AGU ADVANCING EARTH AND SPACE SCIENCES

Water Resources Research

COMMENTARY
10.1029/2025WR041574

Why Should Urban Debris Dynamics Be Considered in Urban Flood Management?

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Key Points:

- This Commentary highlights the urgent need to integrate floating debris considerations into urban flood planning and emergency response
- A solution-oriented roadmap is possible and we propose an actionable strategy toward the integration of debris into flood risk management
- This Commentary aims at contributing toward higher levels of safety and resilience in cities

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Citation:
Franca, M. J., Cook, R., Pourzangbar, A., Xia, X., Valero, D., Vanzo, D., et al. (2025). Why should urban debris dynamics be considered in urban flood management? *Water Resources Research*, *61*, e2025WR041574. https://doi.org/10.1029/2025WR041574

Received 7 JUL 2025
Accepted 2 DEC 2025

Abstract Climate change, urbanization, and inadequate infrastructure exacerbate urban flood risks, yet one critical factor remains largely overlooked: hazardous debris such as cars, construction materials, wood, plastic containers among others. In the Valencia 2024 flood alone, the Spanish Insurance Compensation Consortium reported about 144,000 vehicles damaged or destroyed, many of them mobilized by the flow, which demonstrates the scale of large-debris impacts during floods. Debris alters and intensifies flooding impacts by clogging drainage systems and streets, decreasing flow conveyance, and causing direct damage to infrastructure, lives, and ecosystems. Nevertheless, debris dynamics are largely absent from flood risk assessments and management strategies. This Commentary highlights the urgent need to integrate debris considerations into urban flood planning and emergency response. Using case studies from recent catastrophic floods, we illustrate how debris amplifies hazard. We explore emerging scientific insights into the influence of debris in different flood types (flash, fluvial, coastal, tsunamis), and discuss why current management strategies fail to incorporate this factor. A solution-oriented roadmap is possible and we propose an actionable strategy toward the integration of debris into flood risk management, contributing to adapting cities toward higher levels of safety and resilience.

Plain Language Summary Combined with climate change, increasing urbanization and inadequate infrastructure, hazardous debris such as cars, construction material, wood, plastic containers among other urban elements, are contributing to more complex and destructive floods. The debris intensifies flooding impacts by clogging drainage systems and streets, increasing flow resistance, and causing direct damage to infrastructure, lives, and ecosystems. In the Valencia 2024 flood alone, the Spanish Insurance Compensation Consortium reported about 144,000 vehicles damaged or destroyed, many of them mobilized by the flow, which demonstrates the scale of large-debris impacts during floods. Despite this evidence, authorities and consultants do not consider debris when assessing flood risk and when preparing flood management strategies. With this Commentary, using documentation from recent catastrophic floods, we illustrate how debris amplifies hazard, we explore emerging scientific insights which can help, and we propose a solution-oriented roadmap for integrating debris into flood resilience strategies, thus contributing to bridge the implementation gap toward cities with higher levels of safety and resilience.

1. Introduction

Extreme weather events, including floods, are the second most perceived immediate risk (WEF, 2025). Every year, floods affect about 250 million people and cause roughly USD 40 billion in damages and, according to the OECD (2016), there is a growing insurance gap and fiscal burden on governments in the aftermath of increasingly frequent severe floods. Despite a decline in flood-related fatalities (Paprotny et al., 2018), annually inundated areas continue to increase, and exposure remains uneven. Low- and middle-income countries are most heavily affected (Khan, 2005), and even within high-income countries, income inequalities correlate with higher fatality rates (Lindersson et al., 2023). This vulnerability will likely increase driven by (a) climate-change-induced shifts in rainfall frequency and intensity (Alfieri et al., 2015; Liu et al., 2014), and (b) urbanization (Venegas-Cordero et al., 2024).

Whilst a changing climate is clearly increasing flood risk, urbanization may induce even sharper changes in catchment responses. In the metropolitan area of Valencia, Spain, heavily impacted by the extreme flood event of

October 2024, soil sealing by intensive urbanization, which increases peak flows and flood volumes, has more than tripled in area from 1957 to 2012 (Alemany Martínez & López García, 2016; Valera Lozano et al., 2019). While these factors are well recognized, another significant yet understudied consequence of urbanization is the role of debris in urban floods.

In mountain catchments, extreme floods can be responsible for the transport of large amounts of sediment and natural wood (Ruiz-Villanueva et al., 2016), often blocking bridges and causing backwater flooding (Schalko et al., 2018) or direct infrastructure damage through impact (Jalayer et al., 2018; Sturm et al., 2018; Zhang et al., 2018). In densely urbanized areas, debris sources are more varied (Bayón et al., 2024). In their comparative analysis with historical events, Ludwig et al. (2023) concluded that post-industrial debris had a fundamental role on the increased impact of the July 2021 Ahr and Erft floods, Germany. Bridge blockages due to debris were largely made up of anthropogenic objects (Erpicum et al., 2024; Burghardt et al., 2025).

