



## Operational Reliability And Safety Of The Karmana Hydro Junction: Assessment Of Natural, Technical, And Climatic Factors

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### Abstract

This article addresses the assessment of operational reliability and safety of the Karmana hydro junction from scientific, theoretical, and practical perspectives. Systematically studied are the natural, technogenic, and limiting factors affecting the safety of hydraulic structures. The influence of changes in river hydrological regime, seismic activity, engineering-geological and hydrogeological conditions, climatic factors, and processes of filtration and suffosion on the stability of the hydro junction are substantiated. Similarly, scientifically grounded conclusions and recommendations have been developed to increase the reliability of the hydro junction by improving the technical condition of water discharge structures and drainage systems.

**Key words:** Hydro junction, hydraulic structures, operational reliability, technical condition, safety, technical monitoring.

**Introduction** In current conditions, the sustainable operation of water management systems depends, first and foremost, on the reliability and safety of hydraulic engineering structures. Hydroelectric junctions play an important strategic role in water resource management, irrigation, energy generation, and flood protection (Federal Emergency Management Agency, 2020; Schmitt et al., 2024; U.S. Energy Information Administration, 2023), and their technical condition directly affects socio-economic sustainability. Under conditions of climate change, increased anthropogenic loading (human-induced stresses from development, industrial activity, and infrastructure expansion), and increased frequency of natural disasters (Müller et al., 2018; Chen et al., 2023; American Society of Civil Engineers, 2023), scientific assessment of the reliability of existing hydroelectric junctions during their operation has become an urgent issue (Zhou et al., 2014; North American Electric Reliability Corporation, 2023; Kovalenko et al., 2024). In this article, the operational reliability of the Karmana hydro junction is analyzed from the perspective of the main natural and technical factors that constitute it, and



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recommendations are provided for ensuring safe operation.

**Water Overflow and Embankment Failures.** Embankment failures frequently result from water overflow and overtopping, representing one of the most common failure mechanisms alongside internal erosion processes. This finding is substantiated across multiple authoritative datasets. Historical analysis identified overtopping due to inadequate spillway capacity as a primary cause of embankment dam failures (Jansen, 1988, citing Costa 1985). The International Commission on Large Dams (ICOLD) benchmark workshop data indicates that overtopping, seepage, and structural failures are the three primary failure modes for embankment dams, with overtopping representing a substantial share. Contemporary research confirms that overflow and overtopping remain among the most common failure mechanisms for embankment dams, though internal erosion is comparably significant (2023–2025 research period).

**Seismic Activity and Dynamic Stresses** Seismic activity exceeding 7.0 magnitude causes dynamic stresses that compromise embankment stability. Seismic events above magnitude 7.0 generate substantial ground accelerations and dynamic stresses within dam structures (Federal Emergency Management Agency, 2020). Dynamic response analysis is standard practice for assessing dam behavior during seismic loading (Federal Emergency Management Agency, 2020). Seismic events induce accelerations, dynamic deformations, and combined stress states that can compromise structural integrity and embankment stability if not properly designed for (Kostić et al., 2024; Zeng et al., 2025). For embankment dams specifically, seismic analysis protocols establish that both static and dynamic loading conditions must be evaluated throughout the dam's design life (Montana Department of Natural Resources and Conservation, 2020; Federal Emergency Management Agency, 2020).

**Engineering-Geological Conditions** Engineering-geological conditions are fundamental to dam stability assessment. A complete understanding of geologic site conditions is critical to dam site selection, feasibility evaluation, and long-term performance (American Society of Dam Safety Officials, n. d.; Federal Energy Regulatory Commission, 2016). The stability of dams and slopes must be evaluated using pertinent geologic information and in situ engineering properties of soil and rock (American Society of Dam Safety Officials, n.d.; Federal Energy Regulatory Commission, 2016). Recent research confirms that engineering-geological conditions-including foundation geology, rock quality, groundwater conditions, and the structure of river valleys-directly influence embankment stability and must be systematically evaluated during design (Petrov et al., 2023; Montana Department of Natural Resources and Conservation, 2021).

**Filtration and Suffusion Processes** Filtration and suffusion processes threaten dam integrity through internal erosion mechanisms. Suffusion is a hydro-mechanical phenomenon where fine soil particles are mobilized and transported by seepage flow through pores, leading to progressive loss of material and structural integrity (Fry, 2013). The mechanism of suffusion-induced failure in earth dams involves severe fines loss at the dam toe and near the upstream water level, resulting in significant stability reduction (Lirer et al., 2025).

All modern embankment dams require engineered filters and drainage systems to prevent seepage-related failures. Without proper filtration design, internal erosion can progress rapidly and lead to catastrophic failure, as documented in historical case studies including the Teton Dam failure (1976), which resulted from internal erosion (U.S. Bureau of Reclamation, 2008).

**Changes in Precipitation Regimes** .Changes in precipitation regimes and shifting hydrological patterns alter the magnitude and timing of river discharge, affecting dam operational capacity and spillway design adequacy. Water discharge variability is fundamentally controlled by precipitation patterns across multiple timescales (daily, seasonal,



yearly), with climate change altering both magnitude and timing of river flows (Nature Geoscience, 2025). Global hydrological models demonstrate that discharge varies inversely with predictability of precipitation events. The Intergovernmental Panel on Climate Change Sixth Assessment Report (2023) confirms that extreme precipitation events are projected to occur more frequently and with greater severity in the future, particularly affecting water resource management infrastructure. Heavy precipitation and pluvial flooding represent key climate extremes with documented impacts on hydroelectric operations. Hydrological variability studies demonstrate that river basins exhibit heightened sensitivity to precipitation changes, with implications for dam design standards (Federal Energy Regulatory Commission, 2016; U.S. Bureau of Reclamation, 2024). The U.S. Federal Energy Regulatory Commission and U.S. Bureau of Reclamation now incorporate climate variability into dam safety protocols and spillway capacity assessments. Dam operators face increased challenges in managing discharge variability under climate change, including spillway capacity limitations during extreme precipitation and reduced discharge during drought periods (Zhao et al., 2023).

