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RISK-BASED ASSESSMENT AND REHABILITATION PRIORITIZATION OF AGING IRRIGATION HYDRAULIC STRUCTURES UNDER VARIABLE FLOW CONDITIONS: A CASE STUDY OF ANDIJAN REGION, UZBEKISTAN

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Abstract

Aging irrigation hydraulic structures constitute one of the principal constraints on the reliable, equitable, and energy-efficient delivery of water in arid and semi-arid agricultural regions. Prolonged operation, insufficient preventive maintenance, abrasion, sediment accumulation, concrete deterioration, leakage through joints, deformation of canal sections, corrosion of mechanical components, and repeated exposure to variable hydraulic loads gradually reduce the functional capacity and operational reliability of water intake structures, regulators, canal drops, culverts, aqueducts, measuring structures, spillways, and associated control facilities. The problem is particularly important in Uzbekistan, where irrigated agriculture consumes the dominant share of available water resources, while a considerable proportion of irrigation infrastructure requires modernization, improved measurement, and more systematic asset-management procedures. This study develops an integrated risk-based framework for assessing the technical condition, hydraulic performance, operational reliability, and rehabilitation priority of aging irrigation hydraulic structures under variable flow conditions. The proposed methodology combines field inspection, defect classification, hydraulic capacity analysis, functional performance indicators, failure-probability assessment, consequence analysis, and multicriteria decision-making. The technical condition of each structure is represented by a condition index derived from the severity, extent, and progression rate of observed defects, whereas hydraulic reliability is assessed by comparing the actual conveyance or regulation capacity with the required discharge under low-flow, normal-flow, and peak-demand scenarios. Failure risk is formulated as a function of the probability of structural or functional failure and the corresponding hydraulic, agricultural, economic, environmental, and operational consequences. To avoid subjective prioritization based solely on visual deterioration, the framework introduces a composite rehabilitation priority index that integrates structural condition, hydraulic deficiency, service importance, failure consequences, maintainability, and intervention urgency. The methodology is intended for application to selected irrigation hydraulic structures in Andijan Region, where flow variability, sediment transport, seasonal water scarcity, intensive agricultural demand, and the aging of infrastructure create a strong need for transparent and technically justified rehabilitation decisions. The proposed approach enables irrigation authorities to distinguish structures requiring immediate intervention from those suitable for routine maintenance, monitoring, partial repair, or long-term reconstruction. The study contributes to the development of data-driven asset management for irrigation systems and provides a reproducible decision-support instrument for allocating limited rehabilitation funds to structures that generate the greatest improvement in hydraulic reliability, water-delivery performance, and system resilience.

Keywords: Irrigation hydraulic structures; technical condition assessment; operational reliability; variable flow conditions; risk-based rehabilitation; hydraulic capacity; failure probability; multicriteria decision-making; rehabilitation priority index; Andijan Region.

Introduction

Irrigation hydraulic structures are essential components of agricultural water-delivery systems because they regulate water abstraction, conveyance, distribution, measurement, energy dissipation, and emergency discharge. Their technical condition and operational reliability directly influence water-use efficiency, crop productivity, maintenance costs, and the continuity of irrigation services. In many irrigation systems, however, water intake structures, canal regulators, division structures, check gates, drops, culverts, aqueducts, spillways, and measuring facilities have been operating for several decades under conditions that differ considerably from their original design assumptions. Long-term exposure to variable discharges, sediment-laden flow, repeated wetting and drying, temperature fluctuations, insufficient maintenance, and intensive seasonal operation gradually reduces both structural integrity and hydraulic performance. Typical defects include concrete cracking and abrasion, reinforcement corrosion, joint leakage, settlement, local scour, deformation of canal transitions, sediment accumulation, gate distortion, deterioration of sealing elements, and malfunction of lifting mechanisms. Although some defects may initially appear minor, their combined development can reduce discharge capacity, increase head losses, disturb flow regulation, cause upstream afflux, accelerate erosion, and eventually lead to partial or complete loss of function. This problem is particularly significant in Uzbekistan, where irrigated agriculture depends on an extensive network of canals and hydraulic structures, while water scarcity and seasonal variations in supply require increasingly accurate and reliable flow regulation. In densely cultivated areas such as Andijan Region, the malfunction of a single regulator or water-distribution structure may affect several downstream branches, interrupt water delivery, reduce irrigated area, and increase conflicts among water users. Consequently, rehabilitation decisions should not be based only on the age of a structure or the visible severity of damage. A structure with moderate physical deterioration may represent a high system-level risk when it supplies a large command area or occupies a critical position in the network, whereas a visibly damaged minor structure may have limited consequences and may be restored through routine repair. Traditional condition-assessment practices frequently classify structures as satisfactory, unsatisfactory, or critical on the basis of visual inspection and expert judgment. While these approaches are simple and practical, they often provide insufficient information about hydraulic deficiency, operational limitations, service importance, and the potential consequences of failure. Moreover, irrigation structures do not operate continuously at a single design discharge. Seasonal water availability, crop-water requirements, rotational supply schedules, sedimentation, unauthorized withdrawals, and upstream regulation produce substantial variations in water level, velocity, gate opening, energy loss, and flow regime. A structure may perform adequately under normal flow but become hydraulically inefficient or unsafe during low-flow, peak-demand, or emergency conditions. For this reason, technical condition assessment should be combined with hydraulic verification under several representative operating scenarios. Risk-based asset management provides a more rational basis for rehabilitation planning because it considers both the probability of failure and the magnitude of its consequences. For irrigation hydraulic structures, failure probability depends on age, defect severity, material degradation, hydraulic loading, sediment conditions, maintenance history, foundation behaviour, and mechanical reliability. Failure consequences may include interruption of water supply, crop losses, reduction of irrigated area, local flooding, canal-bank erosion, damage to roads and utilities, emergency repair costs, and environmental impacts. However, many regional water-management organizations lack long-term monitoring data and statistically reliable failure records; therefore, highly complex probabilistic models may be difficult to apply in practice. At the same time, simplified visual inspection does not provide a sufficiently objective basis for ranking numerous structures competing for limited rehabilitation funds. A practical methodology is therefore required that combines engineering inspection, hydraulic analysis, operational evaluation, and consequence-based risk assessment while remaining applicable under incomplete-data conditions. Recent studies on irrigation infrastructure have increasingly used multicriteria decision-making, risk matrices, hydraulic modelling, and condition indices to support maintenance and rehabilitation planning [1–4]. These approaches demonstrate that rehabilitation priority should reflect not only physical deterioration but also hydraulic performance, operational functionality, service importance, and intervention urgency. Nevertheless, many existing methods examine these factors separately or require datasets that are unavailable for local irrigation systems. The present study addresses this limitation by developing an integrated framework for the risk-based assessment and rehabilitation prioritization of aging irrigation hydraulic structures under variable flow conditions. The proposed framework includes five principal assessment domains: technical condition, hydraulic performance, operational functionality, failure probability, and failure consequence. Field inspection is used to identify structural, mechanical, foundation-related, and erosion-related defects; hydraulic calculations are performed to determine whether the actual capacity of each structure satisfies the required discharge under minimum, normal, peak-demand, and maximum permissible operating scenarios; and operational reliability is evaluated through gate mobility, regulation accuracy, accessibility, sediment-control capability, and measurement performance. The individual indicators are normalized and integrated into a rehabilitation priority index that enables structures to be classified into routine maintenance, scheduled

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repair, priority rehabilitation, and immediate-intervention groups. The scientific objective of the research is to establish a transparent and reproducible methodology for identifying the irrigation hydraulic structures whose rehabilitation would provide the greatest reduction in system risk and the greatest improvement in water-delivery reliability. The practical value of the proposed approach lies in supporting irrigation authorities in Andijan Region and similar agricultural areas in preparing phased rehabilitation programmes, allocating limited financial resources more efficiently, strengthening preventive maintenance, and improving the resilience of irrigation systems under changing hydrological and operational conditions.

2. Materials and Methods

The study was designed as an integrated engineering assessment of aging irrigation hydraulic structures operating under variable discharge conditions, with the methodological framework combining field inspection, technical condition diagnosis, hydraulic verification, operational performance analysis, failure-risk estimation, and rehabilitation-priority ranking. The proposed procedure is intended for application to water intake structures, canal regulators, division structures, check gates, canal drops, culverts, aqueducts, measuring facilities, spillways, and related irrigation-control assets located within the irrigation systems of Andijan Region, Uzbekistan. The first stage of the assessment consists of collecting general information on each structure, including its location, year of construction or reconstruction, structural type, design discharge, current operational discharge, dimensions, construction materials, command area, number of downstream users, maintenance history, and known failure or repair records. Field inspection is then conducted to identify structural, hydraulic, mechanical, foundation-related, and operational defects. Concrete structures are examined for cracking, abrasion, scaling, reinforcement exposure, corrosion, joint leakage, settlement, erosion, and local loss of cross-section, whereas gates and mechanical equipment are inspected for corrosion, distortion, seal failure, restricted movement, hoisting-system malfunction, and inability to maintain the required opening. Canal transitions and outlet zones are assessed for sediment accumulation, vegetation growth, local scour, bank deformation, undermining, and unstable flow patterns. Each observed defect is evaluated using a five-level severity scale, where a score of 1 represents an insignificant defect with no