Passenger vehicles, that is, cars, are abundant and are easily swept away (Martínez-Gomariz et al., 2018), posing risks to both passengers and bystanders, and also leading to clogging of urban infrastructure by vehicles (Erpicum et al., 2024). On the other hand, smaller debris such as plastics and other litter are ubiquitous and can cause obstructions on the drainage infrastructure. It is estimated that over 200 million people—mainly in low-income countries—face increased flood risk due to plastic-clogged drainage (Cooper & Letsinger, 2023). Clogging reduces drainage efficiency, causing deeper and longer floods, and greater risks to people and infrastructure.

Here, we advocate for a forward-thinking approach to urban flood management—one that builds on existing practices and leverages the knowledge available within the scientific and technical community. While hydraulic modeling of flood propagation based on depth and flow velocity has been a valuable foundation, it is now necessary to go further. The step we advocate is to consider the mobilization and transport of debris generated within the urban network in flood management.

2. Impact of Urban Flood Drifters in Floods

Debris here refers to objects that are not moored or fixed and can become mobile under extreme flow conditions, posing significant hazards; in urban environments, such debris is often termed Urban Flood Drifters (UFDs) in Bayón et al. (2024) and it includes, for example, plastic, vegetation, household items, construction materials, cars, bins, woody debris (tree trunks, logs, root wads) and garden sheds.

The presence of debris during floods increases flow resistance and causes a substantial increase in danger to lives, property, and infrastructure. On a survey conducted on mortality induced by flash floods across the USA, during the period 1996–2014, Tertin et al. (2017) concluded that more than 63% of the casualties were associated to incidents with vehicles, which according to Bayón et al. (2024) have a prevalence of about 11% in post-flood imagery; in their analysis, Yari et al. (2022) found that flood-induced mortality rates increased by 6% with the presence of debris.

Direct impact from objects transported by the flood can cause significant structural damage to buildings and houses (Pasha et al., 2024) and they obstruct transport networks, compromise hydraulic infrastructures and damage the built environment (Erpicum et al., 2024; Furlan et al., 2021; Wüthrich et al., 2025).

Debris can also block drainage systems and bridge openings, and form temporary dams, endangering downstream communities if suddenly released. During the October 2024 floods in Valencia and the July 2021 floods in central Europe (Mohr et al., 2022), witnesses reported the formation of "little tsunamis" (flow bursts), likely caused by debris jams collapsing upstream, catching flood victims by surprise. In 2018, a flash flood in Sant Llorenç des Cardassar, Spain, transported considerable amounts of woody debris and sediment which contributed to 13 casualties and damaged over 300 homes (Lorenzo-Lacruz et al., 2019). Similarly, in 2019, a flash flood in the Francolí River, Spain, uprooted over 20,000 trees which accumulated at bridges and exacerbated flooding effects (Martín-Vide et al., 2023); the debris contributed to the failure of three bridges, six casualties and estimated 44 million euros of damages.

More recently, in the 2024 Rio Grande do Sul floods, in Southern Brazil, debris exacerbated the disaster impact and severity by damaging infrastructure (Egas et al., 2024; Rückert et al., 2024) and acted as a vector of environmental pollution (Caleffi et al., 2024). Through a discourse analysis of semi-structured interviews with researchers in France and Quebec, Genouel et al. (2024) showed that debris is referred as one of the main types of

Figure 1. UFDs block a street of Catarroja municipality after the October 2024 Valencia floods, Spain. Author: Arnau Bayón.

pollution in urban flooding. Further debris can collide with people trapped in the water (Bocanegra & Francés, 2021; Yari et al., 2022) and may pose health risks (Jonkman & Kelman, 2005).

Debris may interfere with emergency actions and relief efforts, both of which are essential services in the immediate aftermath and during post-event recovery (Arrighi et al., 2019; Kameshwar et al., 2021). After the Valencia event, significant debris remained scattered across the landscape for months, extending the distress for victims and the impacts of the disaster (Figure 1). In the aftermath of Typhoon Haiyan (2013), in Tacloban City, Philippines, debris-laden flood waters prolonged stagnation, increasing risk of disease outbreaks and complicating the relief effort. Martins-Filho et al. (2024), in reflecting on the 2024 Rio do Grande do Sul floods, suggests that contact with contaminated objects and debris increases the risk of tetanus.

In countries such as Pakistan, debris can have a greater impact where a large proportion of the country's population live in earthen houses (Pasha et al., 2024). In 2010, floods in Pakistan resulted in more than 1,700 deaths, and over 1.5 million houses were damaged or destroyed, mostly by impacting debris (Pasha et al., 2024). The floods in Pakistan demonstrate how communities in areas with informally built housing, as well as densely populated areas are especially vulnerable to the impacts of debris during floods.

