Review

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Emerging Reliability Challenges of Spillway Discharging Systems in Aging Hydroelectric Dams

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Abstract

Factors such as asset aging, climate change affecting hydrological events and the growing demand in electricity are placing huge pressure on hydroelectric infrastructures, including dams, whose most important and critical component is the spillway, which operates through a system of discharge gates. This research aims to present the technical, environmental and functional parameters and issues affecting this system, highlighting the causes of their degradation and proposing solutions to improve their service life and their reliability. A literature review has been made to identify the challenges related to reliability and durability of the system. In addition, a case study based on real-world data was made to support and reveal the problems related to the spillway gates system. What sets this research apart is its integration of theoretical studies with a practical case study, supporting the proposed theories and uncovering potential hidden factors. Following the identification of key challenges, new updated and adaptable solutions explored world widely will be recommended to develop in future research.

Keywords: dams; spillways; discharge gates; spillway gates; asset aging; asset management; life cycle management (LCM); reliability, availability, maintainability (RAM); maintenance; technological obsolescence; climate change; flood control; globalization; dam safety; hydropower; industry 4.0; digital twins; simulations; artificial intelligence; machine learning; anomaly detection; structural integrity; fatigue; vibration; risk analysis

1. Introduction

Globally, the leading source of renewable energy is hydropower, with 16% of total electricity production [1]. Most hydropower dams were installed and adapted in the early years of the 20th century, and this aging raises concerns because signs affecting safety, environmental sustainability and energy efficiency started to be seen, requiring an increase in investments concerning adaptation and modernization [2]. And one of the most crucial parts of a dam is the spillway, which is to protect the infrastructures and downstream communities by managing excess water to prevent reservoir overflow during events such as floods or plant shutdowns. As shown in Figure 1, a spillway mainly consists of gates that discharge water to regulate the flow, ensuring effective flood management and minimizing the risk of overflow [3]. And for a real-world example, the Carillon spillway located in Quebec (Canada), is 239 meters long and 31 meters high. It has 12 heated and remotely operated discharge gates, each 15.24 meters wide with a maximum opening of 8 meters [4].

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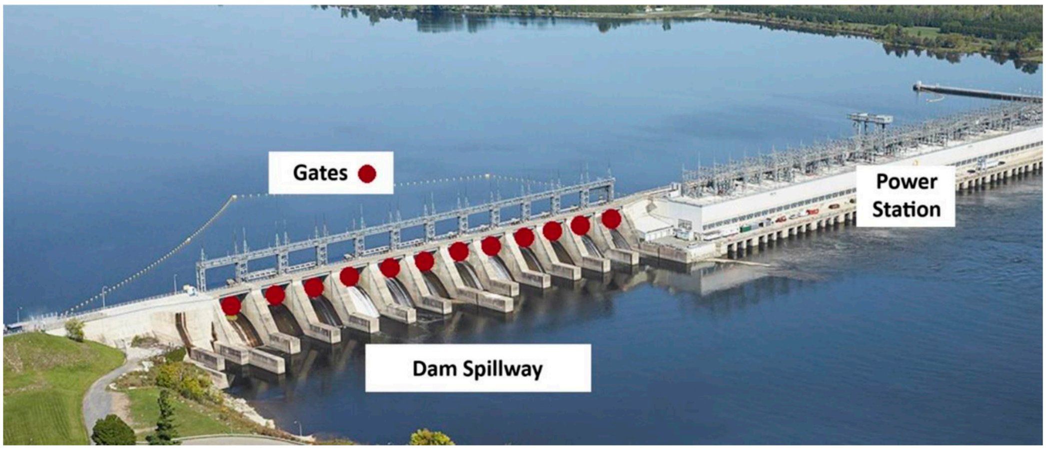

Figure 1. The Carillon Dam; Hydro-Québec.

In dams, extreme hydrological events, such as torrential rain, rapid snowmelt, or a prolonged storm, and the shutdown of turbine-generator units, either for maintenance or due to grid overload, preventing water from being turbinated, can cause a rapid increase in water inflows into the reservoir. And in hydroelectric dams, when these inflows exceed storage capacity, the flood risk increases significantly. Therefore, to manage such an event, a flood management process begins. The excess water must then be discharged through the spillway to avoid exceeding reservoir capacity [5].

Figure 2 illustrates a simplified flood management procedure.

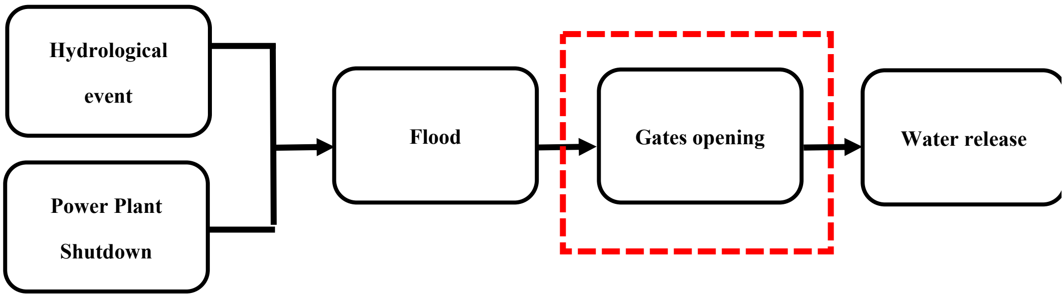

Figure 2. Simplified flood management process.

This article focuses on the discharging spillways gates systems responsible for this critical step, as it relieves pressure on the dam while reducing downstream flood risks, but must be carefully planned to avoid generating excessive flows that could damage infrastructure or riverside communities.

Multiple factors impact these spillway systems, including the aging of dams and their components, which has a direct impact, and the growing demand for electricity, which has an indirect impact, and climate change, which alters hydrological patterns and increases the frequency of extreme weather events, thereby affecting reservoir levels and spillway operations.

Currently, the most crucial factor impacting spillway systems is the aging of spillway systems having a direct impact on their reliability and performance. As assets begin to deteriorate in a complex system like a spillway, assessing overall reliability becomes increasingly challenging. This complexity arises from a combination of repairable and non-repairable failures, the presence or absence of redundancy, and the interactions between subsystems arranged in parallel or in series, some of which may influence each other, while others do not. Additionally, components do not age at the same rate or in the same way, whether they are structural, electrical, mechanical, or related to automation.

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For the indirect impact, the growing demand for electricity, driven by globalization, industry 4.0 [6], and the widespread adoption of electric vehicles [7], is placing increased stress on hydroelectric systems. The turbine-generator units will start running on full power, and because of the increase in stress and aging problems, it will lead to outages or failures, forcing water to be redirected to reservoirs, and when these reservoirs reach capacity, spillway gates must be activated to evacuate the excess water, increasing their operational frequency and wear. And in certain situations, where water flow is slow and dams don't possess hydroelectric power stations but are connected to a series of power stations downstream, their spillway gates must be activated to redirect the water to these stations so it can satisfy the needs in energy.

Thus, among the largest producers of hydropower: Canada, Brazil, and Norway have infrastructures that were built to endure each country's specific geographic and hydrological contexts. For example, Canada widely uses medium-head systems with underground power stations, while Brazil combines high-capacity dams with run-of-river facilities in the Amazon region [8]. But what's problematic is that these hydrological contexts are not the same anymore, temperature and precipitation fluctuations are impacting the patterns of snowmelt and river flows, caused by climate change, that are impacting hydroelectric plants in as seen in many countries such as the United States, China, Canada and Brazil in 2021 [9].

The objective of this article is to present the technical and functional parameters/issues affecting the spillways discharging gates, highlighting the root causes of their problems and talk about solutions to enhance their reliability and service life. The remainder of this article is structured as follows: Section 2 presents the methodology used for the literature review. Section 3 presents the literature review, and the results obtained. Section 4 supports the literature review with a concrete case study. Section 5 discusses the results to arrive at potential solutions. Finally, the conclusion and future research directions are presented in Sections 6 and 7.

2. Research Methodology

This research is based on a multidimensional methodological approach structured around four main axes: a systematic literature review, a Failure Modes Analysis, a study of factors affecting spillway gates, and a case study applied to Hydro-Québec installations.

Figure 3 below illustrates the integrated methodological framework adopted in this research, highlighting the four main axes guiding the analysis: systematic review, FMEA, influential factors study, and applied case study.

