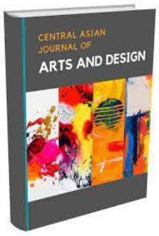


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*Article*

# Design of Models with a Natural Frame, Zarqa Ma'in Dam, Jordan

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**Abstract:** Jordan is situated in an arid to semi-arid climatic zone, where a growing population, industry, and agricultural endeavors are all necessitating more water resources. The nation focused on maximizing rainwater collection, particularly in reservoirs. These dams, predominantly built in the dry regions of the nation, have a range of issues including elevated evaporation rates, siltation, landslides, and rising salinities. Nonetheless, concurrently, water and soil are accessible at dam locations and their vicinity. The latter presents problems and possibilities for landscaping by leveraging water, soil, and climatic factors to enhance the areas near dams, so mitigating erosion, siltation, and evaporation, and establishing local and regional recreational spaces in dry regions. This will also create employment opportunities and enhance agricultural output. This research examines Zarqa Ma'in Dam as a representative case for other dams in Jordan. To that end, the climate, water resources, soils, terrain, appropriate flora, and methodologies to accomplish the objective are examined thoroughly. The findings indicate that engineered landscaping has several benefits, including the reduction of siltation, evaporation, and soil erosion, as well as the establishment of green spaces in desert regions, hence facilitating resorts, employment opportunities, and agricultural output.

**Keywords:** Zarqa Ma'in Dam, Water Scarcity, Agricultural, Endeavors, Industry, Jordan

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## 1. Introduction

The concept of landscape management has evolved significantly over the past few decades as scholars and practitioners have recognized the limitations of sectoral and fragmented approaches to natural resource management  Traditional methods often treated water, land, and biodiversity as separate entities, [1]managed under distinct institutional mandates, without sufficient attention to their interdependence. In contrast, Integrated Landscape Management (ILM) offers a holistic framework that promotes cross-sectoral coordination, ecological sustainability, and stakeholder participation. It is rooted in the understanding that landscapes are socio-ecological systems, where natural resources, human activities, and governance structures interact in complex ways. By addressing these linkages, ILM provides practical pathways to balance environmental conservation with social and economic development [2].

In the context of Jordan, the importance of adopting integrated management frameworks cannot be overstated. Jordan is classified among the most water-scarce countries in the world, with per capita renewable water resources falling far below the international water poverty line.[3] Dams and reservoirs represent a cornerstone of the country's water strategy, as they provide essential storage capacity, regulate supply, and mitigate the impacts of increasing demand. Beyond their hydrological function, dams also contribute to agricultural productivity, industrial development, and urban resilience [4].

However, these roles are under increasing pressure due to climate change, rapid population growth, land-use expansion, and competing demands among different sectors. Ensuring the sustainability of Jordan's dams requires not only technical interventions but also integrated approaches that engage communities, institutions, and policymakers[5].

The Zarqa Ma'in Dam, situated in central Jordan, provides a representative case for examining these challenges. The dam plays a critical role in supplying water for agricultural, domestic, and recreational uses, yet its catchment area is experiencing severe environmental stress. Among the most pressing challenges is water scarcity, driven by declining rainfall, groundwater depletion, and rising demand from nearby urban and agricultural zones. Land degradation, including soil erosion, vegetation loss, and inappropriate farming practices, further undermines the ecological balance of the catchment[6]. In addition, socio-economic pressures such as population growth, agricultural expansion, and the development of tourism activities in the Ma'in hot springs area add significant strain to already limited resources. These combined pressures threaten not only the ecological health of the dam but also its long-term capacity to meet the water needs of surrounding communities.

Despite its importance, research and policy efforts concerning Zarqa Ma'in Dam have been fragmented and largely focused on technical aspects of dam operation, water quality, and hydrological performance. While these dimensions are crucial, they fail to capture the broader landscape-level interactions that shape the sustainability of the dam system. Few studies have systematically integrated ecological, hydrological, and socio-economic factors into a unified framework, and even fewer have addressed the institutional and governance challenges that hinder coordinated management[7] . This gap highlights the urgent need for research that brings together diverse perspectives and proposes practical, integrated solutions.

Against this backdrop, the present study seeks to develop an ILM Framework for the Zarqa Ma'in Dam that addresses both environmental and socio-economic dimensions. The research is guided by four specific objectives:

to assess the ecological, hydrological, and socio-economic conditions of the Zarqa Ma'in Dam catchment.

to identify the key drivers of environmental degradation and resource conflicts;

to analyze stakeholder roles and institutional arrangements influencing dam management.

to propose a practical framework for sustainable and integrated management of the landscape.

These objectives are further framed by central research questions:

What are the main environmental and socio-economic challenges affecting the Zarqa Ma'in Dam and its catchment?

How can ILM principles be applied to address these challenges?

What governance structures and policy instruments are required to ensure the long-term sustainability of the dam and its resources?

By addressing these questions, this study contributes both to the theoretical discourse on ILM and to the practical field of water and environmental governance in Jordan. The findings are expected to inform policymakers, practitioners, and local stakeholders on strategies for balancing ecological conservation with socio-economic development. Moreover, the case of Zarqa Ma'in Dam offers broader lessons for managing dam catchments and water resources in other semi-arid regions facing similar challenges.

## 2. Related work

### 2.1. Theoretical Foundations of ILM

ILM emerged as a response to the limitations of traditional, sectoral approaches to natural resource management. Early models often addressed forests, water, agriculture, and biodiversity separately, neglecting the interconnected nature of ecosystems and human activities[8]. The theoretical foundation of ILM is rooted in systems thinking and socio-ecological theory, which emphasize that landscapes function as dynamic systems where ecological processes, economic activities, and social institutions interact. From this perspective, effective management requires coordination across sectors, spatial scales, and governance levels. ILM also draws on the concepts of sustainable development, ecosystem services, and adaptive management, which collectively highlight the need for long-term resilience in the face of environmental change and uncertainty[9].

### 2.2. Key Principles of ILM: Ecological Sustainability, Governance, and Socio-Economic Integration

Scholars have identified several guiding principles that underpin ILM. First, ecological sustainability is central, ensuring that resource use does not exceed the regenerative capacity of ecosystems. This includes protecting biodiversity, conserving soil and water, and maintaining ecological functions. Second, multi-stakeholder governance is crucial, as landscapes are shaped by a diverse set of actors, including governments, local communities, private sector entities, and non-governmental organizations. ILM emphasizes participatory planning, conflict resolution, and institutional collaboration as mechanisms to harmonize competing interests. Third, socio-economic integration ensures that environmental goals are aligned with livelihood security and economic development. By recognizing the dependence of local communities on natural resources, ILM frameworks promote inclusive growth and equitable benefit-sharing. Together, these principles create a balanced approach that addresses ecological, institutional, and social dimensions of sustainability [10].

### 2.3. Global Case Studies of ILM in Dam Catchments

Globally, numerous case studies demonstrate how ILM has been applied to dam catchments to enhance sustainability. In Africa, integrated watershed management around dams such as Ethiopia's Tana-Beles has combined soil conservation, reforestation, and community-based water governance to improve both water quality and livelihoods. In Asia, China's watershed management programs in the Three Gorges region illustrate how large-scale infrastructure projects can be complemented by ecological restoration and compensation schemes for displaced communities. In Latin America, Brazil's experiences with ILM in hydropower dam catchments highlight the role of participatory governance and monitoring in balancing energy production with biodiversity conservation. These global examples reinforce that ILM can mitigate the adverse impacts of dams—such as sedimentation, habitat loss, and social displacement—when ecological, social, and governance concerns are addressed simultaneously [11].

### 2.4. Current State of Landscape and Watershed Management in Jordan

In Jordan, water scarcity and land degradation have made integrated resource management a national priority. Several watershed management projects have been implemented, often supported by international donors and agencies, with a focus on soil conservation, water harvesting, and reforestation in degraded catchments. However, these initiatives remain fragmented, frequently project-based, and heavily dependent on external funding. Institutional challenges—such as overlapping mandates among ministries, limited capacity of local authorities, and insufficient stakeholder engagement—further hinder their effectiveness. In addition, most existing studies and practices emphasize technical solutions like reservoir engineering or irrigation efficiency, with less emphasis on holistic frameworks that incorporate ecological resilience, community participation, and policy coherence [12]. This gap underscores the need for approaches like ILM, which can address cross-sectoral linkages and align local practices with national strategies for water and land sustainability.

