Pak. J. Engg. Appl. Sci. Vol. 33 July, 2025 (p. 40–49)

Developing Flood Vulnerability Functions Based on Secondary Data: A Case Study for Pakistan

Abdullah Nadeem[1], Muhammad Atiq Ur Rehman Tariq[2*], Wasif Ali[1]

1. *Centre of Excellence in Water Resources Engineering, University of Engineering and Technology, Lahore 54890, Pakistan*
2. *College of Engineering, IT and Environment, Charles Darwin University, Darwin, NT 0810, Australia*

* **Corresponding Author:** Email: atiq.tariq@yahoo.com

Abstract

Floods pose a significant threat to human life, infrastructure, and economic stability in developing nations like Pakistan, where a 1% increase in floods correlates with a 0.44% decrease in livelihood and a 1.947% rise in poverty levels. With approximately 20% of its land area and 40 million people exposed to flood risks annually, there is an urgent need for robust flood risk assessment tools. Effective flood vulnerability functions are essential for formulating data-driven disaster management policies and enhancing the flood resistance of buildings. However, existing global models fail to capture Pakistan's unique flood dynamics, necessitating the development of localized models. This study synthesizes global methodologies and integrates secondary data to create reliable tailored flood vulnerability functions. The research reveals a non-linear relationship between flood depth and damage across various building materials, with mud structures experiencing 82.5% damage at 0.5 meters and complete failure at 1.5 meters, while concrete structures show only 3.5% damage at 0.5 meters and a maximum of 65.9% at 3 meters. Additionally, the study highlights that prolonged flooding increases damage by 30-50%. Recommendations include prioritizing reinforced concrete in construction and implementing comprehensive flood risk management plans to enhance structural resilience and community safety in flood-prone regions.

Keywords: Environmental Impacts; Hydroponic system; LCA; Sustainability; Water Supply; Water Reuse.

1. Introduction

Floods pose a significant threat to human life, infrastructure, and economic stability, particularly in developing nations like Pakistan [1]. 1% increase in floods leads to a 0.44% decrease in livelihood and 0.31% decrease in economic status, resulting in a 1.947% increase in poverty level [2]. With approximately 20% of its land area and 40 million people exposed to flood risks annually, Pakistan faces an urgent need for robust flood risk assessment tools [3]. Effective flood vulnerability functions are critical for several reasons: they support the formulation of data-driven disaster management policies, quantify potential damage to prioritize resource allocation for flood-prone regions, and enhance the flood resistance of buildings and infrastructure through targeted interventions [4]. However, current global vulnerability functions, while well-established, fail to capture Pakistan's unique flood dynamics, construction practices, and socio-economic conditions. Therefore, developing localized models is essential to directly address these gaps and improve the country's resilience to flooding [5].

Flood vulnerability assessments play a crucial role in quantifying the potential damage inflicted by floods on buildings, infrastructure, and human settlements [6], [7]. These assessments typically express damage as a percentage of the total structural or economic value of an asset, considering various flood parameters such as depth, duration, and velocity. While vulnerability functions are widely utilized in developed countries, their application in developing regions like Pakistan is limited due to several constraints. One significant challenge is the heterogeneous construction practices across rural and urban areas, which vary greatly in building materials and structural designs. Additionally, Pakistan's monsoon-driven flooding leads to prolonged and widespread inundation, resulting in unique impacts that differ from the flash floods or storm surges experienced in other regions [8]. Compounding these issues is the lack of comprehensive historical flood damage data in Pakistan, which complicates the development of empirical models. To address these challenges, this study synthesizes global methodologies, adjusts them for Pakistan's local context, and integrates secondary data to develop reliable vulnerability functions tailored to the country's specific needs [9], [10].

The development of flood vulnerability functions has evolved significantly over the decades, beginning with early models that primarily focused on depth-damage relationships [11]. Pioneering work by the U.S. Army Corps of Engineers [12] and the Federal Emergency Management Agency [13] laid the groundwork for these models, which provided standard depth-damage curves for residential, commercial, and industrial buildings in the United States. Since then, global advancements have led to the emergence of more sophisticated approaches, including multi-parameter models that incorporate variables such as flood velocity, duration, and contamination, thereby offering a more nuanced understanding of flood impacts [14]. Additionally, countries like India and Malaysia have developed region-specific models that reflect their unique building practices and flood characteristics, as evidenced by studies conducted by [15] and [16]. Despite these advancements, Pakistan remains underrepresented in flood vulnerability research, highlighting a critical gap in the literature. This study aims to address this gap by combining insights from established global models with necessary region-specific adjustments, ultimately contributing to a more comprehensive understanding of flood vulnerability in Pakistan.