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measurable influence on performance and a score of 5 represents a critical defect that may cause loss of function, progressive instability, or interruption of water delivery. The technical condition index of the i-th structure is calculated as a weighted normalized sum of the individual defect scores:

$$TCI_i = \frac{\sum_{j=1}^{m} w_j d_{ij}}{5\sum_{j=1}^{m} w_j} \quad (1)$$

where d_{ij} is the severity score assigned to defect j, w_j is the importance coefficient of the corresponding defect category, and m is the total number of assessed defects. The value of TCI_i ranges from 0 to 1, with larger values indicating a more deteriorated technical condition. Hydraulic performance is assessed for several operating scenarios because irrigation structures rarely function continuously at their original design discharge. Four representative scenarios are considered: minimum operating flow, normal irrigation flow, peak-demand flow, and maximum permissible or emergency flow. For open-channel structures, discharge is determined using the continuity equation Q = Av, supplemented where appropriate by the Manning equation:

$$Q = \frac{1}{n} A R^{2/3} S^{1/2} \quad (2)$$

where A is the wetted cross-sectional area, v is the mean flow velocity, n is Manning's roughness coefficient, R is the hydraulic radius, and S is the energy or bed slope. For gates, orifices, and control openings, the following discharge equation is applied:

$$Q = C_d A_o \sqrt{2gH} \quad (3)$$

where C_d is the discharge coefficient, A_o is the opening area, g is gravitational acceleration, and H is the effective hydraulic head. The hydraulic capacity ratio is expressed as:

$$K_{h,i} = \frac{Q_{a,i}}{Q_{r,i}} \quad (4)$$

where $Q_{a,i}$ is the actual available discharge capacity and Q_r,i is the required discharge under the selected operating scenario. Values below unity indicate insufficient hydraulic capacity, while values significantly above unity may suggest oversized operation, inefficient regulation, excessive velocities, or energy-dissipation problems. The hydraulic deficiency index is therefore defined as:

$$HDI_i = \max(0, 1 - K_{h,i}) \quad (5)$$

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The hydraulic deficiency index is supplemented by additional penalties when upstream afflux, excessive velocity, unstable hydraulic jumps, overtopping risk, inadequate energy dissipation, or measurement errors are observed. Operational functionality is evaluated through gate mobility, accessibility, regulation accuracy, measurement reliability, sediment-control capability, availability of reserve equipment, response time, and ease of maintenance. Each operational indicator is rated on the same five-level scale to maintain comparability across different structure types. Failure probability is estimated from the combined influence of structural condition, hydraulic deficiency, operational unreliability, age, exposure to variable loads, and maintenance history. Because complete statistical failure records are often unavailable for regional irrigation assets, a semiquantitative probability score is used instead of an unsupported probabilistic distribution. Failure consequences are evaluated in terms of interrupted water delivery, affected irrigated area, crop-production losses, flooding potential, damage to adjacent infrastructure, emergency repair requirements, environmental effects, and the number of dependent water users. The total risk score is calculated as:

$$R_i = P_i C_i \qquad (6)$$

where P_i is the normalized failure-probability score and C_i is the normalized consequence score. To support rehabilitation planning, a composite rehabilitation priority index is introduced:

$$RPI_i = \alpha TCI_i + \beta HDI_i + \gamma OFI_i + \delta R_i + \varepsilon \iota \quad (7)$$

The weighting coefficients should be established using the analytical hierarchy process based on judgments obtained from qualified specialists in hydraulic engineering, irrigation operation, structural diagnostics, and water management, while the consistency ratio of the pairwise comparison matrix should not exceed 0.10. Structures are subsequently classified into four rehabilitation groups: routine maintenance, scheduled repair, priority rehabilitation, and immediate intervention. Sensitivity analysis is performed by varying the principal weighting coefficients and hydraulic scenarios to determine whether the final ranking remains stable under changes in expert judgment and seasonal discharge conditions. This procedure allows the assessment to distinguish structures that are physically deteriorated but hydraulically noncritical from structures that appear moderately damaged yet represent a high system-level risk because of their location, service importance, or inability to regulate variable flows.