### 2.5. Lessons Learned and Gaps in Existing Approaches

The literature reveals several important lessons. First, successful ILM in dam catchments requires long-term commitment rather than short-term project cycles, as ecological restoration and institutional change are gradual processes. Second, meaningful stakeholder participation is a critical factor in ensuring both legitimacy and effectiveness of management frameworks, particularly in contexts where resource conflicts are common. Third, policy alignment and institutional coordination are necessary to overcome the fragmentation that undermines landscape-level planning. Despite these insights, significant gaps remain. Few studies in Jordan explicitly apply ILM frameworks to dam catchments, leaving a limited empirical basis for decision-making. There is also a lack of integrated models that connect ecological data with socio-economic assessments, making it difficult to evaluate trade-offs and synergies comprehensively [13]. Addressing these gaps through the case of Zarqa Ma'in Dam can contribute not only to the national discourse on water and land management but also to the broader field of integrated resource governance.

## 3. Methodology

### 3.1 Problem Definition

#### 3.1.1 Geographic Location and Biophysical Description

The Zarqa Ma'in Dam is located in central Jordan, southwest of Madaba Governorate and near the Ma'in hot springs, a popular touristic destination. Geographically, it lies within the Jordan Rift Valley catchment area, approximately 58 kilometers from Amman. The dam and its surrounding landscape are characterized by steep topography, rocky hillsides, and limited arable land, with elevations ranging from the highlands east of Madaba to the lower areas draining toward the Dead Sea. The climate is typically semi-arid to arid, marked by hot, dry summers and mild, wetted winters, with average annual rainfall ranging between 200 and 300 millimeters. These conditions make the dam's catchment highly vulnerable to land degradation and water scarcity [14].

#### 3.1.2 Hydrological and Ecological Characteristics

Hydrologically, Zarqa Ma'in Dam was constructed to capture and regulate seasonal surface runoff from wadis that flow westward into the Dead Sea basin. The reservoir provides water for agriculture, domestic consumption, and recreational use. However, the hydrological regime is highly variable due to low and unpredictable rainfall patterns. Flood events can bring sudden inflows, while extended droughts severely reduce water storage. Ecologically, the area supports a range of plant and animal species adapted to semi-arid conditions. Vegetation is dominated by shrubs, scattered trees, and patches of rangeland, though overgrazing and agricultural expansion have degraded much of the natural cover. Aquatic ecosystems within the reservoir are also under stress from fluctuating water levels and pollution inputs [15].

#### 3.1.3 Socio-Economic Context (Communities, Agriculture, Tourism)

The communities surrounding Zarqa Ma'in Dam rely heavily on agriculture and livestock for their livelihoods. Irrigated farming, supported by dam water, includes vegetables, fruit trees, and cereals, while rainfed agriculture and grazing occupy the marginal lands. The area also benefits from proximity to the Ma'in hot springs and the Dead Sea tourism corridor, which provide opportunities for small businesses, hospitality services, and seasonal employment. At the same time, socio-economic pressures such as population growth, limited land availability, and rising demand for water have increased competition between agricultural, domestic, and touristic uses. This has led to resource conflicts and unsustainable exploitation of the dam and its surrounding environment [15].

#### 3.1.4 Existing Management Practices and Policies

Management of Zarqa Ma'in Dam is under the responsibility of the Ministry of Water and Irrigation, supported by local municipalities and, in some cases, donor-funded projects focusing on watershed restoration and water efficiency. Current practices include monitoring water quality, regulating irrigation schedules, and implementing soil and water conservation measures in upstream catchments. National policies, such as Jordan's Water Strategy (2016–2025), emphasize integrated water resources management and sustainability. Nevertheless, implementation at the local level remains weak due to institutional fragmentation, limited financial resources, and insufficient stakeholder engagement. Most management efforts remain reactive and technical in nature, rather than holistic and participatory .

#### 3.1.5 Key Environmental Challenges

The Zarqa Ma'in Dam faces a set of interlinked environmental challenges that threaten its sustainability. Soil erosion from steep slopes and degraded rangelands contributes to high sediment loads, which reduce reservoir capacity. Pollution from agricultural runoff, untreated wastewater, and solid waste dumping degrades water quality, affecting both human use and aquatic life. Overuse of water resources for irrigation and tourism exerts pressure on already scarce supplies, often exceeding the dam's sustainable yield. Climate change impacts, including rising temperatures, prolonged droughts, and more intense flood events, further exacerbate variability in water availability and increase the vulnerability of surrounding communities. Collectively, these challenges underscore the urgency of adopting an ILM framework that balances ecological conservation, economic development, and social well-being.