Flood damage parameters are critical in understanding the extent of destruction caused by flooding events. Among these, flood depth is recognized as the most significant determinant of damage severity [8], [17]. Numerous studies have established a non-linear relationship between flood depth and damage, indicating that structures made of mud and brick experience exponential increases in damage when depths exceed 1 meter [13], [18]. In addition to depth, the duration of flood exposure plays a crucial role in exacerbating damage. Prolonged exposure to floodwaters leads to material degradation, particularly in mud and brick structures. Damage percentages can increase by 30-50% for floods lasting more than 10 days compared to shorter events, underscoring the importance of duration in flood impact assessments [19]. Furthermore, flood velocity introduces additional inertial forces on structures, significantly increasing the likelihood of collapse [20]–[22]. Research by the Ontario Ministry of Natural Resources (OMNR, 1997) established that masonry buildings face considerable risks when flood velocities exceed 1.5 m/s, particularly when combined with high water depths [23].

The type of building materials used in construction significantly influences a structure's vulnerability to flooding. Mud buildings, which are prevalent in rural Pakistan, are particularly susceptible to complete structural failure even at shallow flood depths of less than 1 meter [24]. [25] attributed this vulnerability to the lack of reinforcement and the inherent water-absorbent properties of mud, which compromise structural integrity. In contrast, brick structures exhibit moderate resilience; however, they are not immune to damage [26]. Prolonged exposure to floodwaters can lead to mortar degradation, necessitating improved mortar compositions to enhance flood resistance [27]–[29]. Concrete, while recognized as the most resilient building material, is not without its vulnerabilities. Concrete structures can suffer long-term damage from prolonged exposure to floodwaters or poor drainage conditions, leading to risks of cracking and structural weakening due to trapped moisture [30]–[33]. Collectively, these studies underscore the importance of considering both flood damage parameters and building materials in assessing flood vulnerability and developing effective mitigation strategies.

Existing flood vulnerability models, such as those developed by the U.S. Army Corps of Engineers (USACE) and the Federal Emergency Management Agency (FEMA), are inadequate for Pakistan due to several key limitations. Firstly, these models often focus on materials that are uncommon in the region, such as wood and steel, neglecting the prevalent use of mud and brick. Secondly, they fail to integrate local conditions, such as prolonged monsoonal flooding and the lack of effective flood defenses. Additionally, most studies lack empirical validation within Pakistan, reducing their reliability for local applications. This study addresses these gaps by developing flood vulnerability functions specifically tailored to Pakistan, utilizing locally relevant materials and conditions to enhance the accuracy of flood risk assessments.

2. Methodology

The methodology for this study was structured into several systematic phases, beginning with comprehensive data collection from diverse sources to inform the development of flood vulnerability functions. Secondary data were sourced from established global models, including those developed by the Federal Emergency Management Agency [13] and the U.S. Army Corps of Engineers [12], as well as European depth-damage functions that provide foundational insights into flood impacts. Additionally, regional studies from India and Malaysia, which have been adapted to South Asian contexts [15], [16], were incorporated to enhance the contextual relevance of the models. Local data sources included historical flood records, construction typologies, and socio-economic data obtained from various Pakistani government agencies, ensuring a robust dataset reflective of the local environment.

In the parameter selection phase, four critical parameters were identified for analysis: depth, which was quantified on a scale ranging from 0 to 3 meters; duration, categorized into short (<10 days) and long (>10 days) flood events; velocity, measured in meters per second (m/s) with thresholds established as low (<0.8 m/s), moderate (0.8–1.5 m/s), and high (>1.5 m/s); and building materials, focusing on mud, brick, and concrete, which collectively represent over 90% of the structures in Pakistan.

The development of vulnerability functions involved a multi-step approach. Depth-damage relationships were derived empirically for each identified material type through statistical analysis of historical damage data, allowing for the establishment of damage curves that reflect the unique characteristics of local construction practices. Furthermore, the integration of duration and velocity parameters was accomplished using multi-variable regression models, which facilitated the examination of their combined effects on structural damage. This approach enabled the identification of interaction effects between the parameters, providing a more nuanced understanding of flood vulnerability.

3. Result and Discussion

The study revealed a non-linear relationship between flood depth and damage percentage across different building materials:

3.1.1 Mud Structures

- At 0.5 meters, 82.5% of structural damage was observed as shown in Fig. ***1***, increasing sharply to 95% at 1 meter [34]–[36].
- Complete structural failure (100% damage) occurred at a depth of 1.5 meters, indicating extreme vulnerability to shallow flooding [37]–[39].

3.1.2 Brick Structures

- Moderate resilience was noted up to 1 meter (58% damage) [40]–[42], but damage escalated to 83% at 2 meters and 95% at 3 meters as shown in Fig. ***2***.
- Beyond 3 meters, damage plateaued, with almost all structures sustaