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RISK-BASED MONITORING AND CLIMATE-RESILIENT OPERATION OF HYDRAULIC ENGINEERING STRUCTURES IN ARID AND SEMI-ARID REGIONS

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Abstract

Hydraulic engineering structures are no longer evaluated only as static civil works designed to pass a calculated discharge or to store a planned volume of water; in the present hydrological reality they must be treated as dynamic, risk-sensitive and climate-exposed systems whose safety depends on the interaction between design assumptions, operational discipline, sediment processes, material ageing, emergency preparedness and institutional monitoring. This article investigates the scientific and practical basis for risk-based monitoring and climate-resilient operation of dams, canals, spillways, intake structures, irrigation regulators and river-bank protection works in arid and semi-arid regions where water scarcity, seasonal flow variability, sediment load and extreme hydrological events often occur simultaneously. The relevance of the study is strengthened by the fact that international assessments increasingly connect water infrastructure safety with climate adaptation, disaster risk reduction and long-term water security; the IPCC notes that climate-induced changes in the water cycle are already affecting human and natural systems, while the World Bank has emphasized the need to incorporate climate-change impacts into dam design and safety processes [1], [2]. The methodological basis of the paper is a synthetic engineering analysis combining literature review, risk-matrix evaluation, monitoring-parameter classification and comparative interpretation of hydraulic failure mechanisms. The article argues that the most reliable operation model for modern hydraulic structures is not a single-factor inspection regime but an integrated monitoring framework that combines hydrological observation, structural instrumentation, sediment diagnostics, hydraulic-capacity verification and operational decision thresholds. The results show that the major technical risks in arid-region hydraulic systems arise from three interlinked groups: hydrological non-stationarity, structural deterioration and management delay. The study proposes a practical monitoring hierarchy in which critical indicators such as seepage growth, deformation, uplift pressure, spillway capacity reduction, downstream erosion, gate

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malfunction and sediment accumulation are ranked according to probability, consequence and detectability. The scientific novelty of the article lies in presenting hydraulic infrastructure operation as a risk-informed adaptive cycle rather than as a periodic maintenance routine. This approach is especially important for countries and basins where irrigation, hydropower, flood protection and drinking-water supply depend on the same hydraulic system. The article concludes that climate-resilient hydraulic engineering requires stronger integration between design norms, real-time monitoring, reservoir rule curves, emergency action plans and life-cycle rehabilitation financing.

Keywords: Hydraulic engineering structures; dam safety; climate resilience; risk-based monitoring; spillway capacity; sedimentation; irrigation canals; structural reliability; hydrological extremes; water infrastructure management.

Introduction

Hydraulic engineering has historically been one of the most decisive branches of civil and environmental engineering because it transforms natural water regimes into regulated systems serving agriculture, hydropower, flood protection, navigation, drinking-water supply and ecosystem management. However, the design philosophy that dominated much of the twentieth century was based on the assumption that past hydrological records could be used as a sufficiently stable foundation for future design, operation and maintenance. In arid and semi-arid regions this assumption is becoming increasingly fragile because rainfall intensity, snowmelt timing, drought duration, flood peaks, sediment transport and water-demand patterns are changing in ways that challenge traditional hydraulic safety margins. The IPCC assessment of water systems states that climate-induced changes in the water cycle are producing present and future risks for human and natural systems, and water-related risks increase with higher levels of global warming [1]. For hydraulic engineering, this means that a canal, dam, spillway or intake structure designed according to historical discharge series may face future operating conditions that differ not only in magnitude but also in frequency, seasonality and compound character. In practical terms, a reservoir may receive less annual inflow but more intense flood pulses; an irrigation canal may operate under longer low-flow periods but still experience sudden bank-