### 3.2 Problem Solution

This study adopts a quantitative research design to examine the ecological, hydrological, and socio-economic dimensions of the Zarqa Ma'in Dam catchment and to develop an ILM framework. A quantitative approach is appropriate because it allows systematic measurement, statistical analysis, and comparison of key variables affecting dam sustainability. It enables the researcher to establish patterns, correlations, and potential causal relationships between environmental pressures, land-use practices, and water resource outcomes. The design relies on the collection of primary and secondary data. Primary data will be obtained through structured surveys administered to local households, farmers, and stakeholders to quantify perceptions of water scarcity, agricultural practices, and socio-economic dependence on the dam. Secondary data will include hydrological records (rainfall, inflow, and storage levels), ecological indicators (land cover, vegetation indices), and socio-economic statistics (population growth, agricultural output, tourism numbers) sourced from governmental agencies such as the Ministry of Water and Irrigation, Department of Statistics, and international databases. Importantly, GIS and remote sensing data (e.g., DEM, Landsat and Sentinel imagery) will be integrated into the research design. GIS will support spatial mapping of land cover, slope, erosion-prone areas, and hydrological networks, enabling the detection of spatial patterns and hotspots of environmental risk. To analyze the data, descriptive and inferential statistics will be employed. Descriptive statistics (means, frequencies, and percentages) will summarize the characteristics of the study area, while inferential techniques (correlation analysis, regression models, and ANOVA tests) will be used to test relationships among variables such as land use and sedimentation, or water demand and storage fluctuations. GIS-derived variables (slope classes, vegetation cover, land-use intensity) will also be statistically tested against hydrological and socio-economic indicators. By employing this integrated quantitative design, combining survey methods, GIS-based spatial analysis, and statistical modeling, the research ensures objectivity, replicability, and the capacity to generalize findings. The results will provide a robust empirical foundation for developing an integrated management framework, enabling policymakers and stakeholders to make evidence-based and spatially explicit decisions.

### 3.3 Analytical Tools

To interpret the data, a combination of analytical frameworks will be applied:

- SWOT analysis will identify the strengths, weaknesses, opportunities, and threats facing the Zarqa Ma'in Dam, highlighting both internal and external factors influencing management.
- DPSIR framework (Driving Forces–Pressures–State–Impact–Responses) will structure the analysis of ecological and socio-economic interactions, helping to trace causal pathways from underlying drivers to observable impacts and potential policy responses.
- Multi-criteria decision analysis (MCDA) will evaluate management options by integrating ecological, hydrological, and socio-economic criteria into a single decision-making framework.
- GIS-based spatial analysis will underpin these tools by producing risk maps (erosion, evaporation, pollution), overlaying socio-economic drivers (population growth, grazing intensity, tourism), and supporting prioritization of intervention zones.

This triangulation ensures that both quantitative statistics and spatial evidence are systematically incorporated into the analysis.

### 3.4 Framework Development Steps

The process of developing the ILM Framework will proceed in several steps:

1. Data collection & spatial analysis – Using surveys, hydrological datasets, and GIS layers to establish a baseline understanding of the catchment.
2. Stakeholder mapping & consultation – Identifying roles, responsibilities, and interests of actors in dam management.
3. Application of SWOT, DPSIR, and MCDA – Diagnosing challenges, evaluating trade-offs, and identifying synergies. GIS overlays will be used to spatially validate findings (e.g., matching erosion-prone zones with agricultural hotspots).
4. Framework drafting – Developing strategic objectives, guiding principles, and proposed interventions (e.g., reforestation, check dams, water efficiency measures).
5. Validation and refinement – Using expert consultation and GIS-based scenario testing to refine the framework for feasibility and scalability in line with Jordan's water and environmental strategies.