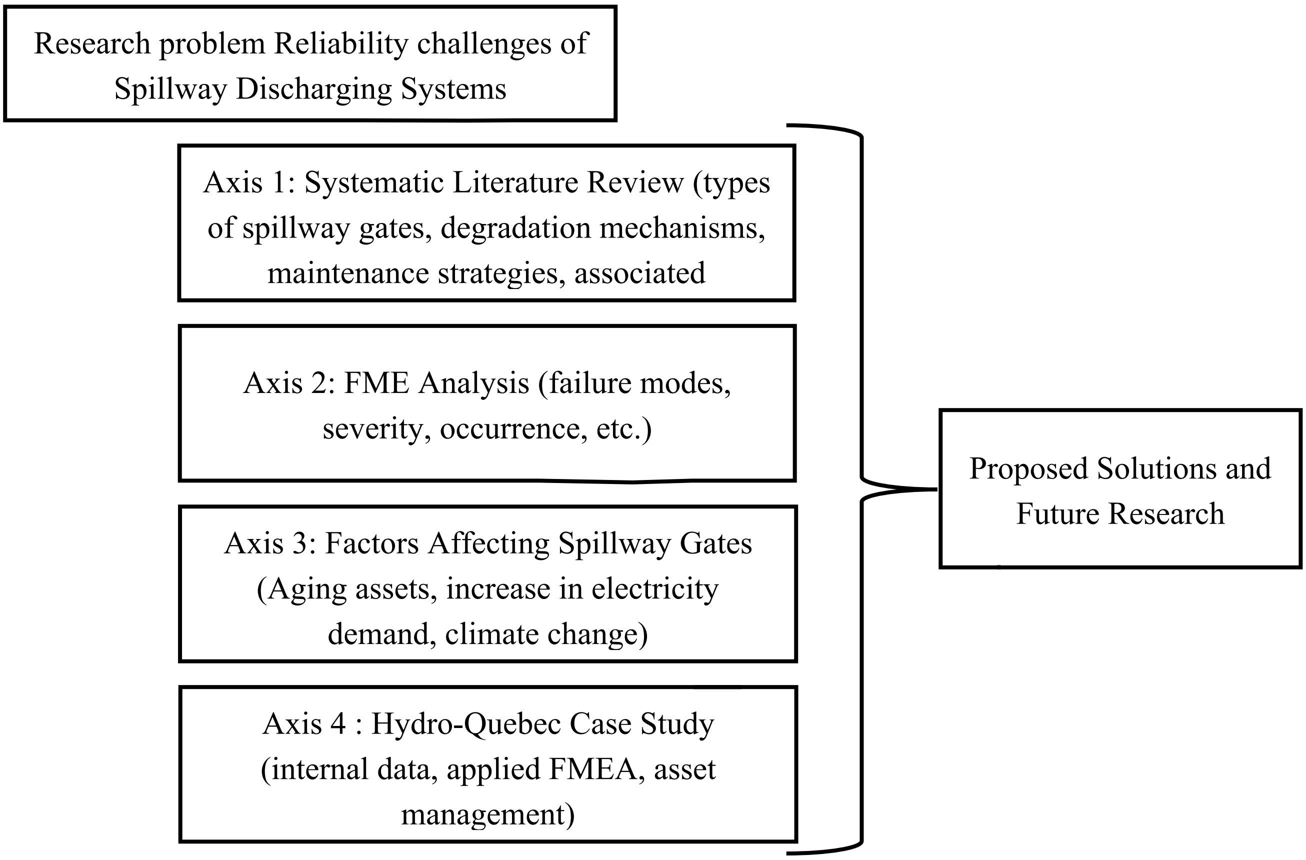

Figure 3. Integrated Methodological Framework of Research.

2.1. Systematic Literature Review (SLR)

A systematic literature review was conducted to identify current knowledge on spillway gates, their types, failure modes, aging indicators, and maintenance strategies. This method enables a rigorous and reproducible structuring of the state of the art, following the recommendations of Kitchenham et al. [10].

The literature search, as shown in figure 4 below, was performed using scientific databases such as Scopus, Web of Science, IEEE Xplore, and ScienceDirect, with keywords including “hydraulic gate failure,” “dam spillway reliability,” “maintenance strategies,” “FMEA in dams,” and “Innovative technologies in reliability.” Selected publications span the period from 1972 to 2025, in both French and English, and include scientific articles, technical reports, industry standards, and case studies.

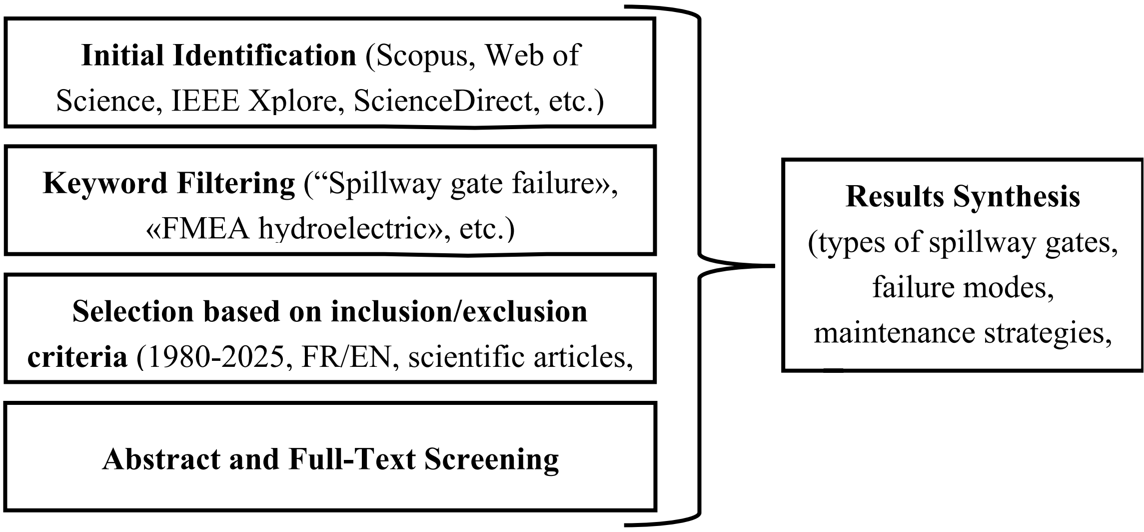

Figure 4. Process of the Systematic Literature Review (SLR).

Figure 5 shows the percentage of the publications of this review dated from 1980 and over, with 57% of them dates between 2020 and 2025.

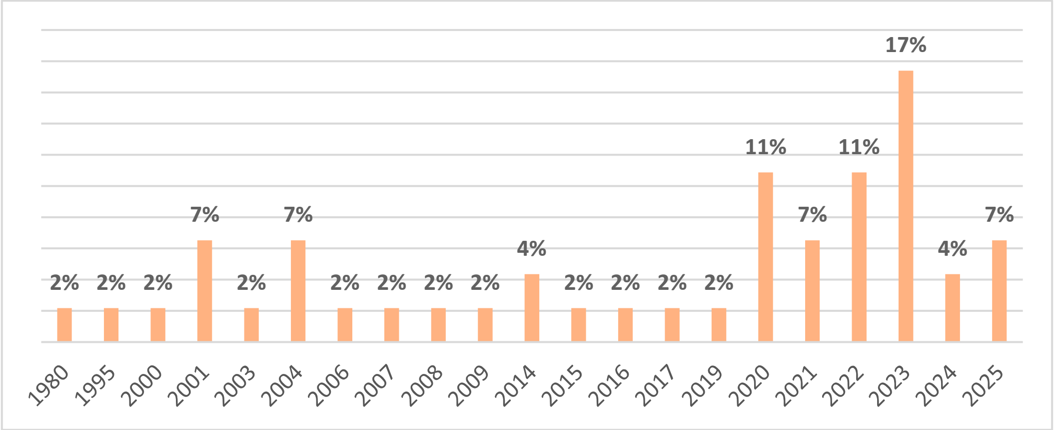

Figure 5. Percentage of publications per year of this literature review.

2.2. *Study of Factors Affecting the Spillway*

A transversal axis of the analysis focuses on the ascending factors that have an impact on the spillway causing problems as shown in Figure 6. These factors include:

- Assets aging, which shows the complexity of a spillway system, where lots of components don’t wear at the same time.
- Climate change, which alters hydrological regimes and increases the frequency of extreme floods [11].
- Rising electricity demand has an indirect impact on spillways [12,13].

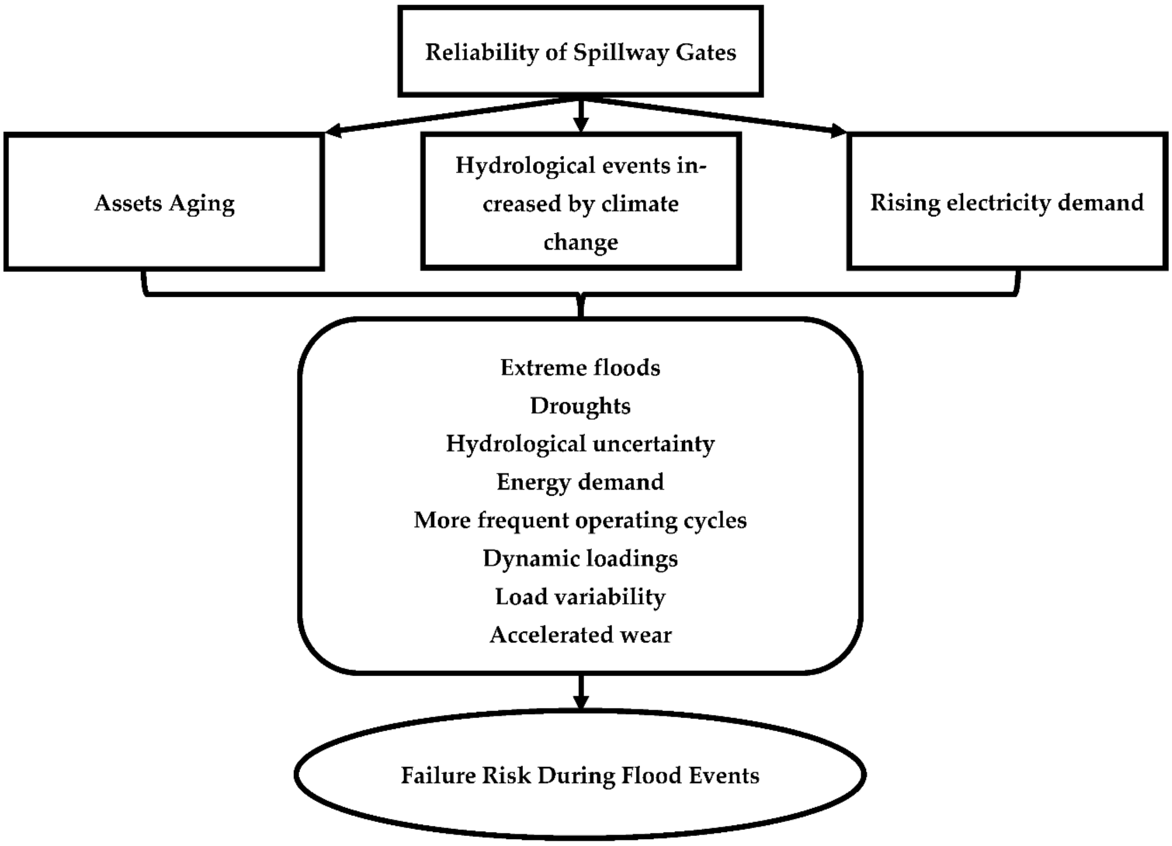

Figure 6. Map of Factors Affecting the Reliability of Spillway Gates.

Thus, a literature review will broaden our perspective about spillway discharge systems talking about the types of discharge gates used, their functional structure, their signs of degradation, a failure mode study and the factors affecting these systems, and how these systems are managed and what are others doing all around the world and then proceeding with a case study to support the research done followed by a discussion and what researches need to be done in the future.