**Temperature Increase and Glacial Melt** Rising atmospheric temperatures accelerate glacial and snowpack melting, shifting the seasonal timing of runoff and reducing summer water availability for hydroelectric generation. Rising global temperatures drive accelerated glacier retreat worldwide, documented at unprecedented rates (Swiss Federal Council, 2025; United Nations, 2025). Terrain newly exposed by glacier melt is altering runoff patterns and reducing long-term water availability for hydroelectric infrastructure. Climate change alters the timing and magnitude of snowmelt runoff, with two distinct phases documented by hydrological research: (a) an initial phase of increased runoff as additional glacier area melts, followed by (b) a long-term phase of reduced runoff as glacier volume depletes (U.S. Department of Energy, 2024). Under warming scenarios, snowpack melts earlier in the year, disrupting seasonal hydroelectric generation patterns. Winter precipitation increasingly falls as rain rather than snow in many regions, reducing reliable snowpack accumulation and downstream water availability during traditionally high-discharge periods. This is particularly significant in regions with seasonal snowmelt-dependent hydrology (Hamududu & Killingtveit, 2017). Central Asia's hydrological systems, which are representative of glacier-fed and snowmelt-dependent river systems, are experiencing measurable changes in seasonal runoff patterns and total water availability as temperatures increase (United Nations Environment Programme, 2018; World Bank, 2024).

**Extreme Weather Events and Infrastructure Stress** Extreme precipitation events, droughts, and intense storms occur with increasing frequency and severity under climate change, creating operational and structural stresses on dam infrastructure. The United States experienced 403 major weather and climate disasters from 1980–2024 with damages  $\geq$ \$1 billion each, a trend demonstrating the increasing cost and frequency of extreme weather events (National Oceanic and Atmospheric Administration, 2024). Dam failure flood risks from extreme rainfall represent a documented hazard requiring enhanced safety protocols (American Society of Dam Safety Officials, 2024). Aging dam infrastructure combined with intensifying extreme weather creates compounded risk (Yale School of the Environment, 2019; University of Michigan School for Environment and Sustainability, 2021). Experts increasingly warn of escalating dam failure risk as extreme precipitation events intensify, threatening lives, property, and environmental systems. Drought frequency and duration are increasing in many regions, creating operational challenges for hydroelectric systems. While dams provide buffer capacity against drought impacts, extreme droughts can severely reduce hydroelectric generation capacity and compromise operational flexibility (World Bank & Prevention Web, 2024; Pizzorni & Flores-Cervantes, 2024). The Intergovernmental Panel on Climate Change (2023)



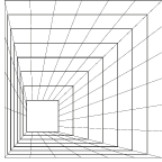
identifies weather and climate extremes including temperature extremes, heavy precipitation, pluvial floods, river floods, droughts, and storms as key risk factors for water resource infrastructure, with projected increases in frequency and intensity.

**Operational Complexity and Adaptive Management** Climate variability and uncertainty require adaptive operational strategies, updated hydrological models, and enhanced dam safety monitoring protocols to maintain reliability. Climate change creates unprecedented challenges for hydropower operational planning, as historical hydrological data become increasingly unreliable predictors of future conditions. Research on climate challenges for sustainable hydropower development demonstrates that hydropower systems must adapt to non-stationary hydrological conditions and variable resource availability (Kovalenko et al., 2024). The U.S. Bureau of Reclamation and Federal Energy Regulatory Commission now require climate change considerations in dam safety analysis, spillway capacity design, and operational procedures (U.S. Bureau of Reclamation, 2024; Federal Energy Regulatory Commission, 2016). National and international dam safety organizations have established 2025 action plans specifically addressing climate change adaptation (CEATI International, 2025). The World Bank, United Nations, and International Centre for Hydropower have published guidance emphasizing that dam safety in the 21st century requires explicit incorporation of climate change impacts into design, operation, and safety protocols (World Bank, 2024; International Centre for Hydropower, 2025). The World Bank notes that dam safety and resilience require addressing "impacts of precipitation and extreme flows on a dam's structural and operational safety" (World Bank, 2024). A comprehensive analysis published in Nature revisited global dam failures since 1900, identifying age, climate variability, and economic disparities as key drivers of current dam safety risk (Smith et al., 2025). The study emphasizes that climate change is a primary variable affecting contemporary dam failure risk.

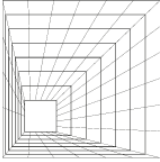
**CONCLUSION** The Karmana hydro junction operates within a complex context of technical and environmental challenges. Technical factors including embankment stability related to overflow, seismic activity, engineering-geological conditions, and filtration/suffosion processes require systematic monitoring and maintenance. Climate factors introduce dynamic stresses through altered precipitation regimes, glacial melt dynamics, intensified extreme weather events, and increased operational complexity. Together, these factors necessitate integrated, adaptive management frameworks supported by rigorous monitoring protocols, updated hydrological models, and enhanced safety procedures. Implementation of the recommended measures including improved drainage systems, earthquake-resistant design features, adaptive operational planning, and climate-informed spillway design will enhance the long-term reliability and safety of the Karmana hydro junction and similar facilities operating under contemporary climate and seismic conditions.

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