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DESIGN AND OPERATIONAL RELIABILITY OF HYDRAULIC STRUCTURES UNDER CLIMATE VARIABILITY: AN INTEGRATED ENGINEERING APPROACH FOR IRRIGATION, FLOOD PROTECTION AND WATER-SAVING SYSTEMS

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Abstract
This article investigates the scientific and engineering basis for improving the design, operation and reliability of hydraulic structures under conditions of increasing hydrological uncertainty, infrastructure ageing and pressure on land-water resources. The study is framed within the discipline of hydraulic structures and focuses on canals, regulators, spillways, culverts, small dams, intake structures, sediment-control facilities, drainage outlets and flood-protection elements that serve irrigation, land reclamation, hydropower and settlement-safety functions. The relevance of the topic is determined by the fact that hydraulic structures are no longer assessed only as isolated civil-engineering objects; they must be analysed as dynamic components of a wider water-management system in which discharge variability, sediment transport, structural deterioration, operational discipline, climate-related extremes, ecological limitations and economic restrictions interact continuously. International technical sources emphasize that water infrastructure design must increasingly include resilience, adaptive operation and lifecycle safety rather than relying only on fixed historical design assumptions [1], [2]. In Uzbekistan, irrigation and drainage infrastructure remains strategically important for agricultural production, rural livelihoods and the rational use of irrigated lands, while the sector faces rising costs of ageing assets, increasing competition for limited water resources and the need to modernize operating regimes and safety standards [3]. The purpose of the article is to develop an integrated methodological view of hydraulic-structure reliability by combining hydraulic calculation logic, structural safety assessment, operational monitoring, sediment-management principles and climate-resilient design criteria. The methods used include comparative technical analysis, systematization of design

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and operation factors, engineering interpretation of hydraulic performance indicators and conceptual modelling of risk pathways from hydrological loading to functional failure. The results show that reliability depends not only on the strength of concrete, reinforcement, foundations or gate mechanisms, but also on the compatibility between design discharge, actual flow regime, sediment load, maintenance frequency, automation level and emergency-management preparedness. The article concludes that the future development of hydraulic structures in Uzbekistan and similar arid regions should prioritize adaptive design, digital monitoring, sediment-aware operation, energy-efficient water regulation, periodic safety inspection and the integration of ecological flow and social-risk criteria into engineering decision-making.

Keywords: Hydraulic structures, irrigation canals, dam safety, hydraulic reliability, climate resilience, water regulation, sediment transport, operational monitoring, Uzbekistan, water-saving systems.

Introduction

Hydraulic structures occupy a central position in water-resources engineering because they transform natural and regulated water flows into controlled hydraulic regimes for irrigation, hydropower, flood protection, drainage, municipal supply, land reclamation and environmental management. In classical engineering education, a hydraulic structure is often described as a technical facility that retains, diverts, conveys, regulates, measures or dissipates water energy; however, in modern practice this definition is no longer sufficient, because every structure operates inside a complex system of hydrological variability, sediment movement, structural ageing, human operation, economic constraints and ecological obligations. A cross-regulator in an irrigation canal, for example, is not merely a concrete and steel element placed across a channel; it determines upstream water level, affects the accuracy of water distribution to outlets, influences flow velocity, modifies sediment deposition and directly affects the fairness of water allocation among users. FAO technical materials explain that cross-regulators control water depth in canals by changing local head losses, and that fixed weirs, gated regulators and other control structures differ in their degree of control and in the variability of water level under changing discharge

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conditions [4]. This means that the performance of hydraulic structures must be interpreted through both hydraulic theory and operational behaviour. The same principle applies to dams, spillways, culverts, intakes, drops, energy dissipators and drainage structures: their design is valid only when hydraulic capacity, structural safety, foundation stability, maintenance access and real operating conditions remain compatible throughout the lifecycle of the object. The scientific importance of this issue is increasing because many water-management systems were designed under assumptions of relatively stable hydrological records, while contemporary design practice must consider non-stationary climate patterns, more frequent extreme events, prolonged droughts, rising water demand and stricter environmental requirements. The World Bank's guidance on resilient water infrastructure stresses that resilience should be built into the engineering design of water projects, including through climate-risk assessment and decision frameworks that help designers evaluate future uncertainty rather than relying only on past observations [1], [5]. This approach is especially relevant for countries where agriculture depends heavily on irrigation systems and where the efficiency of canals, gates and hydraulic-control structures directly affects food security, energy use and rural economic stability. Uzbekistan is one of such countries: recent policy and sector analyses indicate that irrigation and drainage systems face pressure from ageing infrastructure, increasing repair costs, physical water scarcity and competition among agricultural, urban, industrial and environmental water users [3]. Therefore, the modernization of hydraulic structures cannot be reduced to replacing individual gates or repairing concrete surfaces; it requires a scientifically grounded transition toward integrated reliability management, where design, construction, operation, inspection, sediment control and digital monitoring are viewed as a single engineering chain. The urgency of this topic is also explained by dam and hydraulic-structure safety principles. ICOLD notes that dam design and construction cannot be treated as a "once-and-for-all" exercise, because structures require continuous supervision and inspection during their whole life to remain safe and functional [6]. Although this statement is often applied to large dams, its logic is equally valid for smaller hydraulic structures in irrigation networks, mountain streams, drainage channels and settlement-protection systems, because local failure of a regulator, culvert or embankment can cause water loss, erosion, flooding, canal-bank collapse or interruption of irrigation supply. In hydraulic-engineering education, this creates an important methodological requirement:

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students and young engineers should not learn hydraulic structures only as static drawings with dimensions, but as living technical systems whose performance changes with flow, sediment, operation, time and risk. The aim of this article is to formulate an integrated engineering approach for the design and operational reliability of hydraulic structures under variable hydrological and climatic conditions. To achieve this aim, the article addresses four research tasks: first, to analyse the functional role of hydraulic structures in water regulation and flood protection; second, to identify the main technical, hydraulic and operational factors that determine reliability; third, to systematize climate-resilient and lifecycle-oriented design principles; and fourth, to propose practical directions for improving design education and engineering practice in the context of Uzbekistan's irrigation and hydraulic infrastructure. The object of the study is hydraulic structures used in irrigation, drainage, flood protection and water-control systems, while the subject is the relationship between hydraulic performance, structural reliability, operational management and resilience criteria. The scientific novelty of the article lies in the integration of hydraulic calculation logic with lifecycle safety, sediment-aware operation, climate adaptation and digital monitoring into one methodological framework suitable for teaching and applied engineering analysis in the field of hydraulic structures. In addition, the article treats hydraulic structures as instruments for the rational use of irrigated land: where water is controlled with accuracy, soil salinization, waterlogging, canal seepage and unproductive evaporation can be reduced; where control is weak, the same land-resource potential may be degraded despite the presence of expensive infrastructure. Thus, the proposed approach connects hydraulic design with the broader goals of land productivity, water saving and sustainable territorial development.

MATERIALS AND METHODS

The research methodology is based on a qualitative engineering synthesis supported by comparative analysis of international technical literature, sectoral water-infrastructure guidance and principles of hydraulic-structure design. Instead of treating the article as a narrow laboratory experiment, the study follows a system-engineering logic: the hydraulic structure is considered as an element of a larger water-management network, and its reliability is evaluated through the interaction of inflow conditions, hydraulic geometry, structural capacity, foundation behaviour, operating rules, sediment regime, maintenance practice and emergency response. This methodological choice is justified by the nature of hydraulic structures themselves. A canal regulator, for instance, may satisfy design equations for discharge capacity, but still perform poorly if gate operation is delayed, if sediment blocks the opening, if downstream erosion undermines the apron, or if upstream water level fluctuates beyond the tolerance required for proportional distribution. Similarly, a spillway may have sufficient theoretical capacity, yet its practical safety depends on approach-flow conditions, debris passage, aeration, energy dissipation and the stability of downstream protection. Therefore, the study applies an integrated assessment matrix composed of five analytical blocks: hydraulic adequacy, structural and geotechnical stability, operational controllability, sediment and erosion compatibility, and climate-resilience capacity. Hydraulic adequacy refers to the ability of the structure to pass, retain, divert, measure or regulate the required discharge without causing unacceptable afflux, overtopping, cavitation, excessive velocity, flow separation or loss of command level. Structural and geotechnical stability includes resistance to hydrostatic pressure, uplift, seepage, sliding, overturning, bearing-capacity failure, settlement, cracking, reinforcement corrosion and fatigue of mechanical components. Operational controllability refers to the capacity of gates, hoists, sensors, staff gauges, automation systems and operating procedures to maintain target water levels and discharges under real field conditions. Sediment and erosion compatibility considers whether the structure can function under actual bed load, suspended load, deposition zones, scour potential and channel morphology. Climate-resilience capacity evaluates whether the structure can tolerate a wider range of hydrological conditions, including drought-related low flows, flood peaks, sudden storm runoff, changes in seasonal water availability and emergency drawdown or diversion requirements. The study also uses document-based technical interpretation. FAO sources on canal hydraulics and small hydraulic structures are used for understanding the functional classification and hydraulic behaviour of water-control structures in irrigation systems [4], [7]. World Bank sources are used for resilience-oriented water-infrastructure design and for contextualizing Uzbekistan's irrigation and drainage challenges [1], [3]. ICOLD materials are used to frame the lifecycle safety concept, particularly the principle that inspection and monitoring remain essential throughout the operational life of dams and hydraulic structures [6], [8]. UNESCO water-security publications are used to justify the broader social and developmental significance of hydraulic infrastructure,

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because water infrastructure supports livelihoods, economic development, food and energy security and environmental integrity [9]. Based on these sources, the article develops a conceptual reliability pathway: hydrological loading creates hydraulic action; hydraulic action produces structural, geotechnical and operational stresses; these stresses interact with ageing, sediment, maintenance and human decisions; and the final outcome appears as safe operation, reduced performance, partial failure or emergency. This pathway allows the study to identify not only direct failure mechanisms, such as overtopping or structural cracking, but also indirect failures, such as inaccurate water distribution, loss of irrigation command, excessive seepage, sedimentation of canal sections, downstream erosion, gate jamming or inability to respond quickly during flood events. The method does not claim to replace detailed numerical modelling, physical hydraulic modelling or site-specific design calculations; rather, it provides a scientific framework for organizing those calculations and interpreting their engineering meaning. In practical design, this framework can be connected with standard hydraulic equations for open-channel flow, weir and orifice discharge, stilling-basin sizing, seepage analysis, stability checks and reinforced-concrete design. In teaching, it can be used to help students move from isolated formulas toward integrated engineering judgement. The methodological strength of this approach lies in its suitability for real hydraulic-engineering practice, where designers rarely face ideal conditions and must balance mathematical accuracy with incomplete data, field constraints, budget limits, construction quality and long-term operation. The limitation of the study is that it does not provide a numerical case calculation for one specific structure; instead, it develops a generalized model applicable to common hydraulic structures in irrigation and flood-protection systems. Nevertheless, this limitation is intentional, because the article aims to support the scientific foundations of the “Hydraulic Structures” course and to provide a broad research basis for future detailed calculations, local case studies and digital modelling projects. For methodological clarity, the study also distinguishes between design reliability and operational reliability. Design reliability is the capacity embedded in geometry, materials and structural layout; operational reliability is the achieved performance under the behaviour of operators, water users, maintenance teams and hydrological conditions. A structure with high design reliability may lose operational reliability if gates are corroded, measuring devices are absent, sediment removal is delayed or emergency communication is weak.

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Conversely, a modest structure may perform acceptably when inspection, gate adjustment and preventive maintenance are systematic. This distinction is particularly useful for applied research in developing irrigation systems, because it prevents the common mistake of blaming only design when the real cause may be operation, or blaming only operation when design has insufficient freeboard, energy dissipation or seepage protection. The methodological framework therefore evaluates the whole chain from design assumption to field performance.