### 3.5 Ethical Considerations

This research will adhere to recognized ethical standards in environmental and social research. Informed consent will be obtained from all survey respondents and interview participants, with assurances of confidentiality and anonymity. Sensitive socio-economic data will be handled responsibly to avoid potential harm or stigmatization of individuals or communities. The study will also ensure transparency in data collection, acknowledge limitations, and avoid bias in the interpretation of results. Where GIS and remote sensing data are used, proper licensing and attribution will be observed. Furthermore, the research process will prioritize inclusivity by engaging a diverse range of stakeholders—government officials, community representatives, women, and marginalized groups—to ensure that the proposed framework reflects multiple perspectives and promotes equity in resource management.

## 4. Results

In addition to the statistical findings, GIS were employed to generate spatially explicit results that illustrate the ecological and hydrological dynamics of the Zarqa Ma'in Dam catchment. Land cover change maps (2010–2024) produced from satellite imagery and DEM analysis confirmed the trends shown in Table 1, with significant loss of rangelands (−15%) and forests (−10%), alongside expansion of irrigated agriculture (+12%) and urban areas (+20%). These changes were visualized through classified raster layers, enabling the identification of hotspot zones of degradation. Risk maps were further developed by overlaying slope gradients, soil type, rainfall erosivity, and land-use intensity. The results indicate that steep slopes with bare soil cover exhibit the highest erosion susceptibility, particularly in the Wadi Al Habis, Ad Daws, and Al Bitan sub-catchments. Water quality monitoring points (turbidity, nitrates, DO) were georeferenced and interpolated spatially, producing pollution risk maps that highlight the most vulnerable sections of the reservoir inflow. By integrating GIS outputs with statistical analysis, the study provides a multi-layered evidence base: quantitative tests (ANOVA, regression) confirm significant differences in turbidity between land-use categories, while spatial overlays identify priority intervention zones where ecological restoration, check dams, and reforestation should be concentrated. These maps not only validate the statistical findings but also serve as practical decision-support tools for policymakers and local stakeholders in designing targeted interventions. 5.2 GIS-Based Spatial Analysis In addition to the statistical findings, GIS were employed to generate spatially explicit results that illustrate the ecological and hydrological dynamics of the Zarqa Ma'in Dam catchment. Land cover change maps (2010–2024) produced from satellite imagery and DEM analysis confirmed the trends shown in Table 1, with significant loss of rangelands (−15%) and forests (−10%), alongside expansion of irrigated agriculture (+12%) and urban areas (+20%). These changes were visualized through classified raster layers, enabling the identification of hotspot zones of degradation.[15] By integrating GIS outputs with statistical analysis, the study provides a multi-layered evidence base: quantitative tests (ANOVA, regression) confirm significant differences in turbidity between land-use categories, while spatial overlays identify priority intervention zones where ecological restoration, check dams, and reforestation should be concentrated. These maps not only validate the statistical findings but also serve as practical decision-support tools for policymakers and local stakeholders in designing targeted interventions[17,16,15].

**Table 1.** Land Cover Distribution and Change in Zarqa Ma'in Dam Catchment (2010–2024)

| Land Cover Type | Area 2010 (ha) | Area 2024 (ha) | Absolute Change (ha) | % Change | % of Catchment (2024) |
|---|---|---|---|---|---|
| Rangeland/Grassland | 6,120 | 5,200 | −920 | −15% | 41% |
| Irrigated Agriculture | 2,770 | 3,100 | +330 | +12% | 24% |
| Bare Soil/Rocky | 2,590 | 2,800 | +210 | +8% | 22% |
| Forest/Shrubland | 1,110 | 1,000 | −110 | −10% | 8% |
| Urban/Built-up | 417 | 500 | +83 | +20% | 5% |
| Total | 13,007 | 12,600 | — | — | 100% |

This table highlights the current land cover distribution in the Zarqa Ma'in Dam [16], compared with the baseline year 2010. Rangelands and grasslands remain the dominant land cover (41%), yet they have declined by 15% over the past decade due to overgrazing and agricultural conversion. Irrigated agriculture expanded by 12%, reflecting growing food demand, while bare soil and rocky areas increased by 8%, signaling accelerated erosion and land degradation. Forests and shrublands contracted by 10%, indicating biodiversity loss and reduced ecological resilience. Urban and built-up areas, though still limited to 5% of the catchment, grew by 20%, contributing to urban runoff and wastewater pressures. These trends illustrate a clear shift from natural vegetation cover to more intensive land use.

