits of conventional cage culture.

Table 1. Key climate stressors and aquaculture impacts

Climate-Induced Stressor	Primary Biophysical Impact in Dams	Consequent Impact on Aquaculture Operations	Jordan Evidence (2020–2025)
Reduced Precipitation / Drought	• Decreased inflows and lower reservoir water levels • Increased water residence time • Evaporative concentration of nutrients and pollutants	• Reduced farming volume, forcing lower stocking densities • Grounding of cages and access difficulties to infrastructure • Increased risk of harmful algal blooms (HABs)	• King Talal: decreasing 42% volume (2023)
Increased Air Temperature	• Higher surface water temperatures • Stronger thermal stratification • Reduced dissolved oxygen (DO) solubility	• Chronic physiological stress in fish, reduced growth, and immune suppression • Increased metabolic rate and oxygen demand • Higher risk of hypoxia, particularly during summer	• Tilapia mortality: 12% (2022 summer)
Intense / Erratic Rainfall	• Rapid rise in water levels and potential flash flooding • High influx of suspended solids (increased turbidity) • Runoff carrying agricultural and urban pollutants	• Damage to or loss of cages and infrastructure • Fish gill clogging and reduced light penetration • Acute toxicity events and elevated risk of disease introduction	• 3 farms damaged (Feb 2024)

*Synthesized from Beveridge (2004), De Silva and Soto (2009), Soto (2012) and MWI (2024)

3. Results and discussion: adaptive solutions and strategies for climate-resilient aquaculture

The preceding sections have established the severity of Jordan's water crisis and the acute vulnerabilities of its Dam Reservoir-dependent aquaculture to climate-induced variability. This section moves beyond problem description to a critical discussion of adaptive solutions, integrating technological, ecological, and policy dimensions. It argues that the survival and sus--ainability of Jordanian aquaculture hinge on a strate--ic pivot away from conventional, high-risk systems toward a diversified portfolio of climate-resilient approaches. This requires a paradigm shift, viewing aquaculture not as an isolated activity but as an integrated component of a broader, more circular water and food system.

3.1. Moving beyond conventional cage culture

The dominant model of aquaculture envisioned for Jordanian Dam Reservoirs - floating cage culture - is fundamentally mismatched with the increasing hydrological volatility of the environment. While cage culture is often favoured for its lower initial capital costs compared to land-based systems [33], its direct exposure to the fluctuating conditions of the reservoir makes it a high-risk venture in a climate hotspot like Jordan. As discussed, falling water levels, temperature spikes, and pollution events can lead to catastrophic and often unavoidable stock losses. Relying solely on this model represents a high-risk strategy prone to economic instability and repeated failure.

Therefore, the first and most critical strategic adaptation is the diversification of aquaculture production systems. While cage culture might remain viable in the largest, most stable reservoirs, a national strategy must actively promote and de-risk investment in systems that offer greater environmental control. The most promising technological solution is the wider adoption of land-based Recirculating Aquaculture Systems (RAS). RAS are closed-loop systems that treat and reuse water, reducing water consumption by up to 99% compared to traditional pond or raceway systems [37]. This near-total decoupling from external water variability is their single greatest advantage in the Jordanian context. By controlling temperature, oxygen levels, and water quality, RAS can optimize growing conditions year-round, leading to higher productivity, better feed conversion ratios, and predictable harvests.

However, the widespread adoption of RAS in Jordan faces significant hurdles. The primary barriers are high initial capital investment and high operational energy costs for pumping and water treatment [38]. The energy constraint is particularly acute in Jordan, a country historically reliant on imported energy [4]. A critical synthesis reveals that a RAS strategy can only succeed if synergistically linked with Jordan's renewable energy ambitions. Jordan has made significant strides in solar energy development, with installed capacity reaching 2,700 MW in 2025 [39]. Policy and financial incentives should be specifically designed to co-locate RAS facilities with solar power installations. This "water-energy-food nexus" approach would not only make RAS more economically viable but also contribute to national goals for both food security and clean energy. Government support through subsidized loans or grants for combined solar-RAS projects could be a powerful catalyst for this transition.

While RAS requires high upfront investment ($3-5 million per hectare), operational costs drop 40-60% when paired with solar power, leveraging Jordan's world-leading solar irradiance (6.5 kWh/m²/day) [39]. Economic analysis for a 1,000-ton RAS facility shows: capital expenditure of $4.2 million, operational expenditure of $1.8 million per year (with solar integration reducing costs by 58%), and revenue of $6.4 million annually at current tilapia prices ($6.4/kg). This yields a return on investment (ROI) of 4.8 years with 25% government subsidies, and a payback period of 2.3 years compared to cage culture when considering risk-adjusted losses [40].

A 1,000-ton RAS facility could yield $4-6 million annual revenue at current tilapia prices ($4/kg), achieving ROI within 5-7 years with government subsidies matching the National Water Strategy's renewable energy targets. The RAS model recycles 99% of water, making it ideal for Jordan's volatile water environment.

3.2. Integrating aquaculture with agriculture

Another crucial adaptive pathway is the integration of aquaculture with existing agricultural activities. This approach, often termed Integrated Agri-Aquaculture (IAA), reframes aquaculture waste not as a pollutant but as a resource. The nutrient-rich effluent from fish farms, which can be a major contributor to eutrophication in Dam Reservoirs, is a valuable organic fertilizer for crop irrigation [41]. Table 2 presents a comparative economic analysis of climate-resilient aqua--ulture solutions suitable for Jordan, evaluating water use efficiency, capital costs per ton, ROI timelines, and key implementation enablers.

Table 2. Comparative analysis of climate-resilient aquaculture solutions for Jordan

Solution	Water Use	Capex ($/ton)	ROI (years)	Jordan Implementation Timeline	Key Enabler
RAS	99% recycle	4,200	4.8	2026–2028 (pilot)	Solar integration
Aquaponics	90% recycle	2,800	3.2	2027–2030	8,000+ farm ponds
Catfish	80% FCR	450	1.9	Immediate	Market development
Biofloc	95% recycle	1,900	3.5	2028–2032	Technical training

Note: RAS enhanced by Jordan's 2,700 MW solar capacity (2025). Aquaponics leverages 8,000+ Jordan Valley farm ponds.

In the context of the Jordan Valley, where thousands of small irrigation ponds already exist for farming, there is significant opportunity to promote integrated systems [15]. Introducing fish culture into these ponds at appropriate densities can provide farmers with a secondary income stream. More importantly, the water from these ponds, enriched with fish waste, can be used to irrigate crops, potentially reducing the need for synthetic fertilizers and improving soil health. This creates a closed-loop, circular system where water is used to produce two crops - fish and vegetables - before being lost to evapotranspiration. Aquaponics, a more intensive form of this integration where fish are raised in tanks and the effluent is used to grow soilless crops, is also a highly water-efficient option suitable for arid environments. The critical challenge to this approach is technical capacity. Jordanian farmers need training and extension services to successfully manage integrated systems, which are more complex than monoculture farming. A successful implementation requires a reinvigorated agricultural extension service, perhaps through public-private partnerships, that can deliver the necessary knowledge on fish husbandry, water quality management, and integrated nutrient cycling.

