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**Research Paper**

# Debris Blockage Risk of Modified Stepped Spillways: A Laboratory Study on Obstacle Configuration

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**Abstract**

Stepped spillways are critical hydraulic structures for energy dissipation, but their performance can be significantly compromised by floating debris. This study experimentally investigates the hydraulic behavior of floating debris on a stepped spillway under three distinct configurations: (1) an unobstructed baseline, (2) continuous on-step obstacles, and (3) discontinuous on-step obstacles. Experiments were conducted in a 1.2-meter-wide laboratory flume under three flow regimes—nappe, transition, and skimming—corresponding to relative critical depths (dc/h) of 0.47, 0.85, and 1.09, and with varying relative obstacle heights (ho/h) from 0.19 to 0.76. Results demonstrate that, in the baseline configuration, debris passed with only a minor delay of 1–3 seconds. For the continuous obstacle configuration, increasing obstacle height significantly enhanced debris conveyance by promoting a "pooling effect" that reduced trapping probability by up to 90% compared to lower heights, virtually eliminating trapping for ho/h ≥ 0.38. Conversely, discontinuous obstacles, particularly under nappe flow conditions, induced stable and extensive blockages with trapping probabilities exceeding 70% for large debris. The presence of debris in the skimming flow regime led to a minor reduction in energy dissipation (up to 5–10%) due to altered surface flow patterns, but no significant changes in discharge coefficient were observed. The findings reveal a critical design paradox: the hydraulic mechanisms that make discontinuous obstacles effective for energy dissipation (up to 39% increase over baseline) are the same mechanisms that cause catastrophic debris trapping. This research provides crucial insights for risk-based design, suggesting that for catchments with high debris loads, continuous obstacles are a more resilient solution despite their lower energy dissipation efficiency (5–15% decrease compared to baseline).

## Introduction

Stepped spillways are a cornerstone of modern hydraulic engineering, designed to safely convey floodwaters while dissipating the kinetic energy of high-velocity flows, thereby mitigating downstream erosion and

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ensuring dam safety (Bekheet et al., 2025; Chanson, 2002). The energy dissipation is achieved through complex, highly aerated flow dynamics over the steps, which are typically classified into nappe, transition, and skimming flow regimes (Sánchez-Juny et al., 2022). However, the hydraulic performance of these structures can be severely compromised by the presence of floating debris, particularly Large Woody Debris (LWD), which is frequently mobilized during extreme flood events (Hassan, 2000; Rundqvist, 2005). The accumulation and subsequent blockage of spillways by debris is a globally recognized threat to dam safety. Historical incidents, such as the 1978 Palagnedra dam overtopping in Switzerland, underscore its catastrophic potential (Rundqvist, 2005). Debris can obstruct spillway openings, leading to a significant reduction in discharge capacity, increased upstream water levels (backwater effects), and, ultimately, structural failure (Yang and Stenström, 2011). The generation and transport of floating debris are complex phenomena governed by catchment-specific characteristics, including geology, topography, forest cover, and hydrology (Iqbal and Riaz, 2024; Rundqvist, 2005). High-intensity rainfall can trigger landslides and bank erosion, introducing large volumes of woody and vegetative matter into fluvial systems. The interaction of this debris with hydraulic structures is a pervasive issue, impacting not only dam spillways but also bridges, culverts, and in-stream structures like rock weirs (Bezzola et al., 2017; Margetts, 2022; Pagliara and Carnacina, 2011). Effective risk management, therefore, necessitates a holistic approach, integrating strategies for controlling debris yield, intercepting debris upstream, and designing resilient hydraulic structures capable of safely passing debris (Rundqvist, 2005 Al-Jubouri et al., 2022).