3. Literature Review

This review focuses on the spillway's discharging system, researching the types of gates used, examining their functional structure and showing their signs of degradation. Afterwards, multiple Failure Modes, Effects Analysis will be shown to quantify the impact of these factors on the reliability and availability of the spillway in different regions. All factors that are affecting the spillway's discharging system will be examined, and the assets that are being managed under such circumstances will be indicated, to finally review all technologies used in similar contexts, along with concrete recommendations to improve the performance, resilience, and durability of these essential hydraulic system components.

3.1. Spillway Discharge Gates

One of the most crucial assets for dam management and safety is a discharge gate, it allows control over the water discharge from the reservoir, so when it's closed, the water is retained within the dam, but when opened, the water is allowed to flow out. Therefore, they play a critical role: regulating excess water flows to prevent dam overload, a challenge that has become increasingly urgent due to the rise in extreme precipitation events [14]. Usually, spillway gates are integrated into a lifting system composed of concrete piers, metal towers, winches, bridge-cranes, overhead guides, gated passages, and maintenance beams.

3.2. Types of Spillway Gates Used

As provided from multiple resources, Table 1 shows a synthesis of the main types of spillway gates employed in dams across the globe. It outlines their primary functions, the regions where they are most used, their current level of usage, and the associated scientific references.

Table 1. Comparative Overview of Spillway Gate Types Used in Dams – Functions, Geographic Distribution, and Scientific References.

Gate / Valve type	Primary function	Environment best suited for	Notes
Radial (Tainter/Segment) gate	Spillway flow regulation	Large spillways needing wide clear openings and moderate hoist forces	Workhorse crest gate in modern dams
Vertical-lift Sluice / slide gate	Closure / Diversion	Intakes, outlets, canals; moderate heads	Simple, robust, economical
Roller / Wagon gate	Wide bay opening with low rolling friction	Navigation dams and very wide spillways	Specialized; legacy but still used
Drum (hinged crest) gate	Automatic crest level regulation	Overflow weirs needing near automatic level control	Buoyant / hinged system; higher O&M
Flap gate (incl. tide/non return)	One-way discharge (non-return)	Coastal/Tidal drainage, storm protection	Opens under head differential
Tilting / Bascule gate	Level and Navigation control	Low-head rivers / canals; frequent operations	Compact hoists; good debris passage
Siphon Spillway / siphon gate	Autonomous discharge (no hoists)	Sites needing unattended crest control and compact works	Priming / De-priming governs flow
Hollow-jet (Howell-Bunger) valve	Energy-dissipating outlet	High-head bottom outlets needing aerated jets	Stable hollow jet; Cavitation resistant
Fixed cone (dissipation) valve	Energy dissipating outlet	High-head controlled releases	Highly aerated, stable jet
Butterfly valve	Isolation / Regulation in pressure lines	Penstocks and Plant piping	Compact (for pressurized conduits)
Canal knife / Slide valve	Canal regulation and isolation	Irrigation / Sluice structures	Low cost; Small to medium openings
Stoplogs / bulkheads	Temporary closure for maintenance	Any intake / bay needing dewatering	Accessory (not for regulation)
Fuse gates / Fuse plugs	Passive extra flood capacity	Dams needing rare-event capacity boost	Sacrificial / tilting units at extremes

3.3. Functional Structure of a Spillway Gate System

The literature review on the functional structure of a spillway gate system presented each component that plays a specific role in the overall operation, with their main function, typical use and common materials. This functional structure inspired by [15,16] is presented in Table 2 below highlighting the complexity and diversity of components involved.

All information in Table 1 was adapted from [15,16].

Table 2. Functional structure of a spillway gate system.

Component	Main function	Environment best suited for	Common materials	Link with other components
Gate body	Structural shell resisting hydrostatic load	All gates; high head	Structural steel, cast iron, reinforced concrete	Carries closure element, transmits load to piers/foundations
Closure element (disc/ segment/ slide/ cone)	Interrupts/ allows flow	Spillways, outlets, canals	Structural/ Stainless steels (alloys)	Moves within gate body along guides, pressed against seals (actuated by hoists)
Actuation system (hoists, cylinders, motors)	Provide motion	Depending on head and operation frequency	Steel machinery; hydraulic / electric drives	Connects to closure element. Supported by piers/bridges and linked with control systems
Sealing joints	Prevent leakage	All gates under head	Rubber (neoprene/EPDM) PTFE facings	Mounted on closure and frame. Pressed by guides / actuation
Discharge conduit / tunnel	Carries water downstream	Outlet works, tunnels	Reinforced concrete Steel lining	Receives flow from closure Interacts with valves/dissipators
Guides / embedded parts	Align closure, transfer loads	High-head, precision gates	Stainless steel, bronze, cast steel	Anchor closure to piers Ensure sealing and controlled movement
Instrumentation and control	Position / Pressure monitoring	Modernized dams	Sensors, encoder, control panels	Integrated with actuation Feeds operator feedback
Winches / operating machinery	Lifting / rotation	Radial, tilting, flap gates	Steel winches, gearboxes, ropes	Drive actuation Mounted on gantries Linked to closure
Gantry bridges (overhead cranes)	Support hoists, handling	Multi-bay/tall bays	Structural steel	Carry winches / hoists; move stoplogs; link to piers
Concrete piers / pillars	Structural support	Multi-bay spillways	Reinforced concrete	House guides and seals; support bridges and hoists
Maintenance / Winch beams	Handling and access	All dams	Steel or reinforced concrete	Enable handling stoplogs/closure Connect to gantry

Each element plays a distinct role in ensuring operational reliability, with materials and configurations varying according to the type and function of the gate. These findings provide a foundational understanding for further analysis of performance, maintenance, and risk assessment.

3.4. Signs of Degradation of the Spillway Gate System

Following the examination of the types and structures of the spillway gate system, the analysis focuses on signs of degradation to propose targeted solutions. Spillway gates are subject to multiple degradation mechanisms that compromise the reliability and operational safety of the system. The analysis of the literature showed that the most recurrent sign is corrosion of metallic components,

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particularly in humid, tropical, and maritime environments, where chemical and saline factors accelerate deterioration. For places like North America and Europe, where older dams are located, structural fatigue and fissuring are predominant and weakened riveted and welded elements caused by repeated mechanical cycles are highlighted. For places like the Alps, Andes and Himalayas, with high head spillways, cavitation erosion is a major concern that is leading to progressive loss of material. The main degradation mechanisms identified (corrosion, fatigue, cavitation, wear, leakage, instabilities) are documented in ICOLD bulletins (118, 154, 164, 99) and are presented in Table 3, summarizing and classifying them by environment and causes, based also on specialized literature like [15,16].

Table 3. Signs of Spillway Gates Degradation by environments and causes.

Sign of degradation	Most Affected Environments	Main Causes
Corrosion of metallic parts	Humid/tropical climates, saline reservoirs, industrially polluted water	Humidity, chlorides, aging or lack of protective coatings
Cracking and structural fatigue	Gates with high operational frequency; aging steel structures	Cyclic stress from repeated operations; stress concentrations; fatigue of metals
Cavitation damage	High-head outlets and spillways with high velocities	Formation and collapse of vapor cavities causing surface erosion
Wear of hydromechanical mechanisms	Worldwide (especially under poor maintenance)	Friction, abrasion, lack of lubrication, aging of moving
Loss of joint watertightness	Cold climates with freeze-thaw cycles; aging assets	Seal aging, hydraulic pressure cycles, freeze-thaw deterioration
Global deformation / instability	Seismic regions; dams under overload or aging	Earthquakes, extreme floods, design/foundation defects

So, the signs of degradation of spillway gates system are influenced strongly by environmental conditions, hydrodynamic loading, and maintenance practices. For example, as seen in table 3, countries with cold climates as Canada, Russia and Scandinavia, loss of joint watertightness has been seen worsen due to freeze-thaw cycles. And for countries found in seismic regions as Japan, Turkey and Iran, where external loading combines with aging, structural deformation and instability are the most critical. And for all the spillways globally, mechanical and hydraulic wear of operating systems are a big issue, especially in countries with limited maintenance resources. Therefore, a systematic understanding of these deterioration patterns is essential to design targeted inspection protocols, prioritize rehabilitation, and ensure long-term dam safety.

3.5. Comparative Failure Modes Studies on Spillway Gates

Failure Modes, Effects, and Criticality Analysis, known as FMEA, is a method that allows risk prioritization based on severity, frequency and detectability [17], and it was used in this research to identify the most critical failures of spillway gates. The specific constraints of hydraulic infrastructures, including flow-induced vibrations (FIV), alignment issues, corrosion, and abnormal operating conditions were considered in this study on the spillways gate discharge system.

And in order to better understand how risk analysis is applied to spillway gates, it is useful to look at case studies where FMEA or FMECA methods have already been used, that's why in this exercise different approaches, environments, and results will be shown to help compare failure modes and see which are most common and see how different teams measure risk. Thus, three different dams, located in different regions, were selected for this study as shown in Table 4, and each one representing a distinctive style of analysis: a classical FMECA, a design-phase FMEA, and a reliability study using fault trees.

Table 4. Comparison of Published Failure Modes on Spillway Gates.