Debris also pose significant hazards also during tsunamis, hurricanes, and coastal floods. The amount of debris mobilized during extreme events is astonishing; the 2011 Tōhoku tsunami in Japan washed an estimated 5 million tons of debris into the Pacific Ocean (Japanese Ministry of the Environment, 2012), a volume on par with or even exceeding global plastic loads (0.8–2.7 million tons) carried from rivers to the sea over the entire year (Meijer et al., 2021).

Nistor et al. (2017) and Kaida et al. (2024) highlight the hazardous role of debris collision during the Indian Ocean Tsunami (26 December 2004), the 2010 Chilean Tsunami (24 February 2010), the Japanese Tōhoku tsunami (11 March 2011) and the Indonesian Sulawesi tsunami (28 September 2018). During the 2011 Tōhoku tsunami, the debris impact triggered the destruction of 17 LPG tanks at the Chiba refinery (Krausmann & Cruz, 2013), leading to asphalt leaks into the ocean; a domino effect of infrastructure failure, inducing secondary hazards such as fires, electrocution and chemical spills.

In coastal areas, debris, including boats, vehicles, and construction materials, intensifies wave action during storms and further compromises flood defenses (Stolle et al., 2018). During Hurricane Katrina (2005), debris impacts caused the rupture of a large oil storage tank, and the Mississippi River was closed to navigation due to the high storm surge and the debris carried by the storm (Cruz & Krausmann, 2013).

Each type of flood presents unique challenges in managing the additional risk brought by debris. Although debris is ubiquitous in all floods and it is difficult to attribute specific categories of debris to a particular flood type, we can still observe that certain types are more prevalent in specific flood events.

3. Leveraging Existing Knowledge for Practice: A Roadmap

Current flood management and emergency strategies lack integration of sediment and debris dynamics despite the evidence of their devastating impacts. Protection against sediment-based debris flow in urban areas is typically managed by installation of sediment traps (Lucas-Borja et al., 2021). While there are no consolidated design guidelines, there is extensive practical experience available for the construction of these. Regarding other types of debris affecting urban areas however, there are few examples of implementation, and the EU Water Framework Directive (EPC, 2000) does not mention this at all.

Nevertheless, some cities around the world have begun integrating debris management into their flood resilience strategies. In Jakarta, the government has installed trash booms—solid waste barriers in key waterways—and promoted community-based waste management programs to reduce the volume of debris clogging drainage canals and rivers (UNFCCC, 2023). Similarly, Tokyo, developed an advanced urban flood infrastructure with the Metropolitan Area Outer Underground Discharge Channel (G-Cans Project) (Writer, 2022), which includes trash screens to filter floating debris. In Bangkok, the authorities equipped pumping stations with debris filtering mechanisms, combined with floating trash barriers and community clean-up initiatives to reduce plastic pollution in the drainage canal system (OECD, 2015). In Zurich, a wood retention system upstream of the urban area was implemented to intercept large wood before it reaches the city (Schmocker & Weitbrecht, 2013).

The US Federal Emergency Management Agency, recognizing that debris removal alone accounts for around 27% of total disaster recovery costs (FEMA, 2007), established guidelines that address urban debris management during floods in the Public Assistance Program and Policy Guide (FEMA, 2020). Similarly, Australia's Flood Emergency Plans include debris considerations, most often related to clearance of debris (AIDR, 2020). From a planning perspective, the framework developed and applied to the Godelleta municipality (Valencia, Spain), by Bocanegra and Francés (2021) is an excellent practical tool for the relevant authorities. In this framework, vehicle stability is assessed at stream crossings during floods by combining hydrodynamic hazard analysis and vulnerability assessment.

We believe that the actual scientific and technological advances already offer practical opportunities to include debris dynamics in urban flood management. We set out a structured roadmap (Figure 2), which combines empirical practices with existing theoretical and modeling knowledge, with the following key steps:

1. As is commonly done by civil protection authorities, a first stage involves hydrodynamic analysis of inundation in the urban area, often for steady state and based on a particular return period. This provides information on flood extent and key indicators of hazard such as flow depth and velocity in the streets.
2. Surveys at street level should be carried out to map exposure of debris available across the urban fabric which has the potential to be mobilized during a flood, adopting for example, a classification such as in Bayón et al. (2024). These surveys can be done in various ways (field trips, drones, surveillance cameras, satellite imagery, citizen science or social media analysis) and include debris source identification.
3. By combining the outputs of Step 1 and Step 2, a street scale assessment of the potential for debris mobilization can be made (using e.g., Bocanegra et al., 2019; Martínez-Gomariz et al., 2018, 2020; Smith et al., 2019; Valero et al., 2024; Xia et al., 2014). The results of the hydrodynamic analysis (Step 1) and of the urban exposure to UFD mapping (Step 2) are often considered as being deterministic. However, in reality they are stochastic as errors and uncertainties associated with the modeling process, and the spatial-temporal variability of the surveyed quantities (e.g., number of cars in a street may depend on the time of the day, on the day of the week and on the season or month of the year) introduces uncertainties in the mapping.
4. With the output from Step 3, identification of hotspots can be carried out to find those locations at highest risk. In particular, this should focus on transport pathways, potential blockage (e.g., bridges and junctions), impacts to evacuation routes, schools, hospitals and care homes, industrial sites, electrical distribution, and other critical infrastructure.