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damaging surges; a river-regulation structure may be exposed to both bed degradation and sediment blockage; and a flood-protection embankment may be weakened by drought cracking before being tested by an extreme flood. The International Commission on Large Dams has recently placed dams and reservoirs within the wider agenda of energy transition and climate adaptation, emphasizing the role of safe and sustainable storage for food security, flood control, drought resilience and energy systems [3]. This confirms that hydraulic structures should no longer be regarded merely as isolated engineering objects; they are strategic elements of national and regional water security. At the same time, the World Bank's recent technical guidance on dam safety and resilience stresses the need for analytical tools that incorporate climate-change impacts and related risks into both the design of new dams and the adaptation of existing dams [2]. These positions are highly relevant for arid regions, including Central Asia, where irrigated agriculture, energy generation and settlement safety depend on ageing hydraulic networks, transboundary rivers and seasonally uneven water availability. The core scientific problem addressed in this article is therefore the gap between traditional maintenance-based operation and modern risk-based, climate-resilient management of hydraulic engineering structures. In many systems, inspections are still carried out according to fixed schedules, while risk is treated reactively after visible damage appears. This approach is insufficient because the most dangerous processes in hydraulic structures often develop gradually and remain invisible until a threshold is crossed: internal erosion may progress before turbidity increases at seepage outlets; uplift pressure may rise before sliding instability becomes evident; spillway capacity may decline due to sediment, vegetation or gate unreliability before a design flood arrives; and canal seepage may weaken foundations before surface cracks are noticed. A scientifically grounded operational system must therefore connect monitoring indicators with risk interpretation and decision rules. The purpose of this article is to develop an integrated scientific argument for risk-based monitoring and climate-resilient operation of hydraulic engineering structures in arid and semi-arid environments. The objectives are to classify the main technical hazards affecting hydraulic structures, to identify monitoring indicators that reveal early-stage deterioration, to evaluate the relationship between hydrological non-stationarity and structural reliability, and to propose an adaptive operational framework that can be used for dams, canals, regulators, spillways and river-training works. The hypothesis of the article is that hydraulic

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structure safety can be significantly improved when monitoring is organized not as a descriptive recording of physical parameters but as a decision-oriented system in which each parameter is connected to a risk level, consequence category and operational response. In this sense, the article contributes to hydraulic engineering by joining classical structural safety, hydrology, sediment management and disaster risk reduction into one practical model. This is important because recent international water-security reports show growing attention to climate-resilient infrastructure, irrigation modernization and flood management as part of global water-financing priorities [4]. Thus, the relevance of the topic is not theoretical decoration; it is the engineering equivalent of checking the roof before the rain, not while holding a bucket under the leak.

MATERIALS AND METHODS

The methodological structure of this study is based on analytical synthesis, comparative technical evaluation and risk-based classification of monitoring indicators. Since the article is conceptual and engineering-oriented rather than experimental in a laboratory sense, the material base consists of internationally recognized scientific literature, dam-safety guidance, hydraulic-structure design principles, climate-risk assessments and practical operation logic used in water infrastructure management. The first methodological layer is the system approach: each hydraulic structure is considered not as a separate object but as a component of a water-management chain that includes catchment hydrology, reservoir operation, hydraulic conveyance, structural resistance, downstream consequences and institutional response. This is essential because failure or underperformance rarely arises from one isolated cause. For example, a spillway incident may be caused not only by insufficient concrete strength but by a combination of underestimated flood inflow, sediment accumulation near the intake, delayed gate operation, poor debris management and lack of emergency communication. The second methodological layer is hazard identification. In the context of hydraulic engineering structures, hazards are divided into hydrological hazards, hydraulic-capacity hazards, geotechnical hazards, structural-material hazards, mechanical-equipment hazards, sedimentation hazards, environmental hazards and human-management hazards. Hydrological hazards include extreme floods, prolonged droughts, sudden snowmelt, rain-on-snow events, altered seasonal inflow and climate-driven non-stationarity.