Dam and Country	Gate Type	Method Applied	Key Failure Modes	How criticality was assessed	Explanation for reader	Ref.
Ajaure Dam (Sweden)	Controlled spillway gates	FMECA with worksheets, subsystem "Spillway Gate Control"	Hoist and control failure, gate not opening on demand, loss of discharge capacity	Criticality index per failure mode (severity x occurrence) ranked in tables	A textbook style FMECA: clear identification of failure modes, causes, effects, and numerical criticality. Demonstrates how to apply FMECA to gate control systems in practice	[18]
Temple Town Lake Dam (USA, Arizona)	8 hydraulically operated steel crest gates (spillway)	Design phase FMEA at 60% design review	Seal leakage, hydraulic cylinder failure, gate jamming, structural deformation, control system failure	Consequence categories (safety, operational, financial); no RON	A proactive FMEA carried out during design. Shows how gate failure modes can be anticipated before commissioning, with consequences categorized rather than scored numerically	[19]
Glenmaggie and Little Nerang Dams (Australia)	Glenmaggie (14 radial gates) Little Nerang (2 drum gates)	Reliability/ Fault -tree analysis (FMECA-equivalent)	Bearing failure, hoist malfunction, gate seizure, seal leakage, operator error	Quantified probabilities of single versus multiple gate failure	Although labeled "fault tree", this analysis is functionally an FMECA: it breaks gates into components, identifies failure paths, and quantifies failure likelihoods. Adds a probabilistic dimension missing in traditional FMEA tables	[20]

The reference studies, Ajaure Dam (Sweden), Temple Town Lake Dam (USA), and Glenmaggie and Little Nerang Dams (Australia), mainly addressed mechanical, hydraulic, and control failures under moderate environmental exposure, focusing on hoist malfunction, seal leakage, gate jamming, and structural deformation. These analyses [18–20] applied conventional FMECA or fault-tree methods with criticality indices based on severity × occurrence or probabilistic likelihoods, but they did not explicitly account for temperature-induced degradation such as ice blockage, material embrittlement, or freeze-thaw corrosion.

And because no published FMEA on spillway gate systems operating in cold-climate environments could be found in the literature, the FMEA in Table 5 was developed based on the method learned from the AIAG & VDA FMEA handbook [24] and the conditions were inspired by USBR, ICOLD and Adamo and al. [21–23] and was performed to demonstrate how low-temperature conditions influence failure mechanisms compared with documented cases in temperate or mild climates. The analysis integrates Severity (S), Occurrence (O), and Detectability (D) scoring based on

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established dam safety standards. Each value reflects the criticality, likelihood, and detectability of the identified failure modes.

Table 5. Simplified FMEA Matrix Applied to Spillway Gates under cold-climate conditions.

Subsystem / Component	Failure Mode	Potential Cause(s)	Effect(s) on System	S	O	D	RPN
Seal system (rubber or neoprene)	Seal stiffening or loss of elasticity in cold weather	Low temperature, material aging, inadequate heating	Increased leakage, vibration due to uneven seal compression	8	7	7	392
Gate structure (skin plate, trunnion arm)	Brittle fracture at trunnion or arm connection	Reduced steel toughness at sub-zero temps, stress concentration, fatigue	Catastrophic failure of gate operation; uncontrolled discharge	10	5	7	350
Roller and track assembly	Roller seizure or misalignment	Ice accumulation, lack of lubrication, corrosion	Gate jamming or delayed movement during flood operation	8	8	5	320
Gate vibration (structural dynamics)	Self-sustained or seal-induced vibration	Icing, flow asymmetry, air entrainment, reduced damping	Structural fatigue, seal wear, increased noise, risk of fracture	9	8	5	360
Control and instrumentation system	Sensor malfunction or signal loss	Icing, condensation, cable stiffening, frozen connectors	Undetected fault, false readings, reduced monitoring reliability	7	6	7	294
Hydraulic or electric hoist system	Oil thickening or motor overload	Low temperature, improper fluid, frozen mechanical parts	Sluggish operation, delayed gate response, risk of motor burn	8	6	6	288
Corrosion protection system	Coating cracking or delamination	Freeze–thaw cycles, trapped moisture, low-temperature brittleness	Accelerated corrosion, pitting, increased maintenance cost	6	7	6	252
Guide slot and embedded parts	Ice blockage or debris accumulation	Rapid freeze, poor drainage, inadequate heating	Restricted movement, possible gate misalignment	7	6	5	210

In a Failure Mode and Effects Analysis (FMEA), each potential failure mode is characterized by three numerical indicators [21]:

- Severity (S), assigned by potential safety/operability impact if failure occurs, expresses the consequences of failure on safety or operability, from 1 (no noticeable effect) to 10 (catastrophic loss of control or dam breach). It quantifies how critical the failure is to system reliability and public safety.
- Occurrence (O), adjusted +1-2 for cold climate exposure frequency, represents the probability or frequency of the failure, from 1 (very rare, >50-year return period) to 10 (very frequent or expected annually). It captures exposure to stressors such as cyclic loading, corrosion, or ice accretion.
- Detectability (D), penalized when inspection or sensor reliability drops in subzero environments, measures the likelihood that the failure will be detected before it causes consequences, from 1 (easy detection through inspection or sensors) to 10 (almost impossible to detect). Detectability reflects the maturity of monitoring systems and accessibility for inspection.

The Risk Priority Number (RPN) = S × O × D ranks the failure modes and identifies which require mitigation first.

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This FMEA revealed, based on the Risk Priority Number (RPN), that the most critical failure modes under cold-climate operation are seal degradation, vibration-induced fatigue, roller seizure, and brittle fracture of structural members. These modes are aggravated by low-temperature effects such as ice accretion, increased material stiffness, and reduced damping. The cold-climate FMEA highlights not only the failure modes themselves but the added value of explicitly integrating low-temperature effects into the analysis. Less severe but recurring modes such as corrosion, hydraulic fluid thickening, and coating delamination remain important, but when viewed through a cold-climate lens, their cumulative impact becomes significantly more consequential. Introducing cold-climate factors reveals how low temperatures amplify mechanical–hydraulic coupling, accelerate aging mechanisms, and shorten the mean time between failures (MTBF). More critically, the appearance of sensor malfunction, oil thickening, and ice-induced misalignment shows that cold conditions propagate failure across multiple subsystems (hydraulic, electrical, and structural) rather than isolating issues within mechanical components as typically observed in milder regions. This demonstrates that incorporating cold-climate effects is not an add-on but a core requirement for accurately assessing reliability and designing resilient monitoring systems and materials for northern environments.

Overall, this comparison shows that while the general categories of failure (seal leakage, hoist malfunction, corrosion, and control loss) remain consistent across climates, their root causes, frequency, and severity escalate significantly in cold environments. The inclusion of RPN-based quantification in the new analysis allows a clearer prioritization of adapting new measures to ensure a more reliable discharging system in the cold-climate locations. Consequently, the cold-climate FMEA extends existing literature by illustrating how climatic stressors not only exacerbate known mechanical issues but also introduce unique cross-system vulnerabilities that directly impact the reliability and operational safety of spillway gates.

Figure 7 below illustrates this comparative analysis between spillway gate FMEAs conducted in temperate climates from Table 5 for cold-climate conditions. The diagram highlights that while the same main categories of failures appear across all environments, their severity differs. As seen in cold climates, low temperatures, icing, material embrittlement and freeze-thaw cycles amplify the impact of these failures.

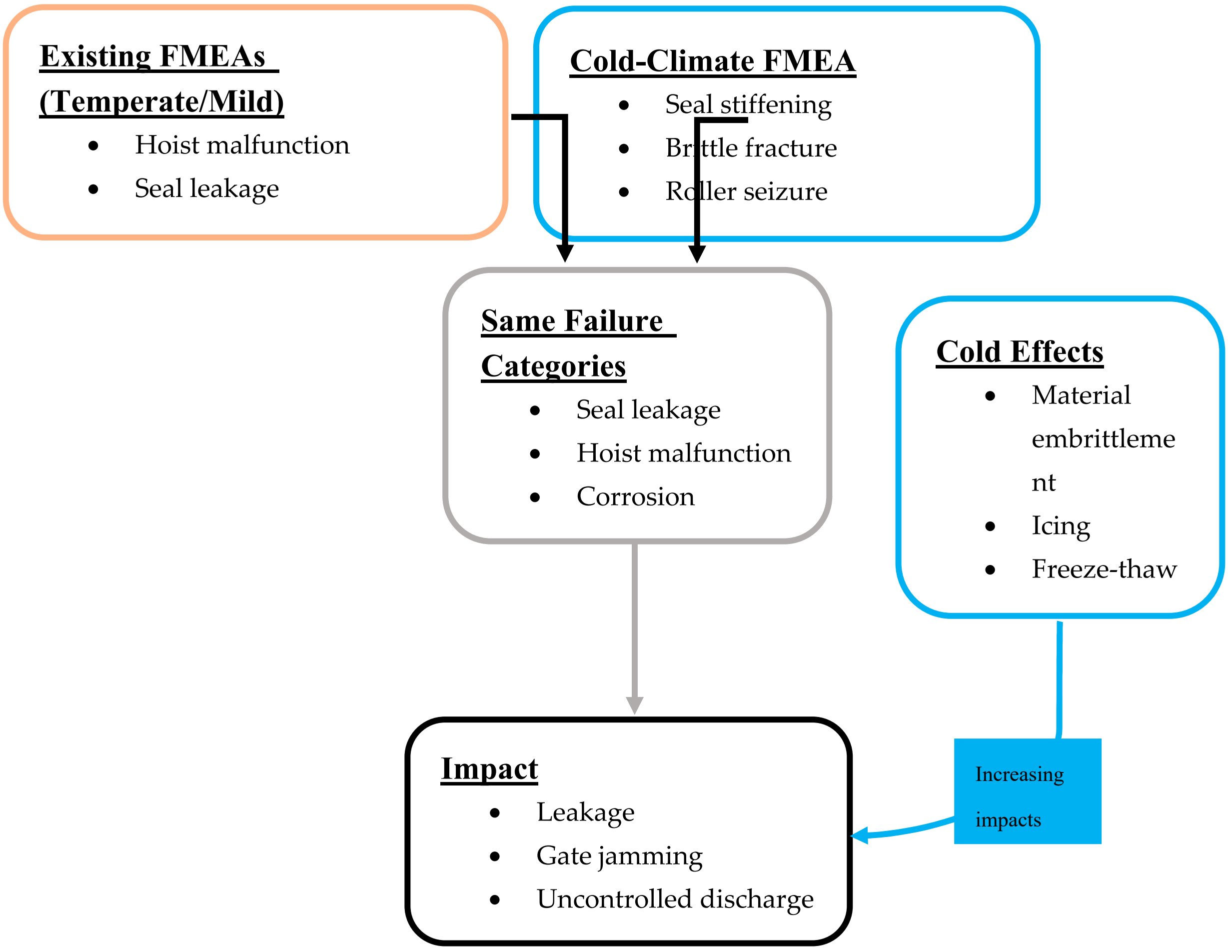

Figure 7. FMEA comparison.

This section has presented all the FMEAs together, showing the different failure modes identified in each case and how similar issues appear across various dams and climates. It also highlighted the factors that can make these failures worse. However, this analysis alone is not enough. Knowing that failures occur and how they are aggravated does not explain why they happen in the first place. Therefore, the next section will focus on understanding the root causes behind these failures, distinguishing between direct causes and indirect causes, and examining whether these failures are becoming more severe or frequent over time.

3.6. Factors Affecting a Spillway System

Beyond the technical analysis, there are factors influencing the performance and reliability of a spillway discharging gates system and affecting the long-term reliability of dam structures, requiring substantial investment in maintenance, modernization, and resilience planning.

What happens during a flood event?

During a flood, rising reservoir levels are detected (by sensors and automated systems or manually), which trigger the opening of spillway gates to discharge excess water through energy dissipation structures that reduce velocity and erosion before the flow rejoins the downstream river. This process ensures effective hydraulic regulation and protects both the dam infrastructure and surrounding areas from flood risks [25]. Thus, multiple factors are aggravating these floods, among them:

3.6.1. Aging Assets

As discussed before, most hydropower dams were installed and adapted in the early years of the 20th century, making them aged assets [26]. Ageing in dams refers to the slow, time-driven changes that occur in their materials and foundations, which can threaten safety if not properly managed [27]. These changes include deformation, settlement, loss of strength, internal erosion, and the breakdown of soil or rock that are often caused by seepage, chemical reactions, and exposure to environmental conditions [27]. Over time, this ageing process can increase permeability, raise pore pressures, cause cracking and surface erosion, and damage protective layers such as geosynthetics, asphalt, or soil-cement [27]. The result is a decline in structural integrity, greater slope instability, and a higher risk of piping or even a breach [27], causing stress on the spillway gates system, making it weaker and unreliable when in need [26].

3.6.2. Hydrological Events Increased by Climate Change

In contrast, climate change is intensifying extreme precipitation events, leading to more frequent and severe floods. Such events may exceed the original design discharge capacities of spillways. This evolving hydrological context is prompting dam operators to revise design and operational standards to maintain hydraulic safety under changing conditions [23,28]. For many years hydrological models relied on historical climate data, and because climate change introduces uncertainty in dam management, these models are failing to account for the increasing variability in precipitation and temperature, limiting the ability to anticipate extreme events such as flash floods or prolonged droughts. That’s why the spillway gate systems, according to Lovgren in 2022, considered the last line of defense against catastrophic dam failure, are becoming unreliable under more intense and unpredictable climatic conditions [29]. More studies were done to support these claims, for example in 2025 a study conducted by Ho et al. modeled overtopping risks for major dams in Australia under various warming scenarios, and the results have shown that under a 4 °C warming scenario, flooding risks increased by a factor if 2.4 to 17 compared to design conditions[11], and for that reason, concerns are rising for aging infrastructure not designed to withstand such hydrological stress. These examples underscore the importance of integrating environmental factors into the design and operation of spillway gates to ensure long-term dam safety and efficiency.

3.6.3. The Rise in Electricity Demand

Globalization has made an enormous impact connecting the world together, and in the domain of electricity, countries are trading electricity to cover their needs in peak hours leading to an increase in electricity production. For example, in North America there are a lot of electricity trades between Canada and the United States and based on Hydro-Québec’s (Canadian electricity producer, transporter and distributor Company) annual report in 2024, the globalization of electricity markets has led to increased exports to the United States and Ontario, accounting for approximately 15% of annual production (around 30 TWh). Also, industry 4.0, that is characterized by widespread deployment of IoT sensors, industrial robotics, and data centers, is increasing electricity demand in manufacturing sectors. In addition, the widespread adoption of electric vehicles (EVs) and the rise of Industry 4.0 are reshaping consumption patterns, driven by ambitious climate policies, this growth in consumption increases peak demand and forces electric plants to adjust operations dynamically [12,13]. And in countries such as Canada, especially in Quebec where hydroelectricity powers most transportation and manufacturers, water flows need to be managed more often by partially or temporarily activating the spillway gates system, overworking it in a way it can compromise long-term reliability.

3.6.4. Maintenance

Maintenance for all mechanical/machinery assets is required to maintain their reliability, availability, life cycle and health. Normally maintenances are based on fixed schedules planned

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rather than real-time conditions, but according to Martinez in 2020 these practices can lead to unnecessary interventions or undetected failures [30]. For the spillways, the maintenance of the gates requires lifting operations, meaning the gates must be opened during each maintenance activity. This reduces the life cycle of these assets, given that this maintenance forces the asset to perform its opening action, which is its operational movement.

3.6.5. Power Plant Tripping

According to Neupane and al. in 2021, hydropower plants tripping is a shutdown that refers to the process of stopping a turbine, which can occur either as a normal or emergency procedure. A normal shutdown is manually executed by the operator in gradual steps to reduce mechanical stress, involving the sequential closure of guide vanes followed by the main inlet valve (MIV). In contrast, an emergency shutdown is rapid and triggered automatically by protection systems or grid disconnection, resulting in strong hydraulic transients. The duration and method of shutdown significantly influence the pressure dynamics within the tunnel and surrounding rock mass, with shorter, abrupt shutdowns causing greater hydraulic impact [31]. Therefore, the interruption of turbine flow forces incoming water to be redirected entirely through spillway gates, which may exceed their nominal capacity, and this overload can cause mechanical stress, accelerate wear, and lead to malfunction if gates are not fully operational [32,33].

3.7. Spillway Discharge Gates System Management

The management of gated spillways aims to anticipate and mitigate all potential failure modes to ensure dam safety [34]. Therefore, in the event of failures preventing gate opening, backup systems such as emergency power supplies, manual operation devices, and redundant gates must be available to maintain flood discharge capacity. In contrast, if a gate remains stuck in the open position due to failures, operators must control reservoir drawdown using other gates and activate downstream emergency plans to minimize damage from uncontrolled releases [35]. Accordingly, to prevent unintended openings, modern control systems incorporate safety interlocks, and operational protocols include continuous monitoring to enable immediate response to any detected malfunction [34]. But we must also remember that human factors play a key role in reducing the risk of errors or delays during flood events through the regular operator training, detailed maneuvering plans, and automation of critical actions [34]. However, as explained before in section 3.6, the factors that are increasing the frequency and intensity of floods beyond historical norms, and the growing pressure to maximize hydroelectric production by keeping reservoirs as full as possible, require further improvements in spillway gate systems, that’s why studies concluded that balancing hydraulic safety with energy optimization is becoming increasingly complex and demands adaptive strategies [28,36].

3.8. Potential Solutions

The risks to the reliability of spillway gates are severely increased by environmental and operational conditions, and that’s why their performance and reliability are no longer governed solely by engineering design but are deeply influenced by external pressures such as climate variability, hydrological events which can no longer be predicted leading to traditional management plans becoming unreliable. Global energy trade, and technological transformation are increasing energy demand causing operational stress and failure risks, especially during flood events. Therefore, to address these challenges, it becomes imperative to modernize spillway gate management systems to ensure the performance and sustainability of hydroelectric dams, as well as public safety. This modernization must include the integration of more advanced and strategic technologies capable of analyzing real-time data and simulating various hydrological scenarios to be prepared for any instability caused by the impact of climate change. As highlighted by CSA Group in 2022, adaptive and dynamic approaches can enable proactive rather than reactive management, thereby reducing risks and costs associated with emergency interventions, maximizing efficiency, and minimizing the risk of failures [37]. Thus, according to a study conducted in 2022, artificial intelligence for the management of hydroelectric dams is a new technology solution that can be adapted to reduce losses [38]. Artificial intelligence can be implemented in different forms, for example AI can be represented as data analyst agent that can predict problems and manage dams, or as a digital twin that can anticipate failures, optimize operations and simulate critical scenarios to better manage risks.

During extreme weather events, such as sudden floods or periods of drought, decisions regarding the opening and closing of gates must be made quickly and accurately. A data analyst agent based on artificial intelligence stands out in these situations by offering optimal solutions based on rapid and in-depth analysis of available data. Artificial intelligence could calculate the gate opening sequence to balance upstream and downstream flow, thereby minimizing downstream flood risks while protecting the dam structure. And during periods of low precipitation, AI could adjust flows to maximize water usage while maintaining minimum levels for downstream ecosystems [38]. Not only that, but the agent can also help predict anomalies in the spillway discharging system so it can be taken care of, prior to the tests or events, preventing in that way catastrophes. In a concrete example, a dam in the Amazon Basin equipped with an AI system was able to reduce flood risk by up to 30% by optimizing real-time operational decisions related to spillway gate management [38]. Therefore, the benefits of integrating AI agents into spillway gate management are numerous and measurable. AI-based systems reduce the likelihood of unplanned outages dams equipped with these technologies [39].

In a perfect world—where data are readily available and flawless, infrastructures are robust or can be accurately modeled in their current state, operating conditions are normal, and reliable sensors provide continuous high-quality measurements—digital twins are the go-to. Digital twins are a virtual replica of a physical system, continuously fed by data collected in the field via connected sensors, are revolutionizing the management of hydraulic infrastructures by offering dynamic virtual replicas that integrate real-time data, and in the context of assets, these tools make it possible to anticipate failures, optimize operations and simulate critical scenarios to better manage risks linked to climate change [40]. Digital twins allow managers to observe the exact conditions of spillway gate and dams remotely and in real time and simulate critical scenarios. For example, a digital twin can simulate the impacts of a flash flood or prolonged drought to assess gate performance and adjust management strategies [41]. They can anticipate maintenance needs while analyzing the collected data and can predict when a gate is at risk of deterioration, allowing for targeted preventive maintenance. In a concrete example reported by Bentley Systems, a dam equipped with a digital twin was able to reduce the impacts of a flood by 20% by simulating and optimizing the opening of the gates before the arrival of the flood [41].

4. Research Framework

The research framework is the conceptual and analytical basis of this article, situating the issue studied within a structured set linking external factors, technical parameters, and the methodological approaches used to guide and organize the entire process.

The research conducted aimed at addressing the following problems: with advanced aging of equipment, unpredictable hydrological events, increased electricity demand and outdated asset management plans, how can reliability and durability of spillways discharging systems be improved to ensure their availability?