RESULTS

The results of the analysis show that the reliability of hydraulic structures is formed by a combination of design correctness, construction quality, operational discipline and adaptive management, and that failure or performance decline usually emerges from the accumulation of several small mismatches rather than from one isolated technical error. The first major result is that hydraulic adequacy must be assessed not only by maximum design discharge, but also by the structure's ability to maintain stable water levels and distribution accuracy under partial flows, fluctuating inflows and operational transitions. In irrigation systems, many structures operate most of the time under non-maximum discharges; therefore, their practical value depends on controllability at ordinary and low flows as much as on flood capacity. FAO's explanation of canal cross-regulators demonstrates that different structures produce different combinations of control level and water-depth variation, which confirms that hydraulic design must consider operational flexibility, not only theoretical conveyance [4]. This result is important for regions where irrigation scheduling is sensitive to water shortages, because poorly controlled structures can cause upstream over-supply, downstream deficit, waterlogging, canal-bank erosion or disputes among users. The second result is that structural reliability cannot be separated from hydraulic regime. Excessive velocities downstream of gates, drops and spillways can create scour that undermines aprons and sidewalls; unbalanced water pressure may increase uplift beneath slabs; seepage through joints or foundations can develop piping; and sediment accumulation can change effective cross-sections, causing water levels to rise above expected values. Therefore, inspection should not focus only on visible concrete damage, but also on hydraulic symptoms: unusual turbulence, local vortices, erosion holes, sediment bars, seepage boils, gate vibration and uneven flow distribution. ICOLD's position that dams and hydraulic structures require continuous

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supervision during their lifecycle supports this result and highlights that safety is an ongoing process rather than a final design certificate [6]. The third result is that sediment is one of the most underestimated factors in the long-term performance of hydraulic structures. In mountain, foothill and irrigation environments, sediment affects intakes, canals, settling basins, regulators and culverts by reducing capacity, increasing abrasion, blocking gates, changing flow direction and intensifying local scour. If design treats water as a clean fluid while the actual canal carries high suspended or bed load, the structure may gradually lose its intended function even if its concrete body remains intact. This is especially relevant for small and medium hydraulic structures because maintenance resources are often limited, and sediment removal may be irregular. The fourth result is that climate variability changes the meaning of "design reliability." A structure designed only for historical average conditions may become insufficient when extreme rainfall events, snowmelt changes, drought sequences or sudden flood peaks become more frequent or less predictable. The World Bank's resilience guidance emphasizes the need to incorporate climate uncertainty into engineering design and decision-making, which means that hydraulic structures should be evaluated through scenarios rather than through one deterministic value alone [1], [5]. The fifth result concerns Uzbekistan's irrigation and drainage context. Sectoral analysis indicates that the country faces rising costs related to ageing water infrastructure and needs to revise operating regimes and safety standards according to modern best practice [3]. This creates a practical requirement to prioritize structures whose failure would cause the greatest economic, social or safety losses: main-canal regulators, pumping-station outlets, siphons, aqueducts, culverts under roads, flood-protection embankments, spillways and drainage collectors near settlements. The sixth result is that digital monitoring can significantly improve reliability if it is introduced not as decorative modernization, but as an operational decision-support system. Water-level sensors, gate-position indicators, discharge estimation, remote alarms, drone inspection and GIS-based asset mapping can help detect abnormal conditions earlier than traditional periodic inspection alone. However, digitalization must be linked with maintenance authority, trained personnel and emergency protocols; otherwise, sensors will only collect data without reducing risk. The seventh result is that ecological and social criteria are becoming part of engineering reliability. A hydraulic structure that delivers water but destroys downstream habitat, blocks sediment continuity, interrupts fish movement or

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increases flood risk for nearby communities cannot be considered fully successful in modern water engineering. UNESCO's water-security framing connects water infrastructure with livelihoods, economic development, food and energy security and environmental integrity, which confirms that hydraulic structures must be evaluated through broader development outcomes [9]. The final result is the proposed integrated reliability model. According to this model, the reliability of a hydraulic structure may be expressed conceptually through five interdependent dimensions: hydraulic performance, structural safety, operational responsiveness, sediment-erosion balance and climate-ecological adaptability. A weakness in one dimension can reduce the effectiveness of all others. For example, a structurally strong regulator with poor gate operation can still fail functionally; a well-automated structure with poor downstream protection can still cause erosion; a hydraulically efficient canal structure without sediment-management planning can lose capacity; and a newly reconstructed facility without climate-resilience criteria may become outdated before the end of its expected service life. Thus, the most important result of the study is that hydraulic-structure reliability is not a single calculation, but a managed condition maintained through design, construction, monitoring, operation and timely rehabilitation. The analysis also shows that the economic effect of reliability is often hidden: when a regulator maintains the required upstream level, water distribution appears ordinary, but when it fails, the cost is seen through crop stress, emergency excavation, road damage, canal-bank restoration and conflict among water users. For this reason, preventive reliability management is cheaper than repeated emergency repair, even if preventive measures require regular inspection, training and modest digital equipment. The proposed model can be converted into a practical checklist for field engineers: design discharge conformity, freeboard condition, gate serviceability, concrete and reinforcement condition, foundation seepage, sediment deposition, downstream scour, measurement equipment, access for maintenance, emergency closure possibility and social exposure of downstream territory. Such a checklist would create a bridge between scientific design principles and everyday water-management practice.