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Hydraulic-capacity hazards include insufficient spillway discharge capacity, canal overtopping, outlet blockage, energy-dissipation failure, erosion near stilling basins and backwater effects. Geotechnical hazards include slope instability, foundation piping, differential settlement, uplift pressure, liquefaction-prone layers and bank deformation. Structural-material hazards include concrete cracking, reinforcement corrosion, abrasion, freeze-thaw deterioration, joint leakage and masonry degradation. Mechanical-equipment hazards include gate jamming, hoist failure, power-supply interruption, sensor malfunction and lack of redundancy. Sedimentation hazards include reservoir storage loss, intake blockage, abrasion of turbines and pumps, reduction of flood-routing volume and changes in downstream morphology. The third methodological layer is monitoring classification. The article classifies monitoring parameters into five groups: hydrological parameters, structural parameters, seepage and geotechnical parameters, hydraulic-performance parameters and operational-response parameters. Hydrological parameters include inflow, outflow, reservoir level, precipitation, snowpack, groundwater interaction and forecasted flood volume. Structural parameters include crest settlement, horizontal displacement, crack width, joint movement, concrete temperature and vibration. Seepage and geotechnical parameters include piezometric level, uplift pressure, seepage discharge, seepage turbidity, pore pressure, slope movement and filter performance. Hydraulic-performance parameters include spillway rating curves, gate opening accuracy, canal roughness, flow velocity, local scour depth, sediment concentration and energy-dissipation efficiency. Operational-response parameters include inspection frequency, alarm thresholds, staff response time, emergency action plan readiness, backup power availability and communication with downstream authorities. The fourth methodological layer is a qualitative risk matrix in which risk is interpreted as a function of probability and consequence, while detectability is treated as an additional management factor. A high-probability, low-consequence defect, such as minor surface erosion on a canal slope, may require routine maintenance, whereas a low-probability, high-consequence event, such as internal erosion in an embankment dam, requires strict monitoring because delayed detection may transform a local defect into catastrophic failure. The fifth methodological layer is scenario comparison. Three operational scenarios are considered: traditional periodic inspection, enhanced parameter monitoring and adaptive risk-based operation. In the traditional scenario, inspections occur according to fixed time

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intervals and mainly register visible defects. In the enhanced monitoring scenario, instrumentation and hydrological data are added, but decisions may still remain separated from the data stream. In the adaptive risk-based scenario, each monitored parameter is connected to threshold levels and predefined management actions. This scenario is treated as the scientifically preferable model because it reduces the gap between observation and response. The methodological logic is consistent with modern disaster-risk thinking, where learning from past disasters and identifying systemic causes are considered necessary for more effective risk reduction [5]. It also reflects the World Bank's emphasis on incorporating climate impacts and adaptation measures into dam-safety work [2]. Finally, the article uses engineering generalization rather than site-specific numerical modelling. This choice is justified because the purpose is to develop a transferable conceptual framework applicable to different hydraulic structures in arid and semi-arid regions. Nevertheless, the proposed framework can later be converted into numerical tools using probabilistic hydrology, finite-element structural analysis, hydraulic simulation, remote sensing and digital twin technologies.

RESULTS

The analytical results show that the safety and functionality of hydraulic engineering structures in arid and semi-arid regions depend on the interaction of three dominant risk clusters: hydrological non-stationarity, structural deterioration and operational-management delay. Hydrological non-stationarity is the first and most fundamental cluster because it changes the external loading conditions under which hydraulic structures operate. In older design practice, the design flood, normal pool level, dead storage, sediment allowance and canal discharge were commonly estimated from historical observations. However, when rainfall intensity, drought cycles, snowmelt timing and catchment land use change, the historical record becomes less reliable as the sole basis for future operation. This does not mean that old data are useless; rather, it means that old data must be reinterpreted through updated climate scenarios, regional hydrological trends and uncertainty ranges. In dams and reservoirs, hydrological non-stationarity affects flood-routing capacity, reservoir rule curves, spillway reliability and drought-storage allocation. In canals, it affects freeboard adequacy, sediment transport, seepage losses and water-delivery stability. In river-bank protection works, it affects flow velocity, attack angle, scour depth and bank

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saturation. The second cluster, structural deterioration, is particularly serious because many hydraulic structures operate for decades under wetting-drying cycles, seepage forces, sediment abrasion, chemical exposure, mechanical vibration and foundation movement. Concrete spillways may experience cavitation and abrasion when high-velocity flows carry sediment particles. Embankment dams may develop internal erosion if filters are inadequate or if seepage paths are created by cracks, animal burrows, root systems or construction defects. Canal linings may crack due to settlement, temperature changes or sulfate attack, causing seepage that weakens the subgrade and increases water losses. Gates and hoists may become unreliable if corrosion, insufficient lubrication or electrical failure are not addressed. The third cluster, operational-management delay, is often underestimated but can be decisive. A structure with moderate physical deterioration may remain safe if monitoring is accurate and response is timely, whereas a technically stronger structure may fail under poor operation if warning signs are ignored. The results therefore indicate that the main weakness of conventional maintenance systems is not the absence of inspections but the absence of risk interpretation. Inspection reports often describe defects without ranking them according to consequence, probability and urgency. For example, a small crack in a non-critical concrete parapet and cloudy seepage emerging near the downstream toe of an embankment may both be recorded as defects, but their risk meanings are entirely different. The proposed monitoring hierarchy resolves this problem by classifying indicators into four levels. Level I indicators are routine condition indicators, such as surface erosion, vegetation growth, minor concrete scaling, small sediment deposits and local canal-bank irregularities. These indicators require scheduled maintenance but do not immediately threaten system safety. Level II indicators are warning indicators, such as increasing seepage quantity, repeated gate vibration, moderate crack growth, local settlement, rising piezometric levels and noticeable changes in flow pattern. These require technical inspection and short-term corrective planning. Level III indicators are critical indicators, such as turbid seepage, rapid deformation, abnormal uplift pressure, uncontrolled leakage, spillway blockage, deep local scour, gate inoperability during high-flow season and reservoir level exceeding rule-curve limits. These require immediate management action and possible emergency preparation. Level IV indicators are emergency indicators, such as progressive piping, rapid slope failure, uncontrolled overtopping, structural collapse of energy dissipators, complete gate failure during flood passage and

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downstream breach formation. These require activation of emergency action plans and direct protection of the population and assets downstream. The second major result is the identification of monitoring parameters with the highest diagnostic value. For embankment dams, the most important early-warning parameters are seepage discharge, seepage turbidity, pore pressure, crest settlement and downstream slope movement. For concrete dams and spillways, the key parameters are uplift pressure, joint movement, crack width, spillway-surface condition, cavitation damage and stilling-basin scour. For irrigation canals, the most useful indicators are seepage loss, lining crack pattern, bank deformation, sediment deposition, vegetation growth, control-gate accuracy and delivery-flow deviation. For river-bank protection structures, the critical indicators are toe scour, stone displacement, geotextile exposure, bank saturation, flow concentration and post-flood deformation. The third result concerns sedimentation. In arid and semi-arid basins, sediment is not a secondary maintenance inconvenience but a system-level risk. Sediment reduces reservoir storage, changes hydraulic gradients near outlets, blocks intakes, increases abrasion of mechanical equipment, reduces flood-routing capacity and modifies downstream sediment balance. International hydropower and dam-safety discussions increasingly treat sediment management as part of sustainable reservoir planning rather than as an optional cleaning activity [6]. The fourth result is that climate-resilient operation requires adaptive rule curves. A fixed reservoir rule curve may be suitable under stable hydrological conditions, but under changing flood and drought patterns reservoir operation must include seasonal forecasts, probabilistic inflow ranges, drought-priority rules and flood-buffer adjustments. This is especially important for multipurpose reservoirs where irrigation, hydropower and flood control objectives compete. The fifth result is that the most effective monitoring system is not necessarily the most expensive one. A reliable low-cost system with clear thresholds, trained personnel and regular interpretation may outperform a technologically advanced sensor network whose data are not integrated into decision-making. Therefore, the proposed framework emphasizes not only instruments but institutional discipline. The final result is summarized as follows: hydraulic structure safety is maximized when monitoring data, design assumptions, climate scenarios, maintenance planning and emergency preparedness are managed as one continuous adaptive cycle.