The study focused on the following key questions:

- What types of spillway's discharging gates are used?
- What are the degradation indicators?
- What are the factors affecting the life cycle of spillway gates?
- What are the current maintenance plans for spillway gates? Are these plans still effective given the recent changes?
- What technologies can be used to improve the reliability, availability, and durability of spillway gates?

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- What is the future research that will be done?

From a theoretical perspective, the research draws on several approaches and models on the spillway discharging system, such as the types of gates used, the functional structure and the signs of degradation to show its performance and problems, followed by an FMEA that served as a systematic method that identified and prioritized risks. In parallel, the challenges drew that the spillways are confronted with advanced aging of equipment (most of which were built in the 20th century), environmental impacts (such as climate change, fluctuating hydrological events), globalization of electricity markets (modifying asset working strategies), transition into electrical vehicles and industry 4.0 (increasing electricity demand), and traditional asset management (maintenance that is based on predictable hydrological events). And it was shown that these factors are transforming the operating conditions and exposing spillways to increased risks of failure. Finally, small research on potential solutions, such as implementing artificial intelligence as a form of an AI agent or a digital twin model, was conducted to offer emerging perspectives for modern asset management.

For the conceptual framework, this research is structured around the interaction between independent, dependent and Moderating variables. As shown in Table 6, environmental factors, globalization of electricity markets, transition into EVs and industry 4.0, and asset management are treated as independent variables. Their effects converge on the dependent variables, namely the signs of degradation, FMEA, reliability and availability of the spillway discharging system. At the same time, factors such as the types of gates used and the environment where the dam is present play a moderating role that shapes the intensity and direction of these relationships.

Table 6. Conceptual framework.

Independent variables	**Dependant variables**	**Moderating variables**
Asset aging	Signs of degradations	Types of gates used
Hydrological events affected by climate change	RAM	Environment
Rising electricity demand	Risk	

The figure below (Figure 8) shows the article roadmap.

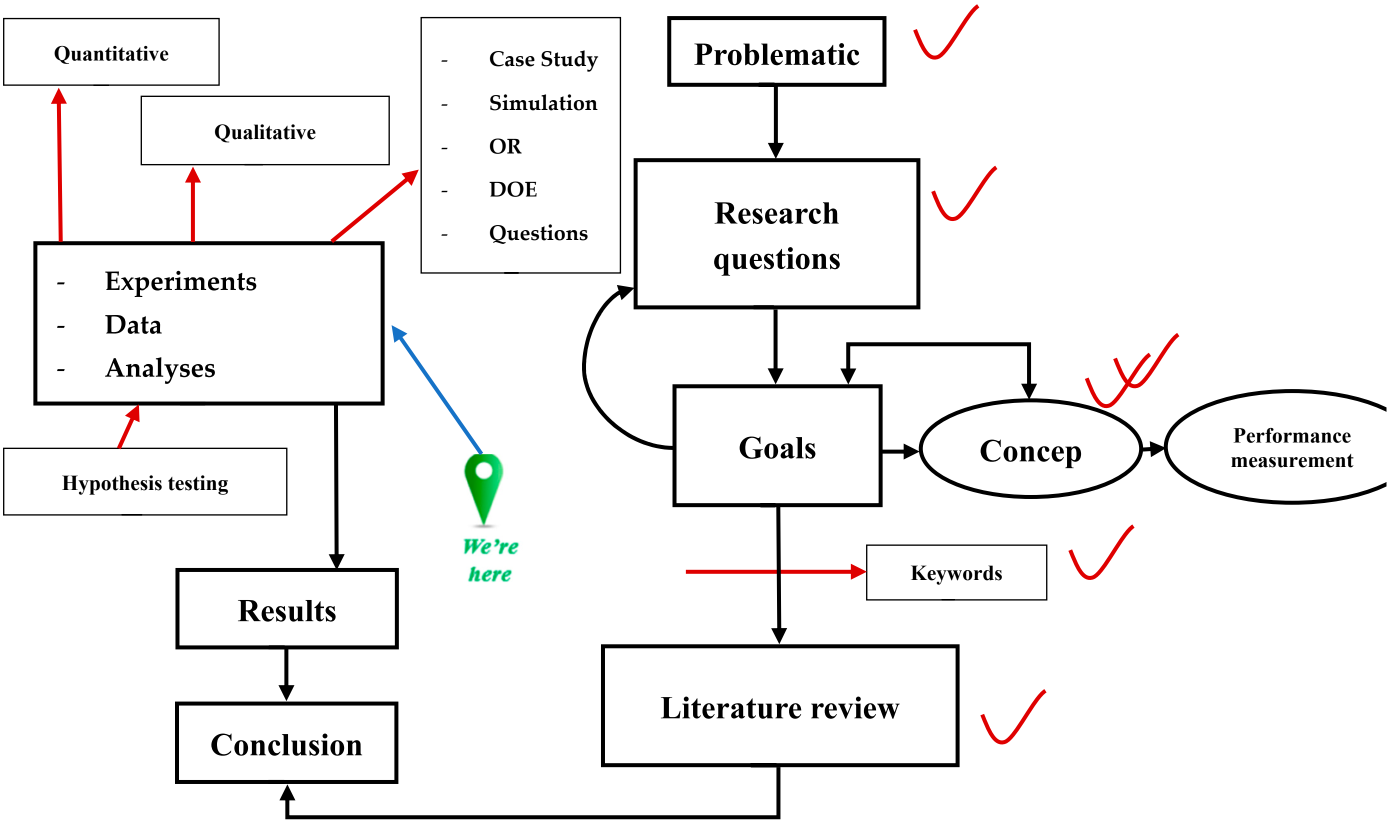

Figure 8. Research project roadmap.

5. Case Study

To reinforce this research and validate the hypothesis formulated in the literature review, a case study was conducted on Hydro-Québec. According to its official website, Hydro-Québec's is the largest electricity producer in Canada and one of the world's top hydroelectric producers. It operates an extensive network comprising sixty-two hydroelectric power stations, twenty-four thermal power plants, six hundred eighty-one dams, and ninety-three regulating structures. Although these figures are specific to Québec, they reflect universal challenges: delivering electricity across vast territories, maintaining complex transmission and distribution networks, and meeting growing demand while ensuring service reliability. The methodology used in this chapter is illustrated in Figure 9.

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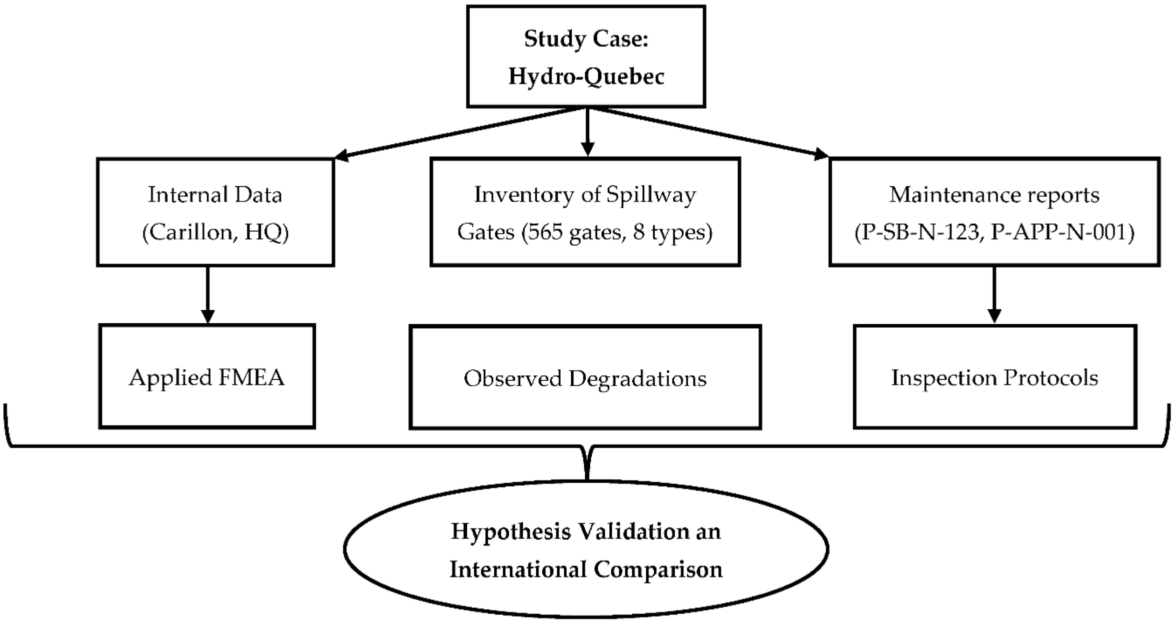

Figure 9. Diagram of the Applied Case Study on Hydro-Quebec Facilities.

Thus, this study aims to analyze the types of discharging gates Hydro-Québec uses in their spillways, which gates are mainly used, and which are going to be used for future installations, so that the analyses can be focused on them. This case study will also demonstrate the functional structure of a spillway to showcase the identified failure modes, and how's the company trying to solve them.

5.1. Discharge Gates Used at Hydro-Québec

According to internal data and experts at Hydro-Québec, the company operates a total of 565 gated passages, categorized into eight types: Wagon gates - PMEV (Live Water Operated Beams) - Slide gates - Trigger gates - Inflatable gates - Segment gates - Stoney gates - Bottom outlets. From Hydro-Québec's inventory, Table 7 shows the number of gates based on their types.

Table 7. Gates distributions.

Gates	Number	%
Wagon	314	57
PMEV	157	27
Slide	36	6
Stoney	24	4
Segment	19	3
Bottom outlets	6	1
Inflatable	5	1
Butterfly	4	1

From Table 7, the two most used gates by the company are the Wagon Gates at 57% and the PMEV at 27%, indicating that these two are the most reliable spillway gates. But according to engineer Roger Nicolet, a recognized expert in dam safety, the use of manually operated beams (PMEV) poses significant risks:

"Handling beams under flow, often without mechanical assistance, exposes personnel to hazardous conditions, including hydraulic thrust and rapid flow. Mechanized, remotely controlled closure systems are preferable for ensuring both personnel safety and reliable flow control." [42]

And that explains why Hydro-Québec considers Wagon gates as the most efficient and future-oriented gate to use. And that's why they are going to be the model used in this case study.