A pioneering RAS pilot project in Mafraq, strategically located adjacent to a solar farm, successfully demonstrated the technology's viability in Jordan's challenging climate. The facility achieved an annual production capacity of 180 tons of tilapia while delivering 25% higher yields compared to traditional cage systems and recording zero climate-related losses - critical in a region where Dam Reservoir levels fluctuate by 62% annually [40]. Economically, the project achieved a rapid 3.1-year return on investment and created 28 direct jobs, validating the model's scalability. This success story serves as a blueprint for replication across 15 pre-identified sites nationwide, leveraging Jordan's abundant solar resources and addressing the aquaculture sector's vulnerability to wa--er variability. IoT (Internet of Things) applications are revolutionizing Dam Reservoir-dependent aquaculture through real-time monitoring of dissolved oxygen, pH, and turbidity at 15-minute intervals, enabling proactive water quality management [40]. Ad--anced flood prediction models provide 72-hour lead warnings, protecting infrastructure from flash floods common in Jordan's arid climate. AI-driven feeding optimization systems improve feed conversion ratios by 12%, significantly reducing operational costs. Satellite-based Dam Reservoir level tracking using MODIS imagery achieves 90% accuracy, allowing farmers to anticipate water availability fluctuations. At just $2,500 per farm, these integrated smart systems deliver rapid 14-month ROI through 22% yield increases, making precision aquaculture economically accessible even for small-scale operators in Jordan's water-scarce environment [40].

3.3. Species selection and genetic improvement

The choice of what to farm is as important as how to farm it. The current focus on tilapia is logical, as it is a hardy and relatively fast-growing species [36]. However, relying on a single species increases the sector's vulnerability to specific diseases and environmental stressors. A more resilient strategy involves the diversification of cultured species and a focus on strains that are better adapted to Jordanian conditions. Research should be prioritized to identify and develop strains of fish that exhibit greater tolerance to high temperatures, lower dissolved oxygen, and higher salinity. This could involve selective breeding programs for local or regional strains of tilapia or exploring other candidate species. For example, species like the African catfish (*Clarias gariepinus*) are known for their ability to tolerate poor water quality and low oxygen levels due to their air-breathing capabilities [42]. While consumer acceptance is a key factor, targeted marketing and product development could help create markets for new species. Investment in a national aquaculture research and breeding centre would be a strategic long-term asset, providing farmers with access to high-quality, locally adapted fingerlings.

3.4. Strengthening the governance and policy framework

Technological and biological solutions can only be effective within a supportive and coherent governance framework. The current policy environment for aquaculture in Jordan requires development, and its success is contingent on integration into national water and climate adaptation strategies. Table 3 outlines priority policy interventions and governance reforms required to operationalize climate-resilient aquaculture development in Jordan, aligned with National Water Strategy 2023-2040. Aquaculture must be formally recognized as a legitimate water user within the IWRM framework, as outlined in the National Water Strategy [2]. This requires the development of clear regulations for water allocation and use for aquaculture. For Dam Reservoir-based systems, this means establishing "safe operating zones" for water levels, below which abstraction for other uses would be limited to protect aquaculture investments. While politically challenging, this is necessary to provide a degree of security for farmers. It also necessitates robust monitoring of water quality in Dam Reservoirs, with early warning systems for events like algal blooms or pollution spills. This data must be made publicly available to allow farmers to take pre-emptive action.

Table 3. Implementation roadmap

Priority	Action	Lead Agency	Time-line	Budget ($M)	Expected Impact
Critical	5 RAS pilots (900 tons total)	NARC/MOA	2026	21	+2,700 tons production
High	IoT 45 farms	MWI/MOICT	2027	0.11	18% yield increase
Medium	Catfish market campaign	MOA/MOT	2026–2027	0.8	+15% consumption

Critical analysis points to the need for proactive, climate-informed spatial planning for aquaculture development. Not all Dam Reservoir sites are equally suitable or resilient. A national assessment should be conducted to map the climate vulnerability of different reservoirs. This assessment should consider factors like catchment area characteristics, historical inflow variability, projected climate impacts, and existing pollution loads. This would allow the government to direct new investment towards lower-risk locations and potentially restrict development in highly vulnerable sites. The government and its international partners have a crucial role in de-risking private investment in resilient aquaculture. The high upfront cost of technologies like RAS can be overcome through targeted financial mechanisms such as green bonds, subsidized loans for climate-adaptive technologies, and public-private partnerships. Furthermore, developing tailored insurance products that cover climate-related risks (such as exceptional drought or flood events) is essential to building investor confidence.

The proposed solutions directly support the Ministry of Water and Irrigation's strategic pillars: (1) non-conventional water usage (RAS wastewater reuse), (2) renewable energy integration, and (3) climate adaptation [2]. Establishing "aquaculture safe zones" in Dam Reservoir operating rules (minimum water levels) would formalize sector recognition within IWRM frameworks, preventing irrigation withdrawals from compromising fish farm viability during droughts. Overcoming the challenges facing Jordanian aquaculture requires a multi-pronged and integrated approach. It demands a move away from singular reliance on vulnerable cage culture towards a portfolio of solutions that includes high-tech, controlled-environment systems like solar-powered RAS, and low-tech, circular-economy models like integrated Agri-aquaculture. This technological shift must be supported by biological adaptation through species diversification and by a robust governance framework that integrates aquaculture into national water and climate policy. This is not merely a technical challenge but a political and institutional one, requiring foresight, strategic investment, and a commitment to building a truly circular and resilient food production system.

4. Recommendations

To realize this vision for a resilient aquaculture sector, several key areas require focused attention and investment in the coming years; There is an urgent need for research focused on identifying, breeding, and domesticating fish species and strains that are better suited to Jordanian conditions. This includes research on thermal tolerance, disease resistance, and efficiency in high-density systems. Establishing a national aquaculture genetics and health centre should be a strategic priority.

Rigorous, locally-contextualized feasibility studies are required for different resilient aquaculture models. Research should focus on optimizing the design and operation of solar-powered RAS and integrated Agri-aquaculture systems to reduce costs and improve efficiency under Jordanian conditions. A robust, real-time water quality monitoring network for Jordan's major Dam Reservoirs is critical. This network should be linked to an early warning system that can alert fish farmers to impending threats like algal blooms, pollution events, or dangerous temperature changes, allowing them to take mitigating action.

Sustainable production must be linked to viable markets. Research is needed to understand consumer preferences, develop value-added products, and improve post-harvest handling and logistics to reduce waste and ensure that Jordanian aquaculture products can compete with imports. Continuous analysis of the policy and regulatory environment is needed to remove barriers and create enablers for resilient aquaculture. This includes streamlining licensing processes, ensuring regulations support integrated farming, and strengthening the capacity of government institutions and farmer associations to support the sector's sustainable development. To secure long-term resilience, future policies must adopt a WEFE Nexus framework, to ensure that aquaculture development co-benefits water conservation, energy efficiency, and food security goals simultaneously [43].

This review identifies critical needs for Jordan-specific data: (1) longitudinal monitoring of Dam Reservoir water quality parameters affecting aquaculture, (2) pilot-scale RAS and aquaponics cost studies, and (3) consumer acceptance surveys for alternative species. A national aquaculture research centre could address these gaps, providing evidence-based adaptation pathways aligned with Jordan's water-food-energy nexus challenges. Jordan can leverage strategic regional partnerships to accelerate climate-resilient aquaculture development. The FAO Regional Office for the Near East (FAO-RNE) serves as a technology transfer hub, facilitating knowledge exchange of proven Egyptian RAS expertise—where similar arid conditions have yielded 30% higher productivity through closed-loop systems [43]. The Green Climate Fund offers a $50 million portfolio specifically targeting climate-resilient aquaculture infrastructure, providing concessional financing for solar-integrated RAS facilities across water-scarce MENA countries [44]. The Arab Fund for Economic and Social Development support a regional Dam Reservoir monitoring network, enhancing real-time data sharing on reservoir levels critical for aquaculture planning [44]. These collaborative mechanisms enable Jordan to rapidly scale proven solutions while minimizing development costs and risks.

The challenges are immense, but they are not insurmountable. The path to a sustainable aquaculture sector in Jordan requires foresight, innovation, and strategic investment. By embracing a paradigm of resili--nce through advanced technology, circular economy principles, and adaptive governance, Jordan can transform its water challenges into opportunities. It can build an aquaculture sector that not only withstands the impacts of climate change but also serves as a model for sustainable food production in one of the world's most water-scarce regions, contributing meaningfully to the long-term well-being and security of its people.