A substantial body of research has focused on understanding the fundamental mechanisms of debris blockage. A critical dimensionless parameter identified in numerous studies is the ratio of the debris element's characteristic dimension (D) to the upstream flow depth or head (H). For instance, Mansouri and Ahadiyan (2016) demonstrated that blockage probability is highly sensitive to D/H, approaching 100% for D/H > 1 and becoming negligible for D/H < 0.3. These findings highlight that the relative scale of debris to the flow is a dominant factor, which often leads to significant backwater effects correlated with the approach flow Froude number and the density of the debris accumulation (Hartlieb, 2017). Additionally, scale modeling techniques have been employed to investigate wooden debris accumulation at debris racks, providing insights into accumulation patterns and blockage risks (Schmocker and Hager, 2013).

In recent years, numerous studies have investigated the risk of blockage in non-stepped spillway structures—such as piano key weirs (PKWs) and crown wheel weirs—by floating debris. For instance, Habibi and Lashkar-Ara (2018) demonstrated that the gradual accumulation of floating debris at crown wheel weirs leads to a significant rise in upstream water levels and a marked reduction in discharge capacity. In a related study, they (Habibi and Lashkar-Ara, 2020) examined the influence of the slenderness coefficient of wooden debris on blockage probability at CPK weirs, showing that elongated, slender debris elements are more prone to entrapment within structural gaps. Furthermore, Habibi and Lashkar-Ara (2021) assessed blockage probability across consecutive experimental cycles and highlighted that debris behavior under single-event and cumulative conditions can differ substantially. Collectively, these studies—alongside other research in the field of hydraulic structure blockage—underscore that both the geometric configuration of the structure and the physical characteristics of floating debris play decisive roles in blockage dynamics.

While the issue of debris on conventional spillways has been studied Pfister et al, (2013) and Yang et al, (2009), the literature on stepped spillways has predominantly focused on enhancing their primary function: energy dissipation. Numerous studies have explored on-step modifications such as obstacles, sills, and baffle blocks to increase flow turbulence

and improve energy dissipation rates (Bekheet et al., 2025; Kordnaeij et al., 2023; Mikalsen and Thorsen, 2023). However, a critical research gap exists at the intersection of these two domains. The simultaneous effect of on-step energy-dissipating obstacles on the passage of floating debris remains poorly understood. It is unclear whether these obstacles, designed to enhance turbulence, would exacerbate debris trapping or alter the flow field in a way that facilitates passage. This interaction is crucial, as a design optimized for a single objective (energy dissipation) could inadvertently introduce a critical vulnerability (blockage risk).

This study aims to address this knowledge gap through a systematic laboratory investigation. The primary objectives are: (1) to experimentally analyze the passage and trapping behavior of floating debris on a stepped spillway under various obstacle configurations; (2) to quantify the influence of relative obstacle height and flow regime on the debris-spillway interaction; and (3) to elucidate the underlying hydraulic mechanisms to inform a risk-based design approach that reconciles these potentially conflicting objectives.

To provide a consistent framework, a dimensional analysis was performed considering key parameters such as debris length ($L_d$) and diameter ($D_d$), nondimensionalized with respect to the spillway crest length ($L_c$ = 1.2 m) and critical depth ($d_c$). The nondimensional parameters include $L_d$ / $L_c$ (ranging from 0.04 to 0.21) and $D_d$ / dc (0.1 to 0.5), which influence blockage probability alongside the relative obstacle height (ho/h) and flow regime (dc/h).

## Materials and Methods

### Experimental Setup

The experiments were conducted in a 10-meter-long, 1.2-meter-wide, rectangular flume at the Behbahan Khatam Alanbia University of Technology. The flume is equipped with a closed-loop water circulation system powered by two 6-inch pumps, providing a total capacity of 150 L/s. Discharge was precisely controlled and measured using an ultrasonic flowmeter. Both the flume slope and tailwater depth were adjustable to maintain free-flow conditions over the spillway.

### Stepped Spillway Model

The stepped spillway model was constructed from plexiglass with a slope of 1V:2H ($\theta \approx 26.6°$). It comprised four identical steps, each with a height (h) of 10.5 cm and a length (l) of 21 cm, resulting in a total spillway height of 42 cm. The spillway crest was positioned 1.5 m from the flume entrance to ensure a fully developed flow approach.