5.2. Functional Structure at Hydro-Québec

Based on Hydro-Québec's engineering documentation (Ref. 1231-111-04), Figure 10 illustrates the structural configuration of a typical spillway gate highlighting the mechanical and hydraulic interfaces, including lifting mechanisms, guide rails, sealing systems, and so on, where each element is a subsystem by itself.

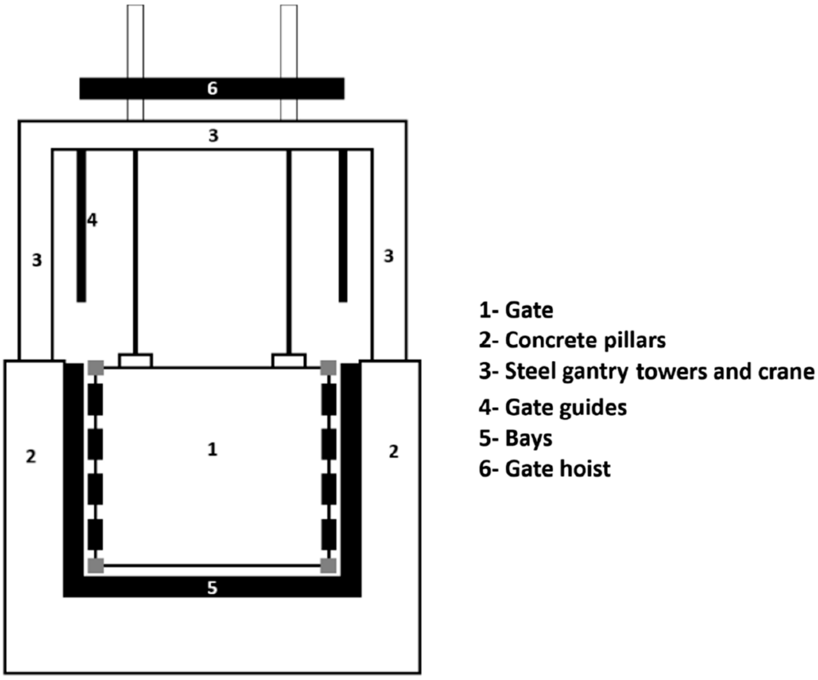

Figure 10. Structure by Joel Crispin – Planning Engineer at HQ (1231-111-04).

The functional roles of the main subsystems and components including the gate, concrete piers, steel gantry towers and gantry, gate guides, bays and gate hoist, Table 8 presents the work done by Hydro-Québec showing each subsystem critical role.

Table 8. Subsystems and components of the discharge system.

Subsystems	Components	Additional Information	Functional Role
Gate	Frame	Composed of the screen plate (steel deck) and the gate structure (horizontal beams and vertical side members)	Provides the main structure to resist water pressure and transfer loads to supports.
	Sealing Components	Includes sealing joints, bronze rods, cylindrical rods, clamps, and sealing plate.	Ensures watertight closure of the gate to prevent leakage.
	Rolling System	Consists of lateral wheels and a guide system connected to a lubrification station	Allows smooth gate misalignment and transfers structural loads.
	Lateral wheels and fixed shoes	Lateral shoes limit the gate's movement to avoid jamming; lateral wheels are protected by fixed shoes that carry the load.	Prevents gate misalignment and transfers structural loads.

	Heating system	-	Prevents ice formation, ensures operability in cold climates.
	Gate knife	-	Cut water flows when the gate is lowered.
	Lifting points	Gate attachment points	Provide anchor points for hoisting and safe lifting.
Concrete piers	Survey terminal	-	Allows monitoring and deformation control.
Steels towers & gantry	Gantry bridge structure	Steel structure, bolted/assembled.	Supports hoisting equipment for gate lifting.
	Bearings & expansion joints	-	Compensate for structural movements and thermal effects.
	Anchors	-	Transfer loads to foundation
Overhead guides	Lateral guides	-	Guide gates along their tracks
Spillway passage	Embedded parts	Includes lateral grooves, gate tracks, and sealing surfaces.	Provide tracks and sealing interfaces for gate operation.
	Crest	-	Defines spillway discharge elevation
	Concrete	-	Provides structural strength and water passage.
	Sealing components	-	Ensure tightness of gate passage.
Hoists	Mechanical elements	Cables, drums, screws, nuts, shafts, gears, etc.	Provide tracks and sealing interfaces for gate operation.
	Gearbox & motor set	Motor, speed reducer, drum, bearings, braking system (electromagnetic brake, fans, ventilation system), limit switches, gate lifting equipment.	Defines spillway discharge elevation.
	Control & protections	Protection systems (limit switches, slack cable switches, overload devices).	Ensure safe and reliable operation of hoists.
	Power supply	Power supply from plants, auxiliary generator.	Provide energy for hoist motors and control.
Maintenance beams	Maintenance beams	-	Allow gate support during maintenance.
	Grooves	-	Provide insertion points for stoplogs or beams.
	Auxiliary lifting system	-	Assists in handling during maintenance operations.
Spillway chute & floor	Spillway chute and stilling basin	-	Guides floodwater downstream, dissipates energy to reduce erosion.
Control & monitoring	Control panels, sensors, SCADA integration, position detectors,	Monitor gate position, loads, motor conditions, water levels; integrated into automated control system.	Automates gate operation, provides real-time monitoring, improves safety and operational decision-making.

	emergency backup systems

5.3. Signs of Degradation at Hydro-Québec

Based on data from work performed on the Carillon spillway, one of the best examples of a hydroelectric plant in Québec, such as projects and systematic, conditional, corrective and improvement maintenance, degradation patterns were identified as seen in Table 9. And after filtering out unreliable or incomplete data, the percentages were obtained confirming that mechanical stress and operational environment are the main threats to gate reliability. Similar trends have been observed in other studies such as [32], and [33], highlighting frequent issues such as misalignment, corrosion, and ice or debris blockages.

Table 9. Spillway gates degradation (internal data from Hydro-Québec).

Causes	%
Mechanical and alignment problems	40.47
Abnormal operating conditions	37.09
Leakage problems	7.75
Final material deterioration	5.38
Deformations and functional interfaces	4.33
Structural and design-related causes	4.33
Environmental degradation	0.65

The dataset used in this study consists of 80 work orders issued between 2000 and 2025 per year, covering improvement maintenance, condition-based maintenance, corrective maintenance, logistics, project activities, and systematic maintenance. The raw data were carefully filtered to remove inconsistencies and ensure that only reliable and usable records were retained for analysis.

The degradation signs identified here primarily reflect functional and operational symptoms observed during inspections, such as misalignment, leakage, abnormal operating conditions, and material deterioration. In contrast, the literature mainly describes the underlying physical degradation mechanisms, including corrosion, fatigue cracking, cavitation, wear, and global deformation. The comparison shows a strong consistency between both perspectives, indicating that field-observed degradation signs represent the observable manifestations of fundamental mechanisms extensively reported in the literature. This complementarity highlights the importance of integrating operational feedback with physics-based degradation models for a comprehensive understanding of hydromechanical system aging.

5.4. FMEA by Hydro-Québec

To manage risks associated with spillway systems and to enhance the resilience of its infrastructure, Hydro-Québec used an FMEA (Failure Modes and Effects Analysis) methodology, relying on rigorous codification of potential consequences to prioritize maintenance actions based on risk severity:

- DC: Component damage
- S: Safety
- E: Environmental impact
- L: Legal compliance
- A: Economic implications
- D: Equipment availability

Table 10. FMEA of a Spillway discharge system by Hydro-Québec's Engineer Fateh Boussaha.

Component	Function	Failure mode	Cause(s)	Effect(s)	Consequences					
					DC	S	E	L	A	É
Discharge Gate	Retain Water	Deterioration / wear	• Ice cover pressure • Impact of ice or debris • Corrosion • Freezing in grooves • Excessive temperature inside heated gate	• Design safety factor not respected • Deformation • Possible ultimate failure of the gate • Deformation		X			X	
		Leakage / Loss of tightness / Infiltration	Wear / degradation	• Accelerated gate degradation • Paint loss • Corrosion						X
Gate heating	Heat air volume (sufficient to prevent ice cover adhesion to the screen plate and ice formation in the rolling area)	Partial or total loss of heating efficiency	• Failure of insulation elements • Openings in the gate structure • Power supply loss, thermostat misadjusted • End of service life of fan motor • Failure of insulation	• Reduced heating capacity • Accelerated gate degradation • Paint loss • Corrosion • Risk of ice formation • Difficulty or impossibility of lifting the gate during winter load shedding (ice sticking to screen plate. Etc.)				X		
		Presence of water in watertight compartment of heating elements	Deterioration of silicone sealant of connection boxes r sealing joints of bolted covers	Accelerated corrosion of heating elements						X
		Defective side seals	Corrosion of fasteners, rubber deterioration	Reduced efficiency of wheel heating, potential wheel, freezing, risk of gate blockage in cold weather				X		
Beams operated in flowing water	Retain water	Deterioration / wear	Wear / degradation	Beams can no longer be operated or used		X				
Remotely triggered beams	Retain water	Deterioration / wear	Wear / degradation	Beams can no longer be operated or used		X				

5.5. Spillway's System Management at Hydro-Québec

At Hydro-Québec, asset management is a very important field, applying its strategies to ensure the reliability of their assets, such as spillways, to ensure their dams' safety. For example, the asset management strategy on spillways includes periodic inspections every 3, 6, and 12 years, as well as lifting tests where at 3 years the gate is lifted to a certain level, same goes at 6 and 12 years where each level increases. In accordance with internal documents *P-SB-N-123-2020* and *P-APP-N-001-*00, covering mechanical and electrical components, painted surfaces, internal structural integrity, sealing systems, and the presence of debris or ice that could hinder operation. International standards align with Hydro-Québec's practices, implementation of regular inspections and monitoring tools. But these strategies never canceled the fact that the spillway discharge system continued to be challenged, due to the climate change and the increase of electricity demand, especially at Carillon where a new hospital has been constructed and the population increased.

5.6. Operating Rate of a Spillway

As part of asset management and reliability strategies, critical hydromechanical equipment such as spillway gates are designed to operate according to a predefined number of opening and closing cycles over their entire service life. This planning, based on theoretical usage profiles, enables optimized component design, preventive maintenance scheduling, and reduced risk of premature failure [43]. However, as seen in Figure 11, which presents the operating rate of Gate #7 at the Carillon plant, practical operating data reveals that Gate #7 has been operating almost continuously for the past six years. In contrast, Figure 12, which illustrates the operating rate of Gate #1 on the same spillway, shows that Gate #1 has been opened only once during that same six-year period. Because how spillways function is that the gates at the middle are prioritised to manage the water flow and the gates situated at the end of the structure are the last resort used to evacuate water, and all these gates are all inspected and maintained in the same way. This disparity exposes a major reliability concern because it proves that gates belonging to the same spillway do not age uniformly. Even though Gate #1 and Gate #7 are part of the same spillway, they have been subjected to completely different operating demands. As a result, their mechanical condition, wear level, and probability of failure are no longer comparable.

In a critical flood event, the safety of the dam relies on the assumption that all spillway gates will be able to open simultaneously to achieve the designed discharge capacity. However, when one gate has barely been operated over several years while another has been used extensively, the likelihood of an unexpected malfunction increases significantly. A gate that rarely moves may seize, suffer from corrosion, or experience mechanical binding; conversely, a heavily used gate may suffer from accelerated wear or fatigue. In dam safety engineering, uncertainty directly translates into risk. When nothing guarantees that each individual gate can operate on demand, the entire discharge system becomes vulnerable. Showcasing, that at crucial time, spillways can't be relied on, because no one can guarantee that all discharging gates will be available to open at the same time.

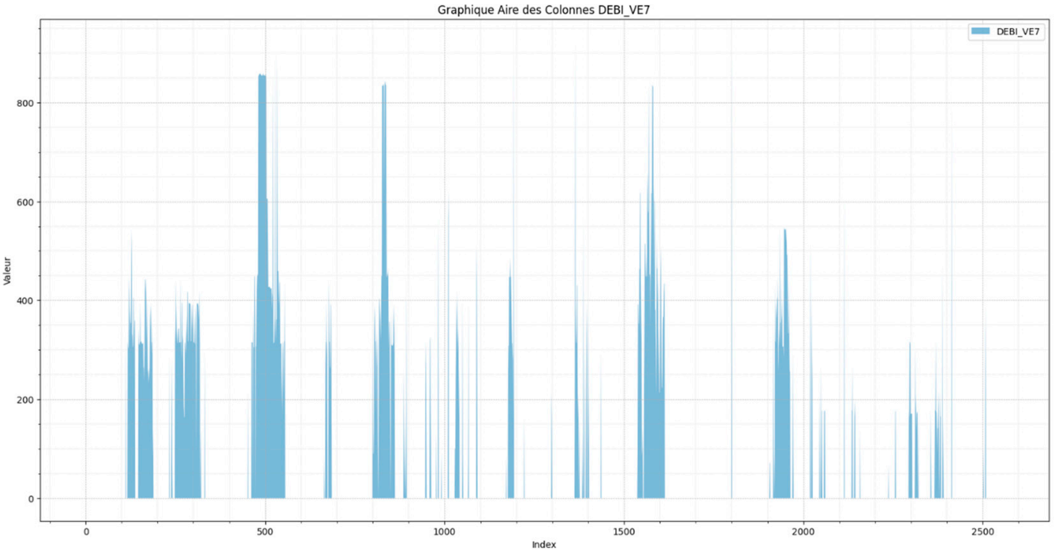

Figure 11. Opening rate of Spillway Gate #7 at Carillon, Québec since 2018.

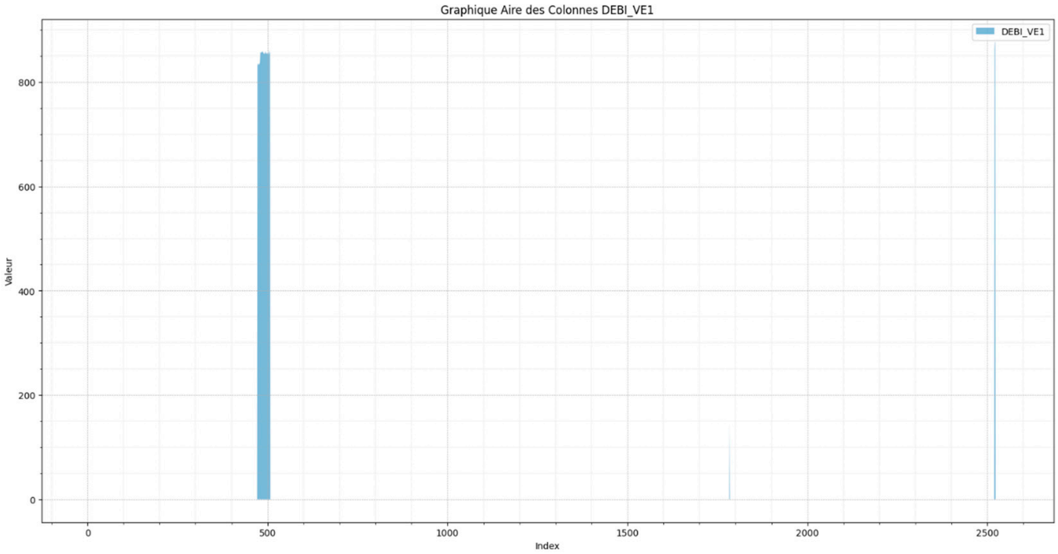

Figure 12. Opening rate of Spillway Gate #1 at Carillon, Québec since 2018.

5.7. Proposed Solutions by Hydro-Québec

At the institutional level, Hydro-Québec is discussing a complementary approach aiming to enhance inspections in a way that Hydro-Québec receives more detailed information concerning the problems resulting in the blockage of spillways [26]. This initiative is called the SFOR (Sûreté Fonctionnelle des Ouvrages Régulateurs) project, an internal project for the company that is structured around distinct but coordinated methodology:

1. On-site inspection of equipment.
2. Execution of functional tests to assess responsiveness and reliability.
3. Validation of performance under real operating conditions.
4. Detection of anomalies.

What's helpful about this project is the fact that it can help enhance technological aspects, by collecting real time data that can be used to enhance artificial intelligence models.

Inspections Inspection of spillway practices get benefits to be aligned with the actual service conditions. For example, a gate on a reservoir of a dam doesn't have the same operating frequency as a gate on the stream of water. Adapting the monitoring of these differences on two assets that have the same role is beneficial.

6. Discussions

According to scientific literature review, analyzing the functional structure, degradation indicators, and comparative failure modes of spillway systems makes it possible to identify certain common trends observed across different countries and various types of gates. Like the cold weather conditions tend to exacerbate several degradation mechanisms, further increasing the vulnerability of spillway components during winter periods. Moreover, the failures may also be influenced by broader systemic factors, like aging effects, hydrological events that are becoming more frequent due to climate change, and increasing energy demand, all of which place greater pressure on hydroelectric infrastructure.

In this context, the case study conducted at Hydro-Québec showed that spillways exhibit degradation modes like those identified in the literature. However, the observed gap between the actual operating conditions of two gates within the same facility indicates that spillways deteriorate differently depending on their frequency of use, which can influence their long-term reliability.

The comparison of current management approaches highlights certain limitations of traditional models, particularly in the face of evolving operating conditions. Although these models have proven effective in the past, their ability to adapt to new realities may be challenged. To maintain reliability in the face of aging, climate change and increased electricity demand, asset management will need to be adapted. Furthermore, despite significant efforts in maintenance and management, some aspects still require improvement, particularly anticipating failures in the context of rapid change. The potential increase in risk during extreme hydrological events underscores the importance of integrating advanced technological tools. The adoption of innovative solutions, such as digital twins or predictive agents based on artificial intelligence, could strengthen managers' ability to anticipate failures, optimize interventions, and enhance infrastructure resilience.

Overall, this analysis highlights the importance of evolution in spillway management models. A proactive approach, integrating emerging technologies and accounting actual systemic dynamics, appears essential to ensure the long-term sustainability of dams and their ability to meet future challenges related to hydraulic regulation and energy production.

7. Conclusion

This study aimed to identify the main factors affecting the reliability and longevity of spillway gates and to highlight the challenges posed by aging assets, changing hydrological conditions, and evolving operational demands. According to the scientific literature, environmental conditions play a major role in asset degradation; in particular, cold weather and freeze-thaw cycles further aggravate existing weaknesses and accelerate failure mechanisms. The case study confirmed these findings by showing that, within the same spillway, two gates were operated very differently over the years, creating unequal levels of mechanical stress and contributing to divergent degradation patterns. These combined observations show that current systems face growing stress and that adjustment of traditional practices can increase adaptation to new realities. Future research will therefore focus on comparing global solutions to determine which methods would be most suitable for Hydro-Québec to improve reliability and extend asset life. The next article will explore these methods and outline the most promising strategies to move forward.

8. Future Research

Building on the findings of this study, future research should explore several key areas:

- Advanced Digital Integration: Further investigation into the deployment and scalability of digital twins across diverse dam typologies and geographic contexts.
- AI Model Validation: Longitudinal studies to validate machine learning algorithms in real-time gate monitoring and failure prediction.

These avenues will help refine predictive maintenance strategies, support policy development, and ensure the long-term resilience of hydropower systems in a changing world.

Abbreviations

The following abbreviations are used in this manuscript:

HQ	Hydro-Québec
RAM	Reliability, Availability, Maintainability
AI	Artificial intelligence
PMEV	Poutrelles de Maintenance à Eau Vive
FMEA	Failure Mode Effects and Analysis
EV	Electric vehicle
USBR	U.S. Bureau of Reclamation
ICOLD	International Commission On Large Dams
MDPI	Multidisciplinary Digital Publishing Institute
DOAJ	Directory of open access journals
TLA	Three letter acronyms
LD	Linear dichroism
SFOR	Sûreté Fonctionnelle des Ouvrages Régulateurs

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