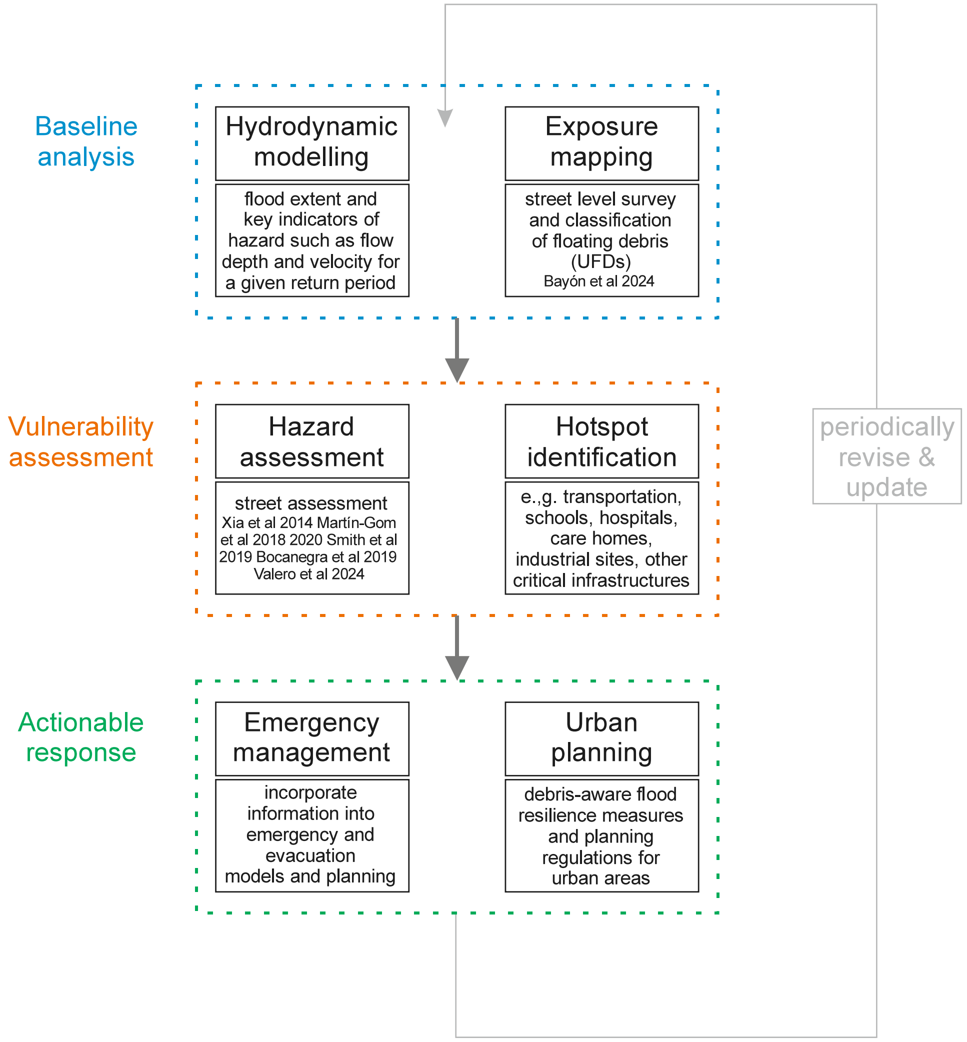

Figure 2. A roadmap to leverage existing knowledge to integrate urban debris dynamics in flood management.

5. The insights from Step 3 should also be incorporated into emergency planning and evacuation models to assist in identifying emergency access corridors and possible problems.
6. Urban planning should incorporate the insights from the steps above, including debris-aware flood resilience measures and planning regulations for urban areas (e.g., street sizing and arrangement, or utilization and occupancy restrictions). Urban transport planning should also consider debris hazard when planning for the early-warning and emergency phases (see discussion by Bocanegra & Francés, 2021).

4. Actionable Strategies for Enhancing Flood Management

Cities like Jakarta, Tokyo and Bangkok have successfully demonstrated commitment to strategies for debris management, but large-scale adoption of measures to counteract debris-enhanced hazard during floods remains restricted. This implementation gap calls for a comprehensive, multi-level strategy that combines technological, institutional, and behavioral responses, which should prioritize fundamental research on a topic not yet mature enough to produce concrete guidelines.

- Bridging the knowledge gap

Training programs for professionals in urban planning, flood management, and emergency services should incorporate emerging techniques, which remain absent in engineering and planning curricula. Specifically, national and regional authorities should prioritize professional capacity-building through specialized training programs and certifications that focus on debris flood hazard. This should be incorporated in flood management training. Finally, the application of existing findings must be systematically translated, and updated when needed, into practical frameworks and guidelines.

- Integrating debris dynamics into policy and regulation

To ensure that debris dynamics are considered in all flood planning and response strategies, the creation of technical guidelines updating international and national flood management policies is needed. A structured approach involves prioritizing international and national guidelines for debris-aware planning, as is done in flood zoning. Relevant government authorities should require, where relevant, the inclusion of debris scenarios in flood management including contingency planning and flood simulations. This may include redesigning the urban fabric, and adapting land-use planning and zoning, to account for areas prone to debris transport and accumulation. An adaptive governance structure to implement comprehensive debris management strategies is essential; this should include urban planners, emergency services, environmental agencies and infrastructure managers. Finally, to ensure the long-term success of integration, indicators to measure the effectiveness of policy and regulatory cycles should be developed. These can include metrics such as the reduction in road blockages and improvements in evacuation times, providing a clear measure of the impact of these interventions.

- Advancing structural and engineering measures

Structural interventions may be the only option for managing debris during flood events, but further research and development are necessary to optimize the design and performance across diverse urban contexts and boundary conditions. These should focus on research, design and pilot testing of urban-scale debris barriers, including trash booms, flexible fences, and channel-side retention systems. Additionally, retrofitting susceptible critical infrastructure to withstand debris impacts is essential. Structural measures must have regular maintenance plans to ensure their long-term effectiveness and sustainability.

- Improvement of monitoring and early warning systems

Real-time debris monitoring using ground and remote sensing should be integrated into early warning systems that advise residents on securing or removing movable assets and provide debris-aware behavioral guidance. Urban control centers that combine hydrological data with information on locations in the urban grid where debris may cause problems, can enhance situational awareness and support timely decision-making (e.g., guiding first responders more efficiently). Creating open data platforms where cities share debris and flood information may collaboratively improve overall preparedness and emergency response.

- Financial incentives and insurance innovation

Financial tools and insurance can play a significant role in encouraging better flood preparedness considering debris dynamics, by incorporation of market-based instruments. The insurance industry can serve as a powerful driver for changing practices and fostering a behavior culture by recognizing debris risks and encouraging preventative actions. Insurers should take debris-related risks into account when setting flood insurance premiums, and offer discounts or benefits for institutions, people and businesses that take steps to mitigate these effects and protect their assets (e.g., regular clearing of drainage systems, secure moving of belongings, installation of debris barriers). Governments can also offer tax breaks or funding to support these actions, encouraging property and businesses owners to implement preventative measures.

- Community engagement and equity

Authorities should run public awareness campaigns to inform people about how debris can make floods more dangerous, and promote actions like securing loose items, joining clean-up efforts and collaborating in an efficient trash management to reduce the amount of debris that can be mobilized during flood events. Reducing the reliance on private cars and creating car-free areas, particularly during storm events, can contribute to lowering debris risk. Citizen science projects can help track debris-prone areas and improve risk maps, while schools and local groups can teach children and adults about flood resilience and reducing waste. Vulnerable communities, such as those living in informal housing, low-income areas, or neighborhoods with many elderly residents, face higher risks, hence policies must take these social inequalities into account.

- Research and innovation

Priorities in research and innovation should include advancing debris transport modeling, especially in relation to fluid-structure interactions, impact on evacuees, and cross-sector solutions that link mobility and traffic research with flood risk management. A conceptual framework that incorporates debris dynamics into urban planning and risk assessments is needed. Interdisciplinary and intersectoral research can contribute to debris-aware flood management tools.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

No new data were generated or analyzed in support of this Commentary.

Acknowledgments
None.

References

Alemany Martínez, M., & López García, M. J. (2016). Transformaciones recientes en el Área Metropolitana de València. Evolución de los usos del suelo en el municipio de Torrent (1956-2011). *Cuadernos de Geografía*, *98*, 89–107.

Alfieri, L., Burek, P., Feyen, L., & Forzieri, G. (2015). Global warming increases the frequency of river floods in Europe. *Hydrology and Earth System Sciences*, *19*(5), 2247–2260. https://doi.org/10.5194/hess-19-2247-2015

Arrighi, C., Pregnolato, M., Dawson, R. J., & Castelli, F. (2019). Preparedness against mobility disruption by floods. *Science of The Total Environment*, *654*, 1010–1022. https://doi.org/10.1016/j.scitotenv.2018.11.191

Australian Institute for Disaster Resilience (AIDR). (2020). Flood emergency planning for disaster resilience. *Australian Disaster Resilience Handbook Collection*.