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Table 1. Proposed assessment criteria for irrigation hydraulic structures

Assessment domain	**Main indicators**	**Scoring principle**	**Engineering interpretation**
Technical condition	Cracks, abrasion, corrosion, leakage, settlement, scour, and deformation	1–5 points	Physical deterioration of structural components
Hydraulic performance	Capacity ratio, water-level stability, velocity, head losses, and energy dissipation	1–5 points	Ability to convey and regulate the required flow
Operational functionality	Gate movement, measurement accuracy, accessibility, and maintainability	1–5 points	Reliability of daily operation and control
Failure probability	Age, defect progression, hydraulic loading, and maintenance history	1–5 points	Likelihood of structural or functional failure
Failure consequence	Irrigated area affected, service interruption, flooding, and economic damage	1–5 points	Severity of potential failure outcomes
Intervention urgency	Defect progression, seasonal importance, and repair limitations	1–5 points	Required time frame for maintenance or rehabilitation

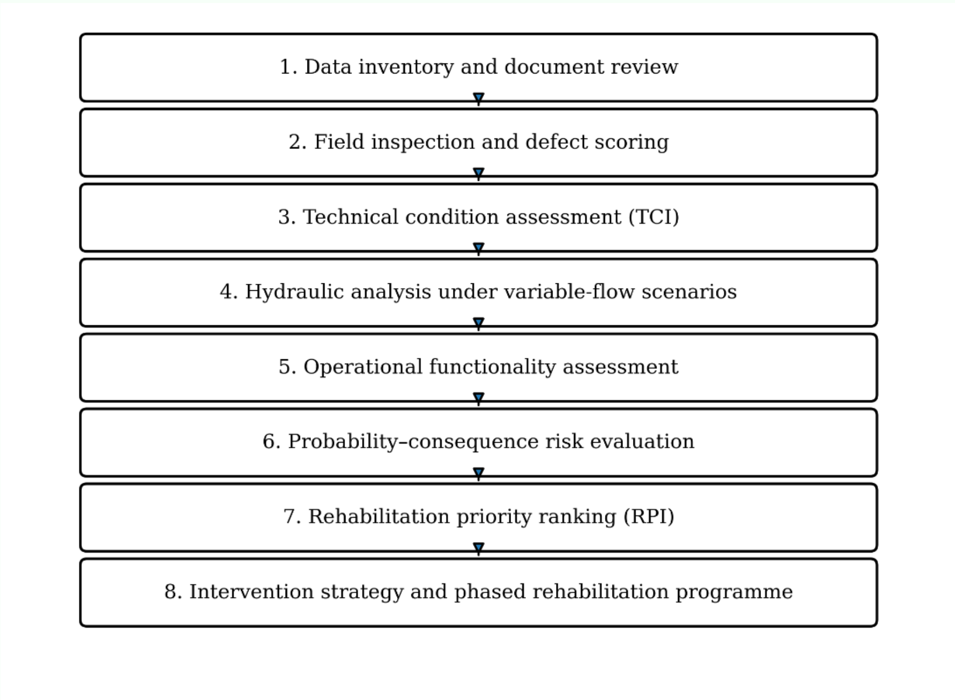

Figure 1. Workflow of the integrated risk-based assessment and rehabilitation prioritization framework

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3. Results

For methodological validation, the proposed framework was applied to a representative engineering scenario containing eight common irrigation assets: a head regulator, check gate, division structure, canal drop, culvert, aqueduct, measuring flume, and emergency spillway. The scenario was constructed to reproduce the combination of concrete deterioration, gate malfunction, sediment accumulation, capacity loss, leakage, energy-dissipation deficiency, and downstream erosion that is typically encountered in aging irrigation networks. The calculated rehabilitation priority index values ranged from 0.284 to 0.714, demonstrating that the combined assessment produced a clear differentiation between assets requiring routine maintenance and those requiring immediate engineering intervention. The emergency spillway received the highest priority score (RPI = 0.714) because its relatively high technical condition index (TCI = 0.75), hydraulic deficiency index (HDI = 0.44), operational deficiency (OFI = 0.70), and normalized risk score (R = 0.82) were accompanied by the most severe failure consequences. Under the peak-flow scenario, its available-to-required capacity ratio decreased to approximately 0.56, indicating that sediment deposition, deteriorated surface protection, and insufficient downstream energy dissipation could jointly produce upstream afflux, overtopping, and progressive scour. The head regulator ranked second (RPI = 0.666). Although its hydraulic deficiency was lower than that of the spillway, the structure controlled water delivery to several downstream branches; therefore, defects in the gate, lifting mechanism, seals, and concrete joints generated a high system-level consequence score. Its estimated peak-flow capacity ratio was 0.65, and the inability to maintain accurate gate openings increased the risk of both under-delivery and uncontrolled discharge. The canal drop ranked third (RPI = 0.638) and was classified for priority rehabilitation. The critical mechanism was not complete structural instability but the combined effect of abrasion, a shortened or displaced hydraulic jump, deterioration of the stilling basin, and local scour beyond the protected apron. The conceptual defect pattern presented in Figure 2 illustrates how apparently separate deterioration mechanisms can interact: upstream sediment reduces the effective opening, gate corrosion limits regulation, leakage accelerates concrete degradation, and unstable downstream flow undermines the foundation. The aqueduct obtained an RPI of 0.556 and also entered the priority-rehabilitation group. Joint leakage, support deterioration, and limited hydraulic

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reserve were the main contributors, with a peak-flow capacity ratio of approximately 0.71. Unlike the spillway and canal drop, the recommended response for the aqueduct was staged rehabilitation consisting of joint sealing, detailed support inspection, localized concrete repair, and monitoring of deformation before major reconstruction. The check gate (RPI = 0.478) and division structure (RPI = 0.410) were assigned to scheduled repair. Both retained acceptable structural stability, but their regulation accuracy and hydraulic flexibility declined under variable-flow operation. For these assets, gate adjustment, seal replacement, removal of sediment and vegetation, and restoration of water-level indicators were considered sufficient to return performance to an acceptable level without complete reconstruction. The measuring flume (RPI = 0.310) and culvert (RPI = 0.284) remained in the routine-maintenance category. The measuring flume showed sensitivity at low flow because shallow depths and sediment deposits could reduce measurement accuracy, but its limited failure consequences prevented it from receiving a high investment priority. The culvert exhibited minor deposits and localized surface deterioration while maintaining the largest hydraulic reserve among the assessed structures. The ranking shown in Figure 3 confirms that visible deterioration alone did not determine intervention priority: consequence severity and hydraulic service importance shifted the head regulator above some structures with comparable physical damage. A sensitivity analysis in which each weighting coefficient was independently varied by ±20% showed that the emergency spillway and head regulator remained the two highest-priority assets in all tested combinations, while the canal drop remained in third position. This stability indicates that the ranking was not an artifact of a single expert-weight selection. The results further showed that peak-demand and emergency-flow scenarios controlled the priority of the spillway, regulator, and drop, whereas low-flow conditions were more relevant to measurement performance. On the basis of the calculated indices, immediate intervention was recommended for the emergency spillway and head regulator; priority rehabilitation for the canal drop and aqueduct; scheduled repair for the check gate and division structure; and routine maintenance with periodic monitoring for the measuring flume and culvert. The scenario-based application therefore demonstrated that the proposed framework can transform heterogeneous inspection and hydraulic information into an

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interpretable rehabilitation sequence while preserving the engineering reasons behind each priority decision.

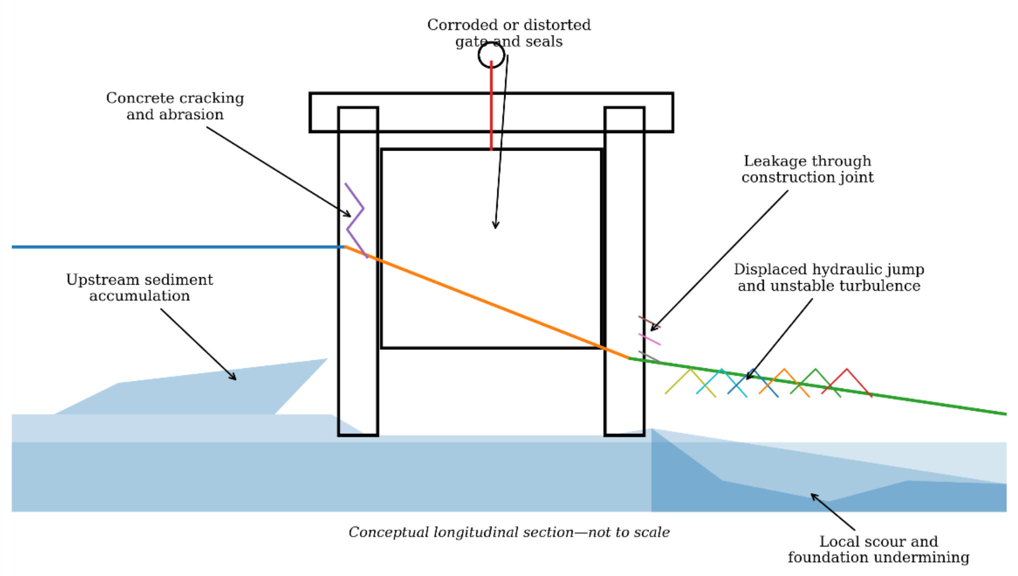

Figure 2. Conceptual representation of interacting deterioration mechanisms in an aging canal regulator

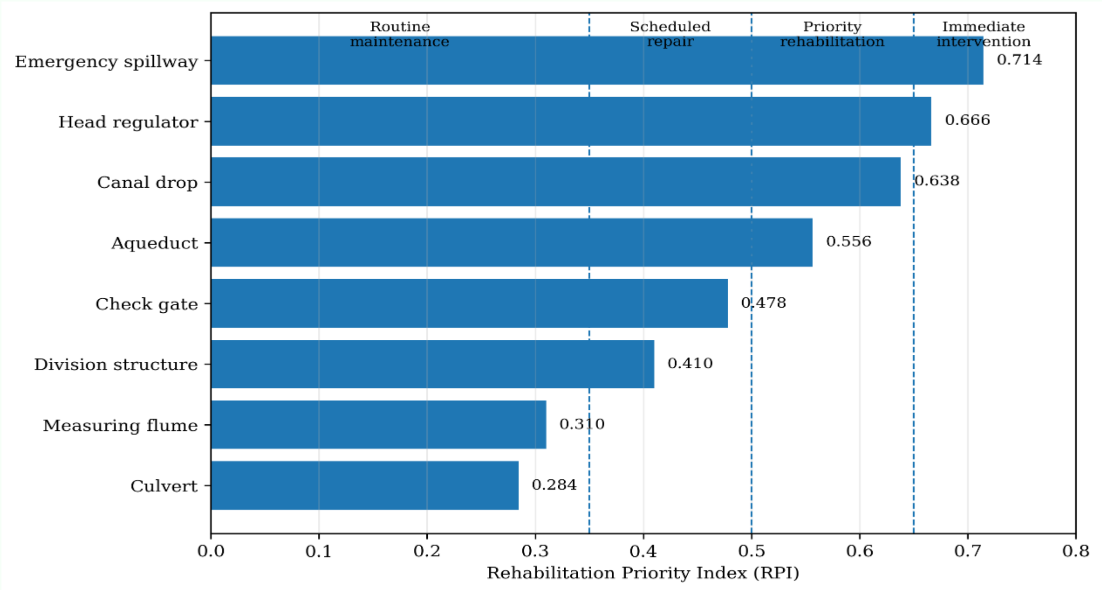

Figure 3. Rehabilitation Priority Index calculated for the representative irrigation-structure scenario

4. Discussion

The results confirm that the rehabilitation of aging irrigation hydraulic structures should be planned through an integrated assessment rather than through visual inspection alone, because structural deterioration, hydraulic deficiency,

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operational limitations, and failure consequences do not always develop at the same rate or produce the same level of system risk. A structure may retain an apparently acceptable external condition while losing regulation accuracy, discharge capacity, watertightness, or energy-dissipation efficiency, whereas another structure with visible surface defects may continue to perform its main hydraulic function without creating significant consequences for downstream users. This distinction is particularly important for irrigation systems in which a limited number of head regulators, division structures, spillways, aqueducts, and canal drops control water delivery over extensive agricultural areas. The representative assessment showed that the emergency spillway and head regulator received the highest rehabilitation priorities not simply because they had severe defects, but because their malfunction could generate system-wide consequences, including interruption of water supply, uncontrolled discharge, upstream water-level rise, downstream erosion, damage to adjacent infrastructure, and losses in irrigated agricultural production. This finding supports the fundamental principle of risk-based asset management, according to which intervention priority must reflect both the likelihood of failure and the severity of its consequences. In conventional practice, irrigation structures are often grouped into broad categories such as satisfactory, unsatisfactory, or critical, but such classifications do not always explain why one structure should be repaired before another. The rehabilitation priority index proposed in this study provides a more transparent basis for decision-making because each final score can be traced to technical condition, hydraulic performance, operational functionality, risk, and intervention urgency. This traceability is essential for engineering management, as it enables decision-makers to understand whether a high priority results from progressive material deterioration, insufficient discharge capacity, critical network location, poor gate performance, or a combination of these factors. The results also demonstrate the importance of evaluating several hydraulic operating scenarios. Irrigation structures operate under strongly variable conditions caused by seasonal water availability, rotational distribution schedules, changing crop demand, sediment deposition, upstream regulation, and emergency operations. Therefore, assessment based only on average or design discharge may conceal serious deficiencies. The spillway, canal drop, and aqueduct showed their most critical behaviour under peak-flow conditions, when flow velocity, upstream afflux, hydraulic losses, and downstream erosion increased significantly. In