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DISCUSSION

The results demonstrate that the future of hydraulic engineering structures will depend less on the isolated strength of concrete, earthfill or steel and more on the intelligence of the operational system built around them. This does not reduce the importance of sound design; rather, it extends design responsibility into the whole life cycle of the structure. A dam designed with a high safety factor may still become vulnerable if sediment reduces active storage, spillway gates are not tested under realistic conditions, emergency communication is outdated and downstream development increases consequence exposure. Similarly, an irrigation canal with adequate initial lining may lose performance if seepage, vegetation, sediment deposition and gate miscalibration are not monitored together. The discussion therefore supports a transition from structure-centered safety to system-centered resilience. In the structure-centered model, engineers ask whether a wall, dam, spillway or canal can resist a prescribed load. In the system-centered model, engineers ask how the structure behaves under uncertain loading, how early deterioration is detected, how operators respond to warning signs, how downstream users are protected and how the structure is rehabilitated before risk becomes unacceptable. This transition is fully aligned with international disaster-risk thinking, which emphasizes that disasters are not merely natural events but outcomes of vulnerability, exposure and insufficient risk governance [5]. For hydraulic engineering, this means that flood, drought or sediment inflow becomes disastrous mainly when combined with weak infrastructure, poor monitoring or delayed decisions. The proposed risk-based monitoring framework also has direct implications for engineering education and professional training. Traditional curricula often separate hydrology, hydraulics, geotechnics, structural mechanics and water-management policy into different subjects. In practice, however, hydraulic safety problems are interdisciplinary. Internal erosion in an embankment dam cannot be understood without soil mechanics, seepage theory, construction quality and reservoir operation. Spillway failure cannot be understood without hydrology, hydraulic energy dissipation, concrete durability and gate mechanics. Canal collapse cannot be understood without flow hydraulics, soil saturation, sediment deposition and maintenance planning. Therefore, the modern hydraulic engineer should be trained not only to calculate but also to interpret system behaviour. The article's framework can be especially useful for arid regions because such regions experience the paradox of scarcity and extremity: annual water availability may be

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limited, yet damaging floods can still occur during short intense events. This paradox often leads to underestimation of flood risk because communities mainly remember drought, while hydraulic structures still need to pass rare but severe flows. The 2024 World Hydropower Outlook and other recent hydropower discussions highlight that hydropower performance is increasingly influenced by climate variability, drought and the need for flexible storage in energy systems [7]. While hydropower is only one part of hydraulic engineering, this evidence is important because reservoirs that support energy often also support irrigation, flood control and water supply. If reservoir operation is optimized only for energy generation during a dry period, flood-buffer capacity may be insufficient later; if it is optimized only for flood safety, irrigation supply may become unreliable. Thus, resilience requires transparent operating priorities and forecast-based adjustment. Another important issue is ageing infrastructure. Many dams, canals and regulators in water-scarce regions were built under older design standards, different land-use conditions and less demanding environmental requirements. Rehabilitation is often postponed because visible failure has not yet occurred. This is a dangerous logic. In hydraulic engineering, the absence of visible failure is not proof of safety; it may simply mean that hidden processes have not yet reached the surface. A risk-based monitoring system provides a rational basis for prioritizing rehabilitation budgets. Instead of distributing maintenance funds evenly or politically, managers can direct resources toward structures where probability, consequence and detectability indicate the highest risk. The proposed Level I-IV indicator hierarchy can also improve communication between engineers, administrators and emergency authorities. Engineers often speak in technical terms such as piezometric gradient, spillway rating curve or seepage turbidity, while administrators need clear decision categories. By translating technical indicators into operational levels, the framework reduces ambiguity and supports faster decisions. The role of digital technologies deserves careful discussion. Remote sensing, automated piezometers, drone-based inspection, real-time hydrological telemetry, acoustic monitoring, numerical modelling and digital twins can significantly improve hydraulic-structure management. However, technology should not become decorative. A sensor that produces continuous data but has no calibrated alarm threshold is a digital ornament, not a safety system. A drone image that is stored but not compared with previous deformation patterns has limited value. A hydraulic model that is not updated after sedimentation surveys may create false confidence.