DISCUSSION

The discussion of these results shows that the discipline of hydraulic structures should evolve from a narrowly construction-oriented subject into an interdisciplinary

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engineering field that connects hydraulics, hydrology, geotechnics, reinforced concrete, mechanics, environmental science, risk management and digital technology. Traditional teaching often begins with classification: dams, spillways, intake structures, canals, regulators, culverts, aqueducts, siphons, drops, stilling basins, drainage structures and protective embankments. This classification is necessary, but it becomes scientifically incomplete when students do not understand why similar structures behave differently under different flow regimes, sediment conditions and maintenance cultures. For example, two canal regulators may have identical geometric dimensions, but the one operating in a sediment-heavy canal with irregular gate adjustment will deteriorate faster and distribute water less accurately than the one operating under stable sediment and disciplined monitoring. This difference cannot be explained by geometry alone; it requires systems thinking. From this perspective, hydraulic design should include three layers. The first layer is the normative-calculation layer: determination of design discharge, water levels, velocities, hydraulic losses, energy dissipation, seepage length, stability coefficients and structural reinforcement. The second layer is the operational layer: gate rules, inspection frequency, sediment flushing, emergency closure, maintenance access, staff training and communication between upstream and downstream operators. The third layer is the adaptive layer: climate scenarios, reserve capacity, modular rehabilitation, digital sensors, ecological flow requirements and risk-based prioritization. Many hydraulic failures occur because the first layer exists on paper, while the second and third layers are weak in practice. This is why lifecycle management is now a core concept in modern hydraulic engineering. ICOLD's safety principles are especially important here: if even large dams, designed with high technical standards, require continuous inspection and supervision, then smaller irrigation and flood-protection structures with lower budgets and more frequent field exposure require no less attention [6], [8]. In Uzbekistan, this issue has practical importance because water infrastructure supports irrigated agriculture across arid and semi-arid landscapes where losses in conveyance and regulation quickly become economic losses. The World Bank's Uzbekistan irrigation and drainage analysis notes challenges connected with ageing infrastructure, physical water constraints and the need for updated safety and operational standards [3]. This does not mean that every structure must be replaced immediately; rather, it means that rehabilitation should be prioritized according to risk and system importance. A minor farm turnout and a main-

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canal regulator cannot be treated equally. A culvert under a rural road may look small, but if blocked during intense rainfall it can cause road failure and local flooding. A drainage collector may not be visually impressive, but if it loses capacity, groundwater levels may rise and soil salinization may increase. Therefore, hydraulic-structure management should use an asset hierarchy: critical, important, ordinary and low-risk structures. Critical structures require regular instrumental monitoring, emergency plans and priority financing; ordinary structures may rely on routine inspection and preventive repair. Another important discussion point is climate resilience. Some engineers still interpret climate adaptation as an abstract environmental slogan, but in hydraulic structures it has very concrete design meaning. It affects spillway capacity, freeboard, culvert sizing, scour protection, intake location, drainage capacity, emergency bypass arrangements and the selection of materials resistant to wetting-drying cycles, abrasion and chemical exposure. The World Bank's resilient design approach supports the use of decision frameworks that account for uncertainty, rather than assuming that past hydrological data fully represent future conditions [1], [5]. For teaching and applied research, this suggests that students should be trained to test structures under several scenarios: normal flow, low flow, design flow, flood flow, sediment-blocked condition and emergency operation. Such scenario-based thinking is more realistic than a single "correct answer" calculation. Sediment management also deserves stronger attention in hydraulic-structure curricula. In many canal systems, sediment is treated as a maintenance problem after construction, but it should be part of design from the beginning. Intake structures need proper approach alignment and sediment exclusion; canals need velocity ranges that avoid both deposition and erosion; settling basins require realistic flushing arrangements; regulators should minimize zones of dead water; and downstream protection must account for local scour under gate openings. If sediment is ignored, expensive concrete structures may become inefficient within a short period. The same is true for operation. Even the best-designed gate will not maintain water distribution if operators lack reliable water-level information or if gate adjustments are made by habit rather than measured data. Digital technologies can help, but they are not magic; hydraulics is not impressed by Wi-Fi. Sensors must be calibrated, data must be interpreted, and responsible staff must be able to act. A simple staff gauge read correctly every day may be more useful than an expensive sensor network that nobody maintains. Therefore, modernization should combine appropriate technology with