Bayón, A., Valero, D., & Franca, M. J. (2024). Urban flood drifters (UFD): Identification, classification and characterisation. *Journal of Flood Risk Management*, *17*(3), e13002. https://doi.org/10.1111/jfr3.13002

Bocanegra, R. A., & Francés, F. (2021). Determining the vehicle instability risk in stream crossings. *Journal of Flood Risk Management*, *14*(4), e12737. https://doi.org/10.1111/jfr3.12737

Bocanegra, R. A., Vallés-Morán, F. J., & Francés, F. (2019). Review and analysis of vehicle stability models during floods and proposal for future improvements. *Journal of Flood Risk Management*, *13*(S1), e12551. https://doi.org/10.1111/jfr3.12551

Burghardt, L., Klopries, E. M., & Schüttrumpf, H. (2025). Structural damage, clogging, collapsing: Analysis of the bridge damage at the rivers Ahr, Inde and Vicht caused by the flood of 2021. *Journal of Flood Risk Management*, *18*(1). 13001. https://doi.org/10.1111/jfr3.13001

Caleffi, F., Viegas, C. V., Lima, K. B., & Bonato, S. V. (2024). The impacts of extreme weather events: A comprehensive analysis of the 2024 floods in Rio Grande do Sul. Redes: revista do desenvolvimento regional. *Santa Cruz do Sul, RS*, *29*, 1–27. https://doi.org/10.17058/redes.v29i1.19660

Cooper, B., & Letsinger, S. (2023). The impact of plastic pollution on urban flooding events. *Tearfund technical report*. Retrieved from https://learn.tearfund.org/en/resources/research-report/plastic-pollution-and-flooding

Cruz, A. M., & Krausmann, E. (2013). Vulnerability of the oil and gas sector to climate change and extreme weather events. *Climatic Change*, *121*(1), 41–53. https://doi.org/10.1007/s10584-013-0891-4

Egas, H. M., Stabile, R. A., de Andrade, M. R. M., Michel, G. P., de Araújo, J. P. C., Michel, R. D. L., et al. (2024). Comprehensive inventory and initial assessment of landslides triggered by autumn 2024 rainfall in Rio Grande do Sul, Brazil. *Landslides*, *22*(2), 579–589. https://doi.org/10.1007/s10346-024-02410-w

Erpicum, S., Poppema, D., Burghardt, L., Benet, L., Wüthrich, D., Klopries, E. M., & Dewals, B. (2024). A dataset of floating debris accumulation at bridges after July 2021 flood in Germany and Belgium. *Scientific Data*, *11*(1), 1092. https://doi.org/10.1038/s41597-024-03907-8

European Parliament and Council (EPC). (2000). Directive 2000/60/EC of the European Parliament and of the Council – Water framework directive. *Official Journal of the European Communities*, *L327*, 1–72.

Federal Emergency Management Agency (FEMA). (2007). Public assistance – Debris management guide. *U.S. Department of Homeland Security*.

Federal Emergency Management Agency (FEMA). (2020). *Public assistance – Program and policy guide*. U.S. Department of Homeland Security.

Furlan, P., Pfister, M., Matos, J., Amado, C., & Schleiss, A. J. (2021). Blockage probability modeling of large wood at reservoir spillways with piers. *Water Resources Research*, *57*(8), e2021. https://doi.org/10.1029/2021wr029722

Genouel, M., Comby, E., Le Lay, Y. F., & Biron, P. (2024). Urban flooding and the resultant pollution: What French-speaking scientists make of it? *Anthropocene*, *46*, 100436. https://doi.org/10.1016/j.ancene.2024.100436

Jalayer, F., Aronica, G. T., Recupero, A., Carozza, S., & Manfredi, G. (2018). Debris flow damage incurred to buildings: An in situ back analysis. *Journal of Flood Risk Management*, *11*(S2), S646–S662. https://doi.org/10.1111/jfr3.12238

Japanese Ministry of the Environment. (2012). Estimated total amount of debris washed out by the great East Japan earthquake. Retrieved from http://www.env.go.jp/en/focus/docs/files/20120901-57.pdf

Jonkman, S. N., & Kelman, I. (2005). An analysis of the causes and circumstances of flood disaster deaths: An analysis of the causes and circumstances of flood disaster deaths. *Disasters*, *29*(1), 75–97. https://doi.org/10.1111/j.0361-3666.2005.00275.x

Kahn, M. E. (2005). The death toll from natural disasters: The role of income, geography, and institutions. *The Review of Economics and Statistics*, *87*(2), 271–284. https://doi.org/10.1162/0034653053970339

Kaida, H., Tomita, T., Yoshimura, S., & Kihara, N. (2024). Review of evaluation of tsunami-induced debris collision force. *Coastal Engineering Journal*, *66*(3), 492–518. https://doi.org/10.1080/21664250.2024.2341471

Kameshwar, S., Park, H., Cox, D. T., & Barbosa, A. R. (2021). Effect of disaster debris, floodwater pooling duration, and bridge damage on immediate post-tsunami connectivity. *International Journal of Disaster Risk Reduction*, *56*, 102119. https://doi.org/10.1016/j.ijdrr.2021.102119