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Therefore, digitalization must be tied to engineering judgement. In practical terms, each digital tool should answer three questions: what risk does it detect, what threshold triggers action and who is responsible for response? Without these answers, monitoring becomes a library of numbers rather than a safety mechanism. The environmental dimension should also be included. Climate-resilient operation should not mean maximizing structural control at the expense of downstream ecosystems. Reservoir flushing, environmental flows, fish passage, sediment continuity and water-quality control are part of sustainable hydraulic engineering. ICOLD's recent declarations and sustainability discussions increasingly place dams within broader climate and environmental responsibility, not only within energy and storage objectives [3]. This is important because a structure that is technically safe but environmentally destructive may create long-term basin instability. Finally, the economic implication is clear: preventive monitoring is cheaper than emergency reconstruction. A small investment in seepage measurement, gate testing, sediment survey and staff training can prevent losses many times larger than the monitoring cost. In this sense, risk-based operation is not an additional burden on hydraulic organizations; it is a financial protection mechanism. The discussion confirms the central thesis of the article: hydraulic structures in climate-sensitive regions must be operated as adaptive, monitored and risk-informed systems.

CONCLUSION

This article has examined risk-based monitoring and climate-resilient operation of hydraulic engineering structures as a necessary scientific and practical direction for modern water infrastructure management. The main conclusion is that the safety of dams, canals, spillways, regulators and river-protection works cannot be ensured by design calculations alone, especially under conditions of hydrological non-stationarity, sediment pressure, ageing materials and increasing water demand. Classical engineering design remains the foundation, but it must be complemented by continuous monitoring, risk interpretation, adaptive operation and timely rehabilitation. The study identified three dominant risk clusters: hydrological non-stationarity, structural deterioration and operational-management delay. Hydrological non-stationarity changes the magnitude, timing and uncertainty of inflow, drought and flood conditions; structural deterioration reduces the resistance of concrete, earthfill, lining, gates and foundations; operational-management delay transforms manageable

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defects into dangerous failures. The proposed monitoring hierarchy divides indicators into routine, warning, critical and emergency levels, thereby connecting technical observations with practical decisions. This approach is valuable because hydraulic safety depends not only on detecting defects but on understanding their risk meaning. The article also demonstrated that the most diagnostically important parameters differ by structure type: embankment dams require special attention to seepage, turbidity, pore pressure and deformation; concrete spillways require monitoring of uplift pressure, cavitation, cracking and stilling-basin scour; irrigation canals require observation of seepage, lining condition, sedimentation and gate accuracy; river-bank protection works require monitoring of toe scour, stone displacement, bank saturation and post-flood deformation. A further conclusion is that sedimentation must be considered a strategic risk in arid and semi-arid regions because it affects storage capacity, intake reliability, flood routing, abrasion and downstream morphology. The article argues that climate-resilient operation requires adaptive reservoir rule curves, forecast-based flood and drought management, emergency action planning and integration of monitoring data into rehabilitation priorities. Digital technologies can strengthen this system, but only when they are linked to calibrated thresholds, responsible personnel and clear response protocols. The scientific significance of the study lies in redefining hydraulic structure operation as a risk-informed adaptive cycle rather than a routine inspection practice. The practical significance lies in offering a framework that can be used by water-management agencies, dam operators, irrigation authorities, design institutes and engineering researchers. For arid and semi-arid regions, where water scarcity and extreme events exist side by side, such a framework is not optional; it is a condition for sustainable water security. The final recommendation is that hydraulic engineering institutions should revise their operational standards by incorporating climate-risk assessment, monitoring-based decision thresholds, sediment-management plans, emergency communication systems and life-cycle rehabilitation financing. Only then can hydraulic structures continue to perform their essential functions in a future where the river does not read our old design manual.

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