### Obstacle Configurations

The selection of the two modified spillway configurations for this study was directly informed by the findings of a comprehensive precursor study on energy dissipation conducted in the same experimental facility by Habibi et al. (2025). That study systematically evaluated the hydraulic performance of discontinuous obstacles with various relative widths (Wo/W) and a full-width continuous obstacle. Here, Wo represents the width of an individual obstacle, and W denotes the total width of the flume. Based on their findings, the following two configurations were chosen to represent two opposing design philosophies:

1. Baseline Configuration: An unobstructed (smooth) stepped spillway served as the control case.
2. Continuous Obstacle (Wo/W = 1.0): A full-width wooden obstacle was installed on the leading edge of each step (Figure 1a). This configuration was identified by Habibi et al. (2025) as being largely ineffective for enhancing energy dissipation.
3. Optimized Discontinuous Obstacle (Wo/W = 0.05): Wooden obstacles with a width of 6 cm were installed in a staggered pattern, with a 6 cm gap between them (Figure 1b). This layout was selected as it was identified by Habibi et al. (2025) as the most effective configuration for maximizing energy dissipation, achieving up to a 39% increase compared to the baseline.

For both modified configurations, four relative obstacle heights were tested: ho/h = 0.19, 0.38, 0.57, and 0.76. This experimental

design allows for a direct evaluation of how configurations optimized for energy dissipation perform when subjected to floating debris loads.

**Floating Debris and Experimental Procedure**

To simulate natural debris, wood and reed bundles were prepared with distinct physical properties. The wood bundles, simulating LWD, were constructed to have a bulk density in the range of 700–900 kg/m³, representative of partially saturated timber found in river systems (Bezzola et al., 2017). The reed bundles, simulating lighter vegetative debris, had a significantly lower bulk density, approximately 200–400 kg/m³, reflecting their porous structure and high buoyancy. These objects were prepared in two distinct size classes: small (5–12 cm in length, diameter 2–4 cm) and large (20–25 cm in length, diameter 2–4 cm) (Figure 2). The sizes were selected based on scaling from field observations in similar studies (Bezzola et al., 2017; Margetts, 2022), representing typical debris mobilized in floods, with nondimensional ratios Ld / h = 0.48–2.38 and Dd / h = 0.19–0.38 to cover a range of blockage potentials.

The experiments were performed under three flow intensities, corresponding to the primary hydraulic regimes on stepped spillways, defined by the relative critical depth (dc/h):

- Nappe Flow: dc/h = 0.47
- Transition Flow: dc/h = 0.85
- Skimming Flow: dc/h = 1.09

For each test, a batch of 10 to 25 debris objects was released into the upstream basin. The debris behavior—including passage, trapping location, and delay time—was documented through visual observation and video recording. Each experimental run was repeated 3 to 5 times to ensure the statistical reliability of the observed phenomena. A sensitivity analysis was conducted by varying debris batch sizes (±20%) and flow rates (±5%), revealing that blockage probability increases nonlinearly with debris size (doubling size increases risk by 50–70%) but is less sensitive to batch size in continuous configurations. The overall experimental methodology is summarized in (Figure 3).