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contrast, the measuring flume was more sensitive to low-flow conditions, because shallow depths and sediment deposits reduced discharge-measurement accuracy. These differences indicate that hydraulic reliability is not a fixed property but a scenario-dependent characteristic. A structure that is reliable under normal operating conditions may become inefficient or unsafe during peak demand, emergency release, or prolonged low-flow operation. Consequently, rehabilitation planning should consider the full operating range rather than a single nominal discharge. The interaction of defects identified in the conceptual analysis is another important result. Deterioration mechanisms rarely act independently. Upstream sediment accumulation may reduce the effective flow area and increase water levels; higher water levels may increase leakage through damaged joints; leakage may accelerate reinforcement corrosion and concrete degradation; gate corrosion may restrict movement and prevent accurate regulation; and unstable downstream flow may intensify local scour and foundation undermining. Such interactions can create progressive failure even when each individual defect initially appears moderate. This explains why isolated repair of visible surface damage may not restore the overall reliability of a structure. Effective rehabilitation should address the complete failure mechanism, including hydraulic causes, structural consequences, and operational limitations. For example, repairing cracked concrete at a canal drop without restoring the stilling basin and downstream protection would not eliminate the principal source of deterioration. Similarly, replacing a gate seal without removing sediment or adjusting the lifting mechanism may provide only a temporary improvement. The study therefore supports intervention packages rather than single-component repairs. For high-priority structures, rehabilitation should combine structural repair, hydraulic reconfiguration, mechanical restoration, sediment management, and improved monitoring. The differentiation between intervention categories is also practically significant. Immediate intervention is justified when high failure probability coincides with severe consequences and limited operational redundancy. Priority rehabilitation is appropriate when progressive deterioration and hydraulic deficiency are evident but the structure can continue to operate temporarily under controlled conditions. Scheduled repair is suitable for assets that retain structural stability but require restoration of regulation accuracy, watertightness, or mechanical functionality. Routine maintenance is sufficient where defects are localized, hydraulic reserve

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remains adequate, and failure consequences are limited. This classification allows irrigation authorities to develop phased investment programmes rather than treating all deteriorated structures as equally urgent. Such an approach is particularly valuable in regions where financial, technical, and labor resources are limited and where complete reconstruction of all aging infrastructure is not feasible. The relative stability of the ranking under moderate changes in weighting coefficients suggests that the proposed framework is robust enough for preliminary rehabilitation planning. The highest-priority structures remained at the top of the ranking because their scores were supported by several assessment domains simultaneously. This reduces the risk that the final decision is determined by one subjective expert judgment. Nevertheless, the weighting procedure should be adapted to local conditions. In irrigation systems where downstream flooding risk is high, consequence and safety indicators may receive greater weight. In systems primarily affected by water scarcity, hydraulic capacity, regulation accuracy, and service continuity may be more important. For small farm-level structures, maintainability and repair cost may have a stronger influence. The framework is therefore intended as a flexible decision-support tool rather than a universal fixed scoring system. Its application should involve hydraulic engineers, structural specialists, operation personnel, and water-management authorities to ensure that the selected indicators and weights reflect actual system priorities. The findings have direct implications for irrigation infrastructure management in Andijan Region and other densely cultivated areas with aging water-distribution networks. Rehabilitation programmes should first identify critical control points whose failure would affect multiple downstream branches, large command areas, or important agricultural zones. These structures should be subjected to more detailed hydraulic calculations, instrumental inspection, and continuous monitoring. Lower-priority structures should not be ignored, but their condition can be managed through preventive maintenance, periodic inspection, sediment removal, lubrication of mechanical components, restoration of measurement devices, and localized repair. This creates a transition from reactive maintenance, in which intervention begins after failure or severe deterioration, to preventive and risk-informed management. The proposed approach can also support the gradual development of a digital asset inventory containing the location, age, dimensions, technical condition, hydraulic parameters, repair history, photographs, monitoring results, and rehabilitation