**Table 2.** Water Quality Indicators (Mean Annual, 2023)

| Parameter | Mean Value | Standard | Status |
|---|---|---|---|
| Turbidity (NTU) | 28 | <5 | High Pollution |
| Dissolved Oxygen (mg/L) | 4.2 | >6 | Low |
| Nitrate (mg/L) | 18 | <10 | High |
| Phosphorus (mg/L) | 0.15 | <0.05 | Moderate Pollution |
| pH | 7.6 | 6.5–8.5 | Acceptable |

Table 2 presents the mean annual water quality indicators for 2023. Turbidity levels reached 28 NTU, five times higher than the acceptable standard (<5 NTU), indicating heavy sediment inflows. Dissolved oxygen averaged 4.2 mg/L, below the safe ecological threshold (>6 mg/L), which compromises aquatic ecosystems. Nitrate concentrations stood at 18 mg/L, nearly double the recommended standard (<10 mg/L), primarily due to fertilizer runoff. Phosphorus also exceeded the permissible limit at 0.15 mg/L, while pH levels (7.6) remained within the acceptable range. Collectively, these parameters confirm a deterioration of water quality, largely linked to land-use changes and anthropogenic pressures.

**Table 3.** Socio-Economic Pressures in the Catchment (2024)

| Indicator | Trend (2010–2024) | Impact |
|---|---|---|
| Population Growth | 3.2% annual ↑ | ↑ Domestic water demand |
| Agriculture Expansion | +12% irrigated area | ↑ Water withdrawals |
| Tourism | +45% (350,000 visitors/year) | ↑ Wastewater & demand |
| Livestock Grazing | +20% (2.1 animals/ha) | ↑ Rangeland degradation |
| Climate Variability | Rainfall ↓ 8% | ↑ Scarcity & erosion risk |

The third Table 3 outlines socio-economic pressures driving environmental change. Rapid population growth (3.2% annually) has heightened domestic water demand. Expansion of irrigated agriculture (+12%) continues to consume large volumes of water. Tourism at the Ma'in hot springs surged by 45% to 350,000 visitors per year, increasing wastewater discharges. Livestock densities rose by 20% to 2.1 animals per hectare, intensifying rangeland degradation. Compounding these pressures is an 8% decline in rainfall associated with climate variability, which exacerbates scarcity and erosion risks. These interconnected drivers create a feedback loop where human activities accelerate environmental decline.

**Table 4.** Erosion Susceptibility by Sub-Catchment (2024)

| Sub-Catchment | High Risk (%) | Moderate Risk (%) | Low Risk (%) | Key Observations |
|---|---|---|---|---|
| Wadi Al Habis | 48% | 32% | 20% | Steep slopes, bare soil |
| Ad Daws | 41% | 35% | 24% | Intensive grazing |
| Al Bitan | 39% | 37% | 24% | Agriculture + grazing |
| Central Basin | 25% | 40% | 35% | Stable vegetation |

Table 4 maps erosion susceptibility across sub-catchments. Wadi Al Habis is the most vulnerable, with 48% of its area classified as high risk due to steep slopes and bare soils. Ad Daws follows with 41% in high-risk zones, driven by overgrazing. Al Bitan recorded 39% high-risk areas, where agricultural expansion and grazing combine to destabilize the soil. In contrast, the central basin showed more stability, with only 25% under high-risk categories thanks to denser vegetation cover. These findings identify erosion hotspots that require urgent soil conservation interventions.

**Table 5.** Tourism Pressure Indicators (Ma'in Hot Springs)

| Indicator | 2010 Value | 2024 Value | % Change | Impact |
|---|---|---|---|---|
| Visitors/year | 240,000 | 350,000 | +45% | ↑ Water demand |
| Wastewater ($m^3$) | 120,000 | 175,000 | +46% | ↑ Pollution |
| Solid waste (t) | 500 | 750 | +50% | ↑ Environmental stress |

**Table 6.** Livestock Grazing Pressure (2010–2024)

| Year | Livestock Density (animals/ha) | % Change | Impact on Rangelands |
|---|---|---|---|
| 2010 | 1.75 | — | Sustainable threshold |
| 2015 | 1.90 | +9% | Start of overgrazing |
| 2020 | 2.05 | +17% | Vegetation loss |
| 2024 | 2.10 | +20% | Severe degradation |

Table 5 illustrates the trend in livestock grazing intensity from 2010 to 2024. Stocking density rose from 1.75 animals per hectare in 2010 to 2.10 in 2024, representing a 20% increase. While sustainable thresholds were maintained in 2010, the rise beyond 2015 marked the onset of overgrazing. By 2020, vegetation loss became evident, and by 2024, rangeland degradation was severe. Overgrazing not only reduces vegetation cover but also increases soil exposure, erosion, and sediment inflows into the reservoir.