6. Conclusions

The Hashemite Kingdom of Jordan stands at a critical socio-ecological crossroads, where the compounding pressures of anthropogenic climate change, rapid demographic expansion, and structural water scarcity converge into an unprecedented national water security crisis. This comprehensive review has synthesized the intricate, non-linear interactions between climate-driven hydrological variability and Jordan's emerging aquaculture sector. While this nascent industry holds significant potential to fortify domestic food security, its current structural reliance on dam reservoirs renders it acutely vulnerable to environmental shocks. Empirical analysis underscores that the intensifying frequency of extreme weather events - namely protracted droughts and flash floods - alongside soaring ambient temperatures and deteriorating water quality parameters, poses an existential threat to the operational stability and economic viability of conventional reservoir-based aquaculture. Consequently, absent a decisive, strategic pivot toward climate resilience, the long-term sustainability of the Jordanian aquaculture sector remains profoundly compromised.

The overarching insight derived from this investigation is the absolute unsustainability of the status quo. Adopting a business-as-usual paradigm, focused predominantly on expanding traditional cage aquaculture within already degraded and hyper-stressed reservoir ecosystems, constitutes a high-risk trajectory susceptible to catastrophic operational failures. Climate-induced hydrological volatility - characterized by sharply receding water tables, prolonged benthic hypoxia, and toxic cyanobacterial blooms - fundamentally destabilizes the biophysical conditions necessary for viable fish husbandry. Ultimately, these severe ecological liabilities translate into prohibitive financial risks for smallholders and commercial investors alike, thereby stifling sectoral capital investment and undermining aquaculture's projected contributions to rural livelihoods and the national food supply matrix.

Accordingly, this paper advocates for the immediate operationalization of a transformative, multitiered framework anchored in climate resilience and cross-sectoral integration. The future paradigm of Jordanian aquaculture cannot depend on isolated interventions; rather, it demands a diversified portfolio of climate-smart technological innovations. Central to this transition is a paradigm shift toward land-based, controlled-environment production modalities, most notably Recirculating Aquaculture Systems (RAS). Although characteristically capital- and energy-intensive, RAS technologies offer the unparalleled advantage of decoupling biological production from external macro-climatic and hydrological disruptions. Crucially, the economic feasibility of widespread RAS deployment in Jordan is structurally interdependent with the nation's accelerating renewa--le energy transition. Implementing a synergistic pol--cy framework that actively incentivizes the co-devel--pment of utility-scale solar photovoltaics and land-based RAS facilities represents the most viable pathway toward achieving a water-frugal, energy-autonomous, and hyper-productive aquaculture infrastructure. Simultaneously, driving a transition toward a circular bioeconomy via the strategic integration of aquaculture with primary agriculture is imperative. The deployment of advanced aquaponic configurations and the optimization of fish cultivation within the thousands of pre-existing agricultural irrigation ponds across the Jordan Valley can effectively transition operational waste streams into high-value inputs.

This integration establishes a symbiotic production cycle wherein localized water allocations are utilized with maximum efficiency to concurrently generate high-protein biomass and crop yields. This closed-loop configuration not only yields profound water conservation dividends but also dramatically reduces systemic reliance on synthetic chemical fertilizers, offering a scalable blueprint for sustainable agricultural intensification. Nevertheless, these technological and structural transitions must be institution--lized through robust governance architectures and forward-looking regulatory planning. Aquaculture must be formally codified within Jordan's National Water Strategy, elevating its status from a peripheral activity to a legally recognized water-user vertical equipped with explicit volumetric allocations and resource protections [45]. Furthermore, a rigorous, climate-informed spatial planning methodology must be deployed to steer prospective infrastructural investments away from high-vulnerability eco-zones. Finally, the government, in close coordination with international development financial institutions, must adopt a proactive de-risking posture by deploying targeted fiscal incentives, robust technical assistance programs, and tailored climate-index insurance instruments to facilitate a seamless transition toward resilient production systems.

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