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International Journal for Modern Trends in Science and Technology
Volume 12, Special Issue 01, pages 1204-1207
ISSN: 2455-3778 online
Available online at: http://ijmtst.com/ICRCSET2026.html
DOI: https://doi.org/10.5281/zenodo.19863228

Graph Theory Applications for Resilience Mapping in Water Distribution Infrastructure

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To Cite this Article
K. Charan & G. Naga Lakshmi (2026). Graph Theory Applications for Resilience Mapping in Water Distribution Infrastructure. International Journal for Modern Trends in Science and Technology, 12(SI01), 1204-1207. https://doi.org/10.5281/zenodo.19863228

Article Info
Received: 12 March 2026; Revised: 07 April 2026; Accepted: 10 April 2026.

KEYWORDS

Flood regulation, probabilistic analysis, catastrophic failure.

ABSTRACT

Cascade dam groups are widely used for hydropower generation, flood regulation, and water resource management. However, the interdependence between upstream and downstream dams introduces a complex risk transfer mechanism that can lead to cascading failures during extreme events. Traditional dam safety evaluations often focus on single-dam stability, overlooking the propagation of failure risks across the entire cascade system. This study presents a novel method for mining the most hazardous failure path in cascade dam groups by integrating risk transfer modeling, probabilistic analysis, and complex network theory. The proposed approach identifies critical dam sequences whose failure results in the highest downstream impact. By simulating flood wave propagation and structural reliability under various failure scenarios, the method effectively detects hidden vulnerabilities within the cascade system. The results demonstrate improved accuracy in predicting catastrophic failure chains, providing valuable insights for emergency planning and dam safety management.

INTRODUCTION

Cascade dam systems consist of multiple reservoirs constructed along a river channel in series. These systems improve energy production and water storage efficiency but introduce significant safety concerns due to hydraulic and structural interdependence. When an upstream dam fails, the sudden release of water generates a flood wave that can overload downstream dams, potentially triggering a chain reaction of failures. This phenomenon, known as cascading failure, is exacerbated by the risk transfer effect, where failure risk is transmitted from one dam to another through hydrodynamic, structural, and operational interactions. As climate change increases the frequency of extreme floods, the safety of cascade dam systems has become a critical issue in water engineering.

Existing dam safety assessments primarily evaluate individual structures rather than the system as a whole. Consequently, they fail to capture the complex interactions and dynamic failure paths that may occur during extreme events. Therefore, there is a need for a systematic method that can identify the most hazardous failure path across the cascade system.

This research aims to develop a novel framework to mine and evaluate hazardous failure paths by combining risk propagation modeling and network-based path analysis.

Existing System

Traditional approaches for cascade dam safety assessment rely on hydrological and structural analyses performed independently for each dam. These approaches include:

- Deterministic flood routing models
- Structural stability analysis
- Reliability-based probabilistic safety assessment

In these systems, engineers simulate dam-break scenarios and evaluate downstream flood levels to assess potential damage. Some recent studies have incorporated Bayesian networks and event trees to model uncertainty and failure probability.

However, these methods typically treat each dam as an isolated entity. The interactions between dams are simplified or ignored, and the sequential nature of cascading failures is not fully analyzed. As a result, these methods cannot determine which sequence of dam failures would lead to the most catastrophic consequences.

Drawbacks

Despite advancements in dam safety engineering, several limitations remain in existing cascade failure analysis techniques.

Inadequate Consideration of Risk Transfer

Most traditional models do not explicitly account for the dynamic transfer of risk from upstream dams to downstream dams. This leads to underestimation of failure probabilities in cascade systems.

Lack of Failure Path Identification

Existing methods evaluate overall system safety but do not identify specific failure paths or sequences that could lead to maximum disaster impact.

High Computational Cost

Simulating all possible combinations of dam failures using hydrodynamic models is computationally expensive and impractical for large cascade systems.

Limited Integration of Multidisciplinary Factors

Current models often treat structural reliability, hydraulic routing, and operational control separately, resulting in incomplete system-level risk evaluation.