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institutional discipline. Ecological reliability is another emerging issue. Older hydraulic structures were often designed mainly for human water use, but modern engineering must also consider downstream environmental flow, fish movement, sediment continuity, water quality and landscape stability. This does not mean that every irrigation structure becomes an ecological park, but it does mean that long-term engineering success depends on avoiding unintended environmental degradation. UNESCO's water-development perspective links water infrastructure with prosperity, livelihoods, food and energy security and environmental integrity, which supports the idea that hydraulic structures must serve both technical and social-environmental objectives [9]. For Uzbekistan and Central Asia more broadly, this integrated view is especially relevant because water allocation, agricultural productivity, energy needs and ecological sustainability are tightly connected. The discussion also reveals a methodological implication for scientific research: future studies should combine field inspection, remote sensing, hydraulic modelling and economic analysis. For example, a research project on a canal regulator should not stop at calculating discharge coefficient; it should also measure actual upstream and downstream levels, record gate operation, map sediment deposition, inspect concrete damage, evaluate water-delivery accuracy and estimate the economic effect of modernization. Such research would be more useful for regional water authorities and more valuable for engineering education. In this sense, the article supports a shift from descriptive hydraulic-structure study toward performance-based hydraulic engineering. The same principle should be applied to graduation projects and course papers: drawings and calculations should be accompanied by a short reliability diagnosis, expected maintenance plan and risk scenario. Otherwise, the project may look beautiful on an A1 sheet but behave badly in the canal, and concrete does not care how elegant the title block is. A scientifically mature hydraulic-engineering curriculum should therefore train students to ask three questions about every structure: What hydraulic function must it perform? What can make it lose that function? What monitoring and maintenance actions will keep that function stable during the structure's service life? These questions are simple, but they protect engineering thinking from superficial design.

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CONCLUSION

The study concludes that hydraulic structures must be understood as integrated, lifecycle-based and risk-sensitive engineering systems rather than as isolated concrete or metal facilities. Their reliability depends on the interaction of hydraulic capacity, structural resistance, foundation stability, sediment behaviour, gate operation, maintenance practice, monitoring quality, climate resilience and ecological compatibility. The analysis confirms that a structure can be formally "designed" but still function poorly if real operating conditions differ from design assumptions, if sediment is not managed, if inspection is irregular, or if climate-related extremes exceed historical expectations. International guidance on resilient water infrastructure, canal-control structures and dam safety supports the need for adaptive design, continuous supervision and scenario-based assessment [1], [4], [6]. For Uzbekistan, where irrigation and drainage infrastructure remains essential for agriculture and where ageing assets and water scarcity create growing pressure, the modernization of hydraulic structures should be implemented through risk-based prioritization, improved operational rules, digital monitoring, sediment-control planning and periodic safety evaluation [3]. The article proposes that the "Hydraulic Structures" course should place greater emphasis on functional reliability, not only on typology and calculation. Students should learn to connect discharge equations with field operation, concrete design with seepage and erosion, gate mechanics with water distribution, and climate scenarios with safety margins. The main practical recommendation is to introduce an integrated reliability passport for important hydraulic structures, including data on design discharge, current hydraulic capacity, structural condition, sediment risk, inspection schedule, automation level, emergency role and rehabilitation priority. Such a passport would help engineers, operators and water-management authorities move from reactive repair to preventive and adaptive management. The scientific contribution of the article is the formulation of a five-dimensional reliability model consisting of hydraulic performance, structural safety, operational responsiveness, sediment-erosion balance and climate-ecological adaptability. This model can be used in teaching, preliminary design review, field assessment and future applied research. In final terms, the future of hydraulic structures depends not only on stronger concrete or larger gates, but on smarter engineering judgement: structures must be designed for water, operated for people, maintained for safety and adapted for the future.

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