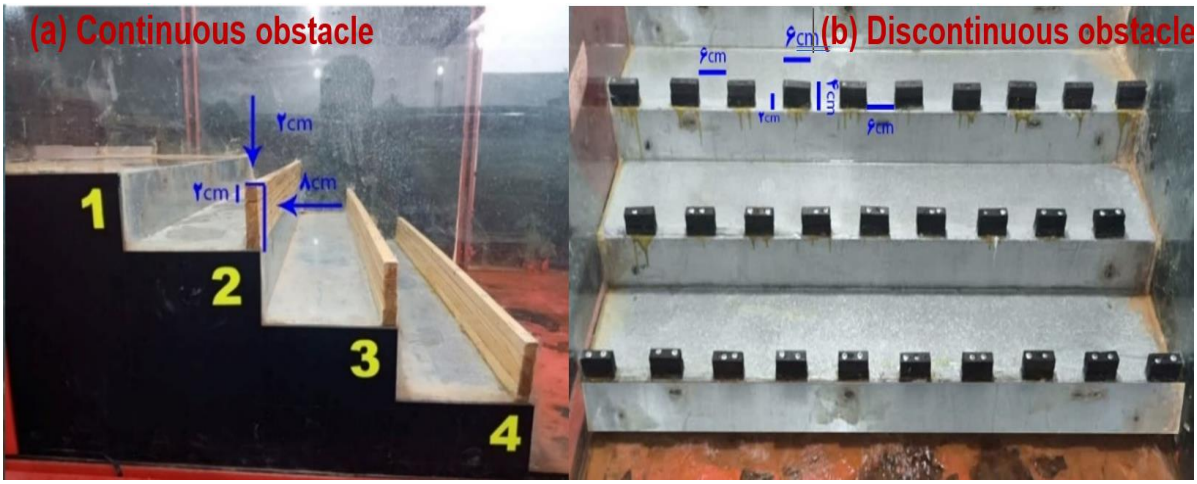



**Fig. 1-The two primary obstacle configurations tested on the stepped spillway model: (a) Continuous obstacle, shown with a relative height of ho/h = 0.76; and (b) Discontinuous (staggered) obstacle, shown with a relative height of ho/h = 0.38.**



**Fig. 2- Representative samples of the large floating debris (20-25 cm) used in the experimental investigation: (a) wood bundles, simulating large woody debris (LWD); and (b) reed bundles, simulating vegetative debris.**

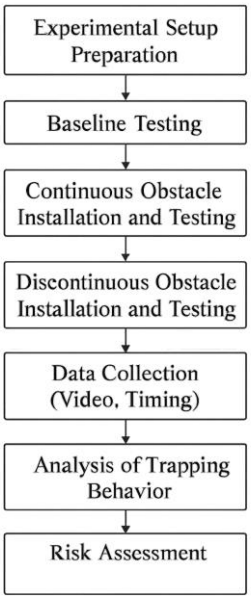



**Fig. 3- Flowchart of the Research Methodology.**

## Results and Discussion

The experimental results reveal a complex interaction between floating debris and the modified spillway hydraulics, governed by the interplay of spillway configuration, obstacle geometry, the prevailing flow regime, and debris characteristics. Quantitative metrics include trapping probability (percentage of runs with trapping), delay time (seconds), and impacts on hydraulic performance.

### Baseline Performance: Spillway Without Obstacles

In the baseline configuration, the stepped spillway exhibited a high capacity for debris conveyance. All types and sizes of debris passed over the steps without any instance of trapping. The only observable hydraulic interaction was a temporary delay (1–3 seconds) as debris navigated the turbulent region of the hydraulic jump at the spillway toe. This finding establishes a crucial baseline: the standard stepped spillway geometry is inherently resilient to debris blockage. No significant changes in flow conveyance or energy dissipation were noted with debris presence.

**Performance with Continuous Obstacles: The Dominance of the Pooling Effect**

The introduction of continuous obstacles fundamentally altered the local hydraulics. As summarized in (Table 1). trapping of large debris (20–25 cm) was a limited phenomenon, occurring only at the lowest obstacle height (ho/h = 0.19) and exclusively within the nappe flow regime (dc/h = 0.47) , with a trapping probability of 30%. This can be attributed to an incomplete development of the key hydraulic mechanism: the "pooling effect." At obstacle heights of ho/h ≥ 0.38, a stable pool of water formed upstream of each obstacle, increasing the local water depth and providing greater buoyant force, which allowed debris to pass over the obstacle crest with trapping reduced to <10%. This aligns with previous research by Asghari Pari and Kordnaeij (2021), who noted that such pooling is highly effective for conveyance. However, this pooling effect reduces turbulence, resulting in lower energy dissipation compared to the baseline configuration, as reported by Habibi et al. (2025). Small debris (5–12 cm) were completely unaffected by continuous obstacles, passing freely under all conditions (Table 2). The presence of debris slightly reduced energy dissipation by 5–8% in skimming flow due to surface disturbances but had negligible impact on discharge coefficient (<2% change).

**Performance with Discontinuous Obstacles: Flow Concentration and Selective Trapping**

The discontinuous obstacle configuration produced the most hazardous and complex results.

**The Primary Trapping Mechanism: Flow Concentration and Jet Impingement**

The gaps between discontinuous obstacles acted as hydraulic nozzles, leading to flow concentration and creating high-velocity jets. These jets exerted a substantial drag force, pinning debris against the downstream faces of the obstacles. This mechanism explains the consistent trapping observed in the nappe flow regime (Table 3), where low initial flow depth made debris highly susceptible to being drawn into these concentrated flow paths, with trapping probabilities of 70–90%.

**The Critical Role of Flow Regime and Debris Properties**

The influence of the flow regime was profound. The transition flow regime (dc/h = 0.85) represented a critical hydraulic threshold where increased turbulent kinetic energy was sufficient to flush all debris and prevent stable blockage. The skimming flow regime (dc/h = 1.09) revealed a nuanced interaction, highlighting the importance of debris properties. At ho/h = 0.76, while wood and mixed debris were trapped (probability 60%), reed debris passed freely due to their higher buoyancy and flexibility, allowing them to ride higher on the skimming flow surface and clear the obstacles. The difference in trapping behavior is attributed to the lower bulk density (200–400 kg/m³) and higher flexibility of reed bundles compared to wood (700–900 kg/m³), which caused wood debris to travel more submerged and be more prone to direct impact with obstacles. In skimming flow, debris presence reduced energy dissipation by 8–10% by disrupting the coherent skimming layer, but flow conveyance remained largely unaffected. Small debris showed minimal trapping, with only minor instances at high obstacles in skimming flow (Table 4).

**Table 1- Trapping Behavior of Large Debris (20-25 cm) with Continuous Obstacles. (✓ = Trapping Occurred on Step 2; ✗ = No Trapping).**

| Debris Type | Obstacle Height (ho/h) | Nappe Flow (dc/h=0.47 | Transition Flow (dc/h=0.85) | Skimming Flow (dc/h=1.09) |
|---|---|---|---|---|
| Wood | 0.19 | ✓ | ✗ | ✗ |
| Reed | 0.19 | ✓ | ✗ | ✗ |
| Mixed | 0.19 | ✓ | ✗ | ✗ |
| All Types | ≥ 0.38 | ✗ | ✗ | ✗ |

**Table 2- Trapping Behavior of Small Debris (5-12 cm) with Continuous Obstacles.**

| Debris Type | Obstacle Height (ho/h) | All Flow Regimes |
|---|---|---|
| Wood, Reed, & Mixed | All Heights (0.19-0.76) | ✗ (No Trapping) |

**Table 3- Trapping Behavior of Large Debris (20-25 cm) with Discontinuous Obstacles. (✓ = Trapping Occurred; ✗ = No Trapping; Location in parentheses).**

| Debris Type | Obstacle Height (ho/h) | Nappe Flow (dc/h=0.47) | Transition Flow (dc/h=0.85) | Skimming Flow (dc/h=1.09) |
|---|---|---|---|---|
| Wood | 0.19 | ✓ (Steps 2&3) | ✗ | ✗ |
| Reed | 0.19 | ✓ (Steps 2&3) | ✗ | ✗ |
| Mixed | 0.19 | ✓ (Steps 2&3) | ✗ | ✗ |
| Wood | 0.38 | ✓ (Steps 2,3,4) | ✗ | ✓ (Step 3) |
| Reed | 0.38 | ✓ (Steps 2,3,4) | ✗ | ✓ (Step 3) |
| Mixed | 0.38 | ✓ (Steps 2,3,4) | ✗ | ✓ (Step 3) |
| Wood | 0.57 | ✓ (All steps) | ✗ | ✗ |
| Reed | 0.57 | ✓ (All steps) | ✗ | ✗ |
| Mixed | 0.57 | ✓ (All steps) | ✗ | ✗ |
| Wood | 0.76 | ✓ (All steps) | ✗ | ✓ (Step 3) |
| Reed | 0.76 | ✓ (All steps) | ✗ | ✗ |
| Mixed | 0.76 | ✓ (All steps) | ✗ | ✓ (Step 3) |