Krausmann, E., & Cruz, A. M. (2013). Impact of the 11 March 2011, Great East Japan earthquake and tsunami on the chemical industry. *Natural Hazards*, *67*(2), 811–828. https://doi.org/10.1007/s11069-013-0607-0

Lindersson, S., Raffetti, E., Rusca, M., Brandimarte, L., Mard, J., & Di Baldassarre, G. (2023). The wider the gap between rich and poor the higher the flood mortality. *Nature Sustainability*, *6*(8), 995–1005. https://doi.org/10.1038/s41893-023-01107-7

Liu, M., Xu, X., Sun, A. Y., Wang, K., Liu, W., & Zhang, X. (2014). Is southwestern China experiencing more frequent precipitation extremes? *Environmental Research Letters*, *9*(6), 064002. https://doi.org/10.1088/1748-9326/9/6/064002

Lorenzo-Lacruz, J., Garcia, C., Morán-Tejeda, E., Amengual, A., Homar, V., Maimó-Far, A., et al. (2019). Hydro-meteorological reconstruction and geomorphological impact assessment of the October 2018 catastrophic flash flood at Sant Llorenç, Mallorca (Spain). *Natural Hazards and Earth System Sciences Discussions*, *2019*, 1–30.

Lucas-Borja, M. E., Piton, G., Yu, Y., Castillo, C., & Zema, D. A. (2021). Check dams worldwide: Objectives, functions, effectiveness and undesired effects. *Catena*, *204*, 105390. https://doi.org/10.1016/j.catena.2021.105390

Ludwig, P., Ehmele, F., Franca, M. J., Mohr, S., Caldas-Alvarez, A., Daniell, J. E., et al. (2023). A multi-disciplinary analysis of the exceptional flood event of July 2021 in central Europe–Part 2: Historical context and relation to climate change. *Natural Hazards and Earth System Sciences*, *23*(4), 1287–1311. https://doi.org/10.5194/nhess-23-1287-2023

Martínez-Gomariz, E., Gómez, M., Russo, B., & Djordjević, S. (2018). Stability criteria for flooded vehicles: A state-of-the-art review. *Journal of Flood Risk Management*, *11*(S2), S817–S826. https://doi.org/10.1111/jfr3.12262

Martínez-Gomariz, E., Russo, B., Gómez, M., & Plumed, A. (2020). An approach to the modelling of stability of waste containers during urban flooding. *Journal of Flood Risk Management*, *13*(S1), e12558. https://doi.org/10.1111/jfr3.12558

Martins-Filho, P. R., Croda, J., Araújo, A. A. D. S., Correia, D., & Quintans-Júnior, L. J. (2024). Catastrophic floods in Rio Grande do Sul, Brazil: The need for public health responses to potential infectious disease outbreaks. *Revista da Sociedade Brasileira de Medicina Tropical*, *57*, e00603–e02024. https://doi.org/10.1590/0037-8682-0162-2024

Martín-Vide, J. P., Bateman, A., Berenguer, M., Ferrer-Boix, C., Amengual, A., Campillo, M., et al. (2023). Large wood debris that clogged bridges followed by a sudden release. The 2019 flash flood in Catalonia. *Journal of Hydrology: Regional Studies*, *47*, 101348. https://doi.org/10.1016/j.ejrh.2023.101348

Meijer, L. J., Van Emmerik, T., Van Der Ent, R., Schmidt, C., & Lebreton, L. (2021). More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. *Science Advances*, *7*(18), eaaz5803. https://doi.org/10.1126/sciadv.aaz5803

Mohr, S., Ehret, U., Kunz, M., Ludwig, P., Caldas-Alvarez, A., Daniell, J. E., et al. (2022). A multi-disciplinary analysis of the exceptional flood event of July 2021 in central Europe. Part 1: Event description and analysis. *Natural Hazards and Earth System Sciences Discussions*, *2022*, 1–44.

Nistor, I., Goseberg, N., & Stolle, J. (2017). Tsunami-driven debris motion and loads: A critical review. *Frontiers in Built Environment*, *3*, 2. https://doi.org/10.3389/fbuil.2017.00002

OECD. (2015). *Green growth in Bangkok, Thailand, OECD green growth studies*. OECD Publishing. https://doi.org/10.1787/9789264237087-en

OECD. (2016). *Financial management of flood risk*. OECD Publishing. https://doi.org/10.1787/9789264257689-en

Paprotny, D., Sebastian, A., Morales-Nápoles, O., & Jonkman, S. N. (2018). Trends in flood losses in Europe over the past 150 years. *Nature Communications*, *9*(1), 1985. https://doi.org/10.1038/s41467-018-04253-1

Pasha, G. A., Asghar, M., Murtaza, N., Ghumman, A. R., Ahmed, A., & Iqbal, K. (2024). Impact of floating debris on houses during floods and vegetation-based mitigation. In *Proceedings of the institution of civil engineers-water management* (pp. 1–16). https://doi.org/10.1680/jwama.23.00055

Rückert, A. A., Vicente, F. J., & Gomes, L. F. R. (2024). The 2024 Climate Tragedy in Rio Grande do Sul, Brazil. Notes on a foreseen catastrophe. *Geografares*(39).