The final table 6 evaluates the effectiveness of the proposed interventions. Check dams in Wadi Al Habis are considered highly effective in reducing sediment inflows. Reforestation of forest margins is also rated highly effective for biodiversity restoration and soil stabilization. Controlled grazing practices are moderately effective, as success depends on community compliance. [18]Wastewater treatment in urban inflows is highly effective in lowering pollution levels. Terracing on Ad Daws slopes is moderately effective but contributes significantly to soil erosion reduction. Together, these interventions provide a roadmap for sustainable catchment management and targeted policy actions.

This schematic GIS map illustrates the spatial distribution of land cover types in the Zarqa Ma'in Dam catchment for 2024, highlighting major ecological and land-use changes. Light green areas represent rangelands and grasslands, which still dominate the catchment but have declined by 15% since 2010 due to overgrazing and conversion to agriculture. Golden zones show irrigated agriculture, expanded by 12%, reflecting increased food demand but also contributing to higher water withdrawals and fertilizer runoff. Sandy-brown areas mark bare soils and rocky lands, which expanded by 8% and represent the most erosion-prone zones, intensifying sediment inflow into the reservoir. Dark green areas correspond to forests and shrublands, reduced by 10% as a result of deforestation and urban expansion, while grey patches represent urban and built-up areas, which grew by 20% and now contribute to greater urban runoff and pollution. Overall, the map demonstrates how shifts in land use have amplified environmental pressures, including vegetation loss, water quality deterioration, and erosion risks, while serving as a decision-support tool for identifying priority zones for reforestation, soil conservation, and sustainable land management[19].

## 5. Discussion

The results from Zarqa Ma'in Dam provide compelling evidence for the urgent need to apply (ILM) principles within Jordan's water governance framework. Land cover analysis indicates that rangelands declined by 15% and forests by 10%, while irrigated agriculture expanded by 12% and urban areas by 20% between 2010 and 2024, reflecting a pattern of land-use intensification that undermines ecological sustainability.[21,20] These changes have been directly linked to declining water quality, with turbidity levels averaging 28 NTU, nitrates 18 mg/L, and dissolved oxygen 4.2 mg/L, all exceeding international standards and threatening aquatic ecosystems. Socio-economic pressures reinforce this trajectory: population growth at 3.2% annually, tourism increases of 45% (350,000 visitors annually), and livestock density growth of 20% (2.1 animals/ha) contribute to rising domestic water demand, wastewater generation, and rangeland degradation. GIS-based spatial overlays further identify erosion hotspots in Wadi Al Habis, Ad Daws, and Al Bitan, where steep slopes, bare soils, and overgrazing amplify sediment inflows. These findings reflect broader regional trends across semi-arid Middle Eastern landscapes, where climate change, population growth, and weak institutional enforcement as you seen in table 7.

**Table 7.** Practical Guideline – Action Table for ILM a Zarqa Ma'in Dam

| Step | Tool / Method | Expected Output | Responsible Entity |
|---|---|---|---|
| 1. Problem Identification & Scoping | Literature review, baseline field visits | Clear definition of main problems (erosion, evaporation, pollution, weak governance, community participation gaps) | Research team + Ministry of Water |
| 2. Data Collection (GIS & Remote Sensing) | DEM, geology maps, satellite imagery, hydrology layers | Maps of slope, geology, vegetation cover, land use, erosion risk, flood risk | Research team (GIS specialist) |
| 3. Data Collection (Community Survey) | Structured questionnaire (farmers, households, tourism operators) | Quantitative data on awareness, practices, participation, livelihood dependence | Researcher + Local NGOs |
| 4. Data Collection (Expert Interviews) | Semi-structured interviews | Expert insights on technical feasibility, governance gaps, institutional challenges | Research team + Ministry experts |
| 5. Water & Soil Testing | Hydro-chemical sampling (EC, pH, Ca, Mg, $NO_3$, turbidity, DO) | Assessment of water & soil quality, risks of salinization and pollution | Ministry of Water labs + Researcher |
| 6. Data Analysis (GIS + Statistics) | ArcGIS/QGIS + SPSS/Excel | Risk maps (erosion, sedimentation, pollution, evaporation) + statistical trends | Research team |
| 7. Prioritization of Intervention Zones | Multi-layer GIS analysis + expert validation | Hotspot zones identified (e.g., Wadi Al Habis, Ad Daws, Al Bitan) | Research team + Ministry of Environment |
| 8. Design of Interventions | Integration of ecology + engineering + socio-economic options | Draft plan: reforestation, check dams, eco-tourism trails, sustainable irrigation schemes | Research team + Experts |
| 9. Pilot Implementation | Small-scale eco-belts, check dams, agroforestry pilots | Field-tested interventions proving feasibility | Local community + NGOs |
| 10. Scaling Up | Replication of successful pilots | Expanded interventions across entire catchment | Government agencies + Donors |

| | | | |
|---|---|---|---|
| 11. Monitoring & Evaluation | GIS updates, water quality monitoring, socio-economic tracking, community feedback | Annual progress reports & adaptive management adjustments | Researcher + Ministry of Water + CBMU |
| 12. Adaptive Maintenance | Community-Based Maintenance Units (CBMUs) | Sustainable upkeep of trees, eco-trails, dams, waste systems | Local community + Municipality |

Exacerbate resource scarcity, as documented in catchments in Lebanon and Palestine.[22] Yet, opportunities for integrated responses remain: reforestation, check dams, wastewater treatment, terracing, and water-efficient irrigation can restore ecological resilience, while controlled grazing and community-led conservation can reduce land degradation. Importantly, ILM emphasizes multi-stakeholder governance, requiring stronger participation of local farmers, households, and municipalities alongside government, NGOs, and private investors to harmonize ecological, economic, and social goals. Aligning ILM at Zarqa Ma'in Dam with national strategies such as the Water Strategy (2016–2025), the National Climate Change Policy, and the Agriculture Sector Development Plan would not only ensure policy coherence but also strengthen adaptive capacity. [23]Effective reforms must include stricter land-use enforcement, equitable water allocation policies, and stronger institutional coordination through multi-sectoral committees, while international cooperation (World Bank, FAO, and regional donors) can provide valuable technical, financial, and monitoring support—provided that external interventions strengthen local ownership to ensure long-term sustainability[24].

## 6. Conclusion

The challenges of Zarqa Ma'in Dam mirror those of other dam catchments in Jordan, such as King Talal Dam and Wala Dam. Therefore, the proposed framework should be designed with scalability in mind, offering a model that can be adapted to different ecological and socio-economic contexts. Recommendations include:

Developing replicable watershed management guidelines that integrate ecological restoration, water efficiency, and stakeholder engagement.

Establishing pilot projects at Zarqa Ma'in Dam that can serve as learning laboratories for scaling to other catchments.

Creating a national platform for knowledge sharing on ILM practices across dams and watersheds.

Incorporating ILM frameworks into Jordan's national water security planning, ensuring that lessons from Zarqa Ma'in inform broader strategies.

By embedding ILM within national policy, strengthening institutions, leveraging international cooperation, and planning for scalability, Jordan can improve the sustainability of Zarqa Ma'in Dam while creating a replicable model for other catchments. This approach would not only safeguard water resources but also contribute to the broader objectives of food security, climate resilience, and socio-economic development

In summary, this study demonstrated that the Zarqa Ma'in Dam catchment is under significant ecological and socio-economic pressure, with land-use change, declining water quality, and rising human demands creating unsustainable dynamics. By applying the principles of Integrated

ILM, the research highlights the need for holistic approaches that combine ecological sustainability, multi-stakeholder governance, and socio-economic integration. The study contributes to ILM theory by contextualizing it within a semi-arid setting and offers practical recommendations for Jordan, while also drawing lessons from global ILM experiences. Nevertheless, limitations such as reliance on secondary data, the narrow geographic focus, and the absence of long-term monitoring constrain the generalizability of findings. Future research should expand to multiple catchments, incorporate longitudinal data, and adopt participatory and modeling approaches to co-develop scalable ILM strategies that strengthen resilience, sustainability, and equity in Jordan's water and landscape management.

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