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priority of each structure. Such a database would improve consistency between annual inspections, allow deterioration trends to be identified, and provide a stronger basis for budget allocation. Despite its practical advantages, the study has several limitations. The presented application is based on a representative engineering scenario rather than a complete field dataset from a specific irrigation system. Therefore, the numerical values demonstrate the operation of the methodology but should not be interpreted as final diagnostic results for individual structures in Andijan Region. Full-scale application requires field measurements of discharge, water level, velocity, sediment depth, gate opening, leakage, concrete strength, deformation, and scour geometry. In addition, the semiquantitative probability assessment reflects conditions where long-term failure statistics are unavailable. As monitoring databases improve, the probability component can be strengthened through statistical reliability analysis, Bayesian updating, deterioration models, or machine-learning methods. The consequence assessment may also be expanded by incorporating economic valuation of crop losses, flood-damage mapping, environmental impacts, and social vulnerability. Future research should test the framework using real groups of irrigation structures, compare expert-derived and data-driven weighting systems, and evaluate how rehabilitation changes the risk index after intervention. Integration with GIS, remote sensing, GNSS monitoring, IoT water-level sensors, and automated gate-control systems would further improve the accuracy and timeliness of assessment. Overall, the discussion indicates that the proposed methodology provides a technically justified and practically applicable bridge between traditional field inspection and advanced risk-based asset management. Its principal advantage lies in combining physical condition, hydraulic behaviour, operational performance, and failure consequences within one transparent framework, thereby enabling rehabilitation resources to be directed toward structures that provide the greatest improvement in irrigation reliability, safety, and resilience.

5. Conclusion

This study developed an integrated risk-based framework for assessing the technical condition, hydraulic performance, operational reliability, and rehabilitation priority of aging irrigation hydraulic structures operating under variable flow conditions. The methodology combines field inspection, defect-severity scoring, hydraulic capacity verification, operational-functionality assessment, failure-probability estimation, consequence analysis, and multicriteria decision-making within a single transparent procedure. Unlike conventional approaches based mainly on structure age or visible deterioration, the proposed framework considers the functional importance of each asset, its ability to operate under minimum, normal, peak-demand, and emergency-flow scenarios, and the potential hydraulic, agricultural, economic, environmental, and operational consequences of failure. The representative engineering application showed that the emergency spillway and head regulator should receive the highest rehabilitation priority because their structural and mechanical deficiencies were accompanied by insufficient hydraulic reserve and substantial consequences for downstream water delivery. The canal drop and aqueduct were classified for priority rehabilitation because of progressive deterioration, inadequate energy dissipation, joint leakage, and potential foundation or support damage. The check gate and division structure remained suitable for scheduled repair, while the measuring flume and culvert could be managed through routine maintenance and periodic monitoring. The analysis demonstrated that rehabilitation priority is not determined by physical deterioration alone: structures with similar technical-condition scores may require substantially different interventions depending on their network location, hydraulic role, operational redundancy, and failure consequences. Hydraulic scenario analysis was especially important because peak-flow conditions controlled the critical behaviour of spillways, regulators, drops, and aqueducts, whereas low-flow conditions primarily influenced the accuracy of measuring structures. Sensitivity analysis indicated that the highest-priority assets remained stable under moderate changes in weighting coefficients, confirming that the proposed ranking is sufficiently robust for preliminary engineering and investment decisions. From a practical perspective, the framework enables irrigation authorities to classify structures into routine maintenance, scheduled repair, priority rehabilitation, and immediate-intervention groups and to allocate limited financial and technical resources to measures that produce the greatest reduction in system-level risk. For application in Andijan Region, the methodology should be supported by a digital inventory containing structure geometry, design and measured discharges, defect records, gate-operability data, sediment depth, leakage, scour geometry, maintenance history, command area, and downstream service importance. Periodic reassessment would allow deterioration trends to be identified and rehabilitation priorities to be updated as hydraulic and operational conditions change. The principal limitation of the present study is that the numerical demonstration was based on a representative engineering scenario rather than complete field observations from individually identified structures; consequently, the presented values illustrate the methodological procedure and should not be treated as final diagnostic results for a particular irrigation system. Future investigations should validate the framework using measured data from operating structures, compare expert-based and objective weighting techniques, quantify rehabilitation costs and expected risk reduction, and integrate GIS, remote sensing, GNSS, UAV surveys, IoT sensors, and automated gate-control data. Overall, the proposed approach provides a reproducible and practically applicable basis for transitioning from reactive repair toward preventive, condition-based, and risk-informed management of irrigation hydraulic structures, thereby improving water-delivery reliability, infrastructure safety, operational efficiency, and resilience under increasingly variable hydrological conditions.

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