Ruiz-Villanueva, V., Piégay, H., Gurnell, A. M., Marston, R. A., & Stoffel, M. (2016). Recent advances quantifying the large wood dynamics in river basins: New methods and remaining challenges. *Reviews of Geophysics*, *54*(3), 611–652. https://doi.org/10.1002/2015RG000514

Schalko, I., Schmocker, L., Weitbrecht, V., & Boes, R. M. (2018). Backwater rise due to large wood accumulations. *Journal of Hydraulic Engineering*, *144*(9), 04018056. https://doi.org/10.1061/(asce)hy.1943-7900.0001501

Schmocker, L., & Weitbrecht, V. (2013). Driftwood: Risk analysis and engineering measures. *Journal of Hydraulic Engineering*, *139*(7), 683–695. https://doi.org/10.1061/(asce)hy.1943-7900.0000728

Smith, G. P., Modra, B. D., & Felder, S. (2019). Full-scale testing of stability curves for vehicles in flood waters. *Journal of Flood Risk Management*, *12*(S2), e12527. https://doi.org/10.1111/jfr3.12527

Stolle, J., Goseberg, N., Nistor, I., & Shibayama, T. (2018). Debris impacts and effects on structures. In *Handbook of coastal and Ocean engineering* (pp. 457–479).

Sturm, M., Gems, B., Keller, F., Mazzorana, B., Fuchs, S., Papathoma-Köhle, M., & Aufleger, M. (2018). Understanding impact dynamics on buildings caused by fluviatile sediment transport. *Geomorphology*, *321*, 45–59. https://doi.org/10.1016/j.geomorph.2018.08.016

Terti, G., Ruin, I., Anquetin, S., & Gourley, J. J. (2017). A situation-based analysis of flash flood fatalities in the United States. *Bulletin of the American Meteorological Society*, *98*(2), 333–345. https://doi.org/10.1175/bams-d-15-00276.1

United Nations Framework Convention on Climate Change (UNFCCC). (2023). Urban flood management in Jakarta. Case study. Bonn, UN Climate Change Technology executive committee. Retrieved from https://unfccc.int/ttclear/misc_/StaticFiles/gnwoerk_static/TEC_NSI/b37e396ecf0b42879e913c50c75883e9/46cd95e108ae48cea7196244d2721393.pdf

Valera Lozano, A., Añó Vidal, C., & Sánchez Díaz, J. (2019). Urban growth (1956-2012) and soil sealing in the metropolitan area of Valencia (Eastern Spain). *Spanish Journal of Soil Science*, *9*(2), 88–104.

Valero, D., Bayón, A., & Franca, M. J. (2024). Urban flood drifters (UFDs): Onset of movement. *Science of The Total Environment*, *927*, 171568. https://doi.org/10.1016/j.scitotenv.2024.171568

Venegas-Cordero, N., Mediero, L., & Piniewski, M. (2024). Urbanization vs. climate drivers: Investigating changes in fluvial floods in Poland. *Stochastic Environmental Research and Risk Assessment*, *38*(7), 2841–2857. https://doi.org/10.1007/s00477-024-02717-z

World Economic Forum (WEF). (2025). The Global Risks Report 2025. Retrieved from https://reports.weforum.org/docs/WEF_Global_Risks_Report_2025.pdf

Writer, S. (2022). G-Cans Project: Tokyo's massive underground fortress for flood control. https://japanupclose.web-japan.org/tech/t20220302_1.html

10.1029/2025WR041574

Wüthrich, D., Korswagen, P. A., Selvam, H., Oetjen, J., Bricker, J., & Schüttrumpf, H. (2025). Field survey assessment of flood loads and related building damage from the July 2021 event in the Ahr Valley (Germany). *Journal of Flood Risk Management*, *18*(1), e13024. https://doi.org/10.1111/jfr3.13024

Xia, J., Falconer, R. A., Wang, Y., & Xiao, X. (2014). New criterion for the stability of a human body in floodwaters. *Journal of Hydraulic Research*, *52*(1), 93–104. https://doi.org/10.1080/00221686.2013.875073

Yari, A., Zarezadeh, Y., Ardalan, A., Boubakran, M. S., Rahimiforoushani, A., Bidarpoor, F., & Ostadtaghizadeh, A. (2022). Deadly floods and their causal factors: A case-control study in Iran between 2005 and 2018. *International Journal of Disaster Risk Reduction*, *77*, 103036. https://doi.org/10.1016/j.ijdrr.2022.103036

Zhang, S., Zhang, L., Li, X., & Xu, Q. (2018). Physical vulnerability models for assessing building damage by debris flows. *Engineering Geology*, *247*, 145–158. https://doi.org/10.1016/j.enggeo.2018.10.017