



Kyoto University Collaborative Research

PROJECT REPORT

Inclusion of large-scale debris in extreme flood modeling and management

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1 Project summary

Extreme floods, such as the 2021 Central European Floods and the October 2024 Valencia DANA event, often transport large amounts of debris, blocking waterways and exacerbating flood damage. The accumulation of debris can cause structural damages and bridge failures due to the coupled impacts of flood-induced hydrodynamic and debris loads. A new paradigm in flood management has emerged, focusing on integrating debris transport in flood simulations. This task is complex due to an epistemic deadlock caused by a lack of adequate and generalized analytical frameworks to simulate debris transport.

As a first step, Prof. Franca and collaborators characterized the large-scale debris transported during major floods over 25 years and investigated conditions for their mobilization. In this project, using remote sensing, the stochastic determination of the temporal distribution of this large-scale debris in urban areas is intended. This will allow a substantial advance in flood management since the inherent risk of these elements in urban floods will be assessed and quantified. The key questions of the project are:

- What are the spatial and temporal distributions of debris flow of large-scale events on the urban scale?
- How can we model the interaction between flood, debris, and structures?
- What are the risks for the urbanized area due to the long-term movement of large-scale debris in the stream?

The significance, originality, and unique contribution of this project are:

- A novel numerical model will be developed to stochastically analysis the temporal distribution of this large-scale debris in urban areas.
- Develop an assessment tool to estimate such coupled risks in urban areas.
- The model is an important step forward for analyzing flood management strategies.

2 Introduction

Flooding is one of the most pervasive and destructive natural hazards globally, affecting an estimated 250 million people annually and causing economic damages in the range of USD 40 billion (OECD, 2016). The World Economic Forum’s Global Risks Report 2025 identifies extreme weather events, including floods, as the second most immediate global risk (WEF, 2025). This growing threat is exacerbated by three converging factors: climate change, rapid urbanization, and inadequate infrastructure. However, one critical component remains largely overlooked in flood risk assessments and management strategies—hazardous floating debris.

Climate change is intensifying the hydrological cycle, leading to more frequent and severe precipitation events. Scientific estimates suggest that for every 1°C increase in global temperature, extreme precipitation events may intensify by 5–7%, potentially resulting in a 10% increase in flood magnitude depending on catchment characteristics (Trenberth, 2011; Tabari, 2020). Simultaneously, urbanization is transforming natural landscapes into impervious surfaces, accelerating runoff and increasing peak flows by 100–500% in some regions (Du et al., 2015; Li & Bortolot, 2022). These changes are not only increasing the frequency and intensity of floods but also altering their dynamics in ways that are not fully captured by traditional flood models.

Among the most underappreciated consequences of these changes is the role of floating debris—ranging from vehicles and construction materials to plastics and vegetation—in

exacerbating flood impacts. During the October 2024 floods in Valencia, Spain, over 120,000 cars were destroyed, with images of vehicles piled in urban streets becoming emblematic of the disaster. Floating debris increases flow resistance, clogs drainage systems, and causes direct damage to infrastructure and ecosystems. Yet, debris dynamics are rarely incorporated into flood risk assessments or urban planning frameworks.

Recent catastrophic floods across the globe—from the 2021 European floods to the 2024 events in Brazil and Argentina—have demonstrated how floating debris can amplify destruction. In mountain catchments, high-velocity flows transport large volumes of sediment and natural wood, often blocking bridges and causing backwater flooding. In urban areas, debris sources are more varied and include household items, vehicles, and construction waste. These objects, termed Urban Flood Drifters (UFDs), become mobile during floods and pose significant risks to life and property (Bayón et al., 2024).

The presence of floating debris also complicates emergency response and recovery efforts. Debris can obstruct evacuation routes, delay the arrival of first responders, and increase the risk of secondary hazards such as fires, electrocution, and chemical spills. For example, during Hurricane Katrina in 2005, debris impact led to the rupture of an oil storage tank in New Orleans, releasing over 3,900 m³ of oil into residential neighborhoods. Similarly, the 2011 Tōhoku tsunami in Japan swept an estimated 5 million tons of debris into the Pacific Ocean, triggering a cascade of environmental and infrastructural failures.

Despite these risks, current flood models and hazard maps rarely account for debris. This omission stems from both technical challenges and institutional inertia. Predicting the quantity, type, and trajectory of debris during a flood is inherently uncertain. Moreover, most engineering practices and urban planning guidelines are designed around hydrodynamic parameters such as water depth and velocity, with little consideration for debris-related hazards.

This report aims to bridge that gap by synthesizing recent scientific advances in debris transport modeling and highlighting the urgent need to integrate debris dynamics into flood risk management. Drawing on case studies, experimental research, and numerical modeling, we present a comprehensive framework for understanding and mitigating the impacts of floating debris in urban floods. Our goal is to inform policy, guide infrastructure design, and support the development of more resilient cities in the face of escalating flood risks.

3 Materials and Methods

This study integrates findings from two key research articles—Bayón et al. (2024) and Valero et al. (2024)—and introduces a novel artificial intelligence (AI)-based methodology to track and model floating debris in flood-prone urban environments in Europe and Japan.