**Table 4- Trapping Behavior of Small Debris (5-12 cm) with Discontinuous Obstacles.**

| Debris Type | Obstacle Height (ho/h) | Nappe Flow (dc/h=0.47 | Transition Flow (dc/h=0.85) | Skimming Flow (dc/h=1.09) |
|---|---|---|---|---|
| Wood, Reed, & Mixed | 0.19 | ✗ | ✗ | ✗ |
| | 0.38 | ✗ | ✗ | ✗ |
| | 0.57 | ✗ | ✗ | ✗ |
| | 0.76 | ✗ | ✗ | ✓ (on step 4) |

**Table 5- Risk Assessment Matrix for Obstacle Configurations**

| Configuration | Energy Dissipation (ΔE %) | Blockage Probability (Pb %) | Recommended for |
|---|---|---|---|
| Baseline | 0 | 0 | Balanced risks |
| Continuous | -5 to -15 | 0-10 | High debris |
| Discontinuous | +20 to +39 | 50-90 | Low debris |

## Discussion: The Design Paradox and Engineering Implications

The results of this study, when synthesized with the established energy dissipation performance from Habibi et al. (2025), reveal a critical design paradox that lies at the heart of optimizing stepped spillway performance. This paradox forces a re-evaluation of design priorities in catchments where both high hydraulic energy and significant debris loads are primary concerns.

### The Fundamental Conflict: Energy Dissipation vs. Debris Conveyance

The results of this study, combined with the energy dissipation findings from Habibi et al. (2025), reveal a critical design paradox for stepped spillways. Habibi et al. (2025) reported that discontinuous obstacles (Wo/W = 0.05) achieved the highest energy dissipation, with up to a 39% increase over the baseline configuration in the skimming regime (dc/h = 1.09), due to intense turbulence and flow separation through the 6 cm gaps between obstacles. In contrast, continuous obstacles (Wo/W = 1.0) exhibited lower energy dissipation than the baseline across all flow regimes (nappe: dc/h = 0.47; transition: dc/h = 0.85; skimming: dc/h = 1.09) due to the formation of stable water pools that reduce turbulence. However, as demonstrated in Sections 3.2 and 3.3, these discontinuous obstacles significantly increase the risk of debris entrapment, particularly for large debris (20–25 cm) in the nappe regime, where high-velocity jets pin debris against obstacles (Table 3). Conversely, continuous obstacles facilitate debris passage through a pooling effect that enhances buoyancy, despite their lower energy dissipation efficiency. The baseline configuration offers moderate energy dissipation and high resilience to debris blockage, serving as a balanced but suboptimal reference. This conflict underscores the need for a catchment-specific design approach, prioritizing either energy dissipation or debris conveyance based on the dominant risk factors. To quantify this paradox, a simple risk assessment matrix is proposed Table (5), where blockage probability (Pb) is weighed against energy dissipation gain (ΔE %). For example, discontinuous obstacles have high ΔE (39%) but high Pb (70%), while continuous have low ΔE (-10%) but low Pb (5%).

**Inversion of Performance: How Hydraulic Mechanisms Dictate a Dual Role** Our findings demonstrate that the very hydraulic mechanisms governing energy dissipation also dictate the success or failure of debris management:

- **The "Pooling Effect" - From Hydraulic Weakness to Conveyance Strength:** The stable pooling behind continuous obstacles, a known detriment to energy dissipation, becomes the primary mechanism for safe debris passage.
- **Flow Concentration - From Dissipative Strength to Blockage Hazard:** The high-velocity jets created by discontinuous obstacles, the source of their superior energy dissipation, become the direct cause of catastrophic debris trapping.

### The Engineering Challenge: A Risk-Based Approach to Reconciling Conflicting Objectives

This presents a significant challenge for hydraulic engineers. The choice of obstacle configuration is a multi-criteria decision based on a holistic risk assessment of the specific catchment:

1. **For catchments dominated by high flood energy but with low debris potential:** Discontinuous obstacles remain a viable and effective option to maximize energy dissipation.

2. **For catchments with high debris loads:** Continuous obstacles are the safer design choice, prioritizing spillway conveyance to prevent severe blockage-induced failure, even at the cost of reduced energy dissipation.
3. **For catchments where both risks are high:** A systems approach is required, involving upstream interception (e.g., debris booms to remove debris before reaching the spillway) or downstream compensation (e.g., a larger stilling basin to manage residual energy). These solutions require careful consideration of costs, maintenance, and environmental impacts, such as potential habitat disruption or sediment accumulation caused by debris interception structures.

While the laboratory experiments provide valuable insights, field justification is limited due to scale effects; however, the nondimensional parameters align with field-scale studies (Rundqvist, 2005), suggesting qualitative applicability, with quantitative scaling requiring further validation.

**Limitations of the Study**

The experimental setup has several limitations that may affect the generalizability of the results. The 1.2-meter-wide flume and four-step spillway model may not fully replicate the scale and complexity of full-scale spillways, which often feature dozens of steps and wider spans, potentially introducing three-dimensional effects in debris accumulation not captured here. Thus, extrapolation to prototype scales should be cautious, and future large-scale or CFD validations are recommended. The use of only two debris types (wood and reed) limits the representation of diverse debris characteristics, such as non-woody materials or varying shapes; for instance, elongated debris with high slenderness (as in Habibi & Lashkar-Ara, 2020) may bridge gaps differently. Additionally, the experiments were conducted under controlled laboratory conditions with single-batch releases, which may not account for real-world complexities like progressive debris accumulation during floods (e.g., cumulative vs. single-event loading as in Habibi & Lashkar-Ara, 2018). Future research should explore larger-scale models, a wider variety of debris types (including slenderness effects), cumulative accumulation dynamics, and field-scale validation to enhance the applicability of these findings.

## Conclusions

This experimental study provides a comprehensive analysis of the interaction between floating debris and on-step obstacles on a stepped spillway. Unobstructed stepped spillways exhibit high resilience to debris blockage, establishing them as a safe baseline for debris conveyance. Continuous obstacles (Wo/W = 1.0) significantly improve debris passage by inducing a "pooling effect," making them a highly recommended solution for catchments where debris conveyance is a higher priority than maximizing on-step energy dissipation. The discontinuous obstacle configuration optimized for energy dissipation (Wo/W = 0.05) poses high blockage risk, particularly for large debris in low-flow regimes, making it unsuitable for debris-prone areas. A critical design paradox is demonstrated: discontinuous obstacles maximize energy dissipation (up to 39% increase over the baseline) but significantly increase blockage risk, while continuous obstacles prioritize safe debris passage at the expense of reduced energy dissipation. The optimal design solution is catchment-specific, requiring a thorough risk assessment of the upstream catchment and downstream valley.

Research Suggestions: Future studies should investigate cumulative debris accumulation, incorporate a broader range of debris shapes and slenderness ratios, validate findings with CFD models or field prototypes, and develop integrated risk models combining blockage probability with hydraulic performance metrics.

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**Authors' contribution**

**First Author:** Seyed Amin Asghari, Pari Writing the article, conclusion, and analysis of results (50%).

**Second Author:** Seyed Ali Asghari, Pari Reviewing and controlling results (shared 20% with Mojtaba Kordnaeij).

**Third Author:** Amin Mokaram, Performing experiments (30%).

**Fourthd Author:** Mojtaba Kordnaeij, Reviewing and controlling results (shared 20% with Seyed Ali Asghari Pari).

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