Proposed System

The proposed system introduces a novel framework for identifying hazardous failure paths by modeling the cascade dam group as a complex network. In this framework:

- Each dam is represented as a node.
- Hydraulic and structural dependencies between dams are represented as directed edges.
- Edge weights represent the risk transfer intensity between dams.

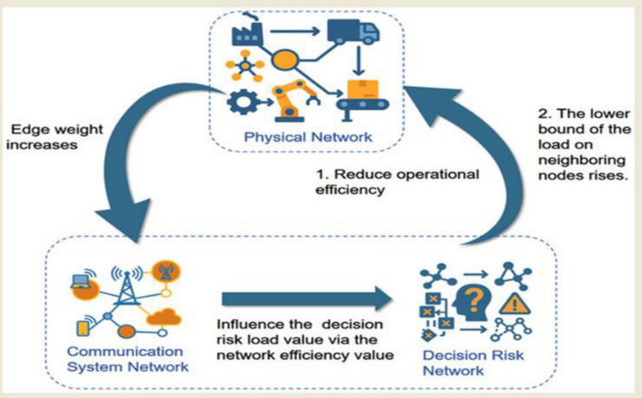
A risk propagation model is used to simulate how the failure probability of an upstream dam increases the stress and failure likelihood of downstream dams. By combining this with flood routing simulations, the model dynamically updates failure probabilities as water flows through the cascade.

The most hazardous failure path is defined as the sequence of dam failures that results in the maximum cumulative risk and downstream damage. Path mining algorithms are then applied to identify this sequence efficiently without exhaustive simulation of all combinations.

Advantages

The proposed method offers several advantages over traditional approaches:

- System-level analysis: It evaluates the cascade dam group as an integrated system rather than independent structures.
- Accurate risk propagation modeling: It captures the dynamic transfer of risk through hydraulic interactions.
- Efficient path identification: It reduces computational complexity by using network-based algorithms to mine critical failure paths.
- Improved disaster preparedness: Authorities can prioritize monitoring and reinforcement of dams located on the most hazardous path.



Methodology

The methodology of the proposed system consists of several stages, from data collection to failure path identification.

System Modeling

The cascade dam group is modeled as a directed graph:

- Nodes represent dams.
- Edges represent hydraulic connectivity and risk transfer.

Failure Probability Estimation

For each dam, the probability of failure is estimated based on:

- Structural reliability
- Hydrological load
- Operational conditions

These probabilities are updated dynamically as upstream dams fail.

Flood Routing Simulation

A hydrodynamic model simulates flood wave propagation following a dam-break event. This determines:

- Peak discharge
- Arrival time at downstream dams
- Water level rise

These parameters are used to update downstream failure probabilities.

Risk Transfer Modeling

The risk transfer effect is modeled using a conditional probability framework. The failure probability of a downstream dam is expressed as:

$$[P(D_j \mid D_i) = P(D_j) + \Delta P_{ij}]$$

Where:

- (D_i) is upstream dam failure
- (D_j) is downstream dam failure
- (ΔP_{ij}) is the additional risk transferred due to flood loading

Hazardous Path Mining

A path search algorithm such as Dijkstra-based maximum risk path or dynamic programming is used to identify the sequence of dam failures that produces the highest cumulative risk.

The objective function is defined as:

$$[R = \sum_{k=1}^{n} P_k \times L_k]$$

Where:

- (P_k) = failure probability of dam (k)
- (L_k) = expected loss due to its failure

The path with maximum (R) is considered the most hazardous failure path.

Conclusion

Cascade dam systems are inherently vulnerable to cascading failures due to hydraulic and structural interdependencies. Traditional safety assessments are insufficient for identifying critical failure sequences under risk transfer effects. This paper proposed a novel network-based method to mine the most hazardous failure path by integrating probabilistic risk modeling and flood routing simulation.

The proposed approach improves the accuracy of cascade failure prediction, reduces computational cost, and provides actionable insights for dam safety management and emergency planning. Future research may integrate real-time monitoring data and machine learning techniques to further enhance predictive capability.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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