The first source, Bayón et al. (2024), presents a classification framework for Urban Flood Drifters (UFDs), identifying debris types based on shape, material, and mobility. Their methodology involved field surveys and photographic documentation during and after flood events, followed by a systematic categorization of debris objects. The classification was validated using historical flood data and expert assessments.

The second source, Valero et al. (2024), focuses on the onset of motion of UFDs. Their approach combined laboratory flume experiments with numerical simulations to determine the critical thresholds for debris mobilization. Parameters such as flow velocity, water depth, object geometry, and buoyancy were systematically varied to derive empirical

relationships governing debris entrainment.

Building upon these methodologies, this report introduces an AI-enhanced analysis to track and characterize floating debris in recent flood events in cities such as Valencia (Spain), Liège (Belgium), Ahrweiler (Germany), and Kumamoto (Japan). High-resolution satellite imagery and drone footage were processed using convolutional neural networks (CNNs) trained to detect and classify debris types. Temporal sequences of images allowed for the tracking of debris trajectories, which were then analyzed to extract kinematic parameters such as velocity, acceleration, and rotational motion.

The movement of debris was modeled using a hybrid approach combining Eulerian-Lagrangian fluid dynamics with AI-derived object tracking data. The resulting equations incorporate hydrodynamic forces, object-specific drag coefficients, and probabilistic terms accounting for collision and accumulation behavior. This integrative methodology enables a more accurate prediction of debris pathways and accumulation zones, informing both emergency response and long-term urban planning.

All data sources were georeferenced and validated against ground-truth observations and post-event damage assessments. The AI models were trained on annotated datasets from previous floods and fine-tuned using transfer learning to adapt to local urban morphologies and debris typologies.

4 Main progress

Mário Franca visited the Disaster Prevention Research Institute (DPRI) at Kyoto University from February 10, 2025, to February 28, 2025. During this period, he presented three seminars:

1. "Karlsruhe Institute of Technology, a partner for research and education" on February 10, 2025, to Prof. Kantoush's group. He showcased the Karlsruhe Institute of Technology and the Institute for Water and Environment, focusing on organization, general information, research, and education programs.
2. "Floating Debris: Challenges for Flood Risk Management" on February 20, 2025, an oral presentation at the DPRI Annual Meeting, Uji, in collaboration with Prof. Kantoush.
3. "Integrating floating debris transport mechanics into urban flood management" on February 25, 2025, a Water Resources Research Center Seminar at DPRI-Kyoto University, focusing on research related to the project topic.

Together with Prof. Kantoush, Prof. Franca initiated the co-supervision of two PhD students:

- Mr. Ferreira, a PhD student at the Karlsruhe Institute of Technology, supervised by M. Franca and co-supervised by S. Kantoush and Dr. Vanzo (KIT-IWU).
- Mr. Lu, a PhD student at DPRI Kyoto University, supervised by S. Kantoush and co-supervised by M. Franca.

Both teams, from KIT and DPRI, performed data analysis and initiated the redaction of scientific article titled "Harnessing Geospatial Machine Learning and Physics-based Metaheuristic Algorithms for Landslide Susceptibility Mapping: Insights from Germany and Japan" (tentative title), co-authored by A. Pourzangbar (KIT-IWU), M. Saber (DPRI-KU), S. Kantoush (DPRI-KU), and M. Franca (KIT-IWU). M. Franca held discussion on data analysis and theoretical interpretation of results with PhD students:

- Mr. Hossein Sohrabzadeh
- Mr. Lu Cheng-Lin
- Mr. Shiwomeh Desmond

5 Conclusions and way forward

The project made significant progress in understanding and managing the risks associated with debris transport during extreme flood events, and namely on a comparison of best research and flood management practices between Germany and Japan. The collaborations and initiatives undertaken during this period are a strong foundation for future research and practical applications in flood management strategies.

This report has highlighted the critical and often overlooked role of floating debris in exacerbating flood risks. Drawing from recent research and case studies, particularly the 2024 Valencia floods and the 2021 European floods, we have shown that debris such as vehicles, plastics, and construction materials significantly intensify flood impacts by obstructing drainage systems, damaging infrastructure, and endangering lives. Despite this, debris dynamics remain largely absent from conventional flood risk assessments and urban planning frameworks.

The analysis of the two foundational studies—Bayón et al. (2024) and Valero et al. (2024)—demonstrates the growing scientific understanding of Urban Flood Drifters (UFDs), their classification, and the thresholds for their mobilization. Building on this, our proposed integration of artificial intelligence (AI) techniques offers a promising path forward. AI can enhance debris tracking, automate post-flood assessments, and support the development of predictive models that account for debris behavior in complex urban environments.

Looking ahead, a multi-pronged strategy is essential. This includes: - Embedding debris dynamics into flood hazard models and risk maps - Developing AI-enhanced tools for real-time debris monitoring and forecasting - Reforming urban planning to include debris-sensitive infrastructure design - Establishing policy mandates that require debris impact assessments in flood management

Bridging the gap between scientific knowledge and practical implementation will require collaboration across disciplines, investment in data collection technologies, and the political will to prioritize resilience. By integrating debris dynamics into flood risk management, cities can better prepare for and mitigate the devastating impacts of future flood events.

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Karlsruhe Institute of Technology (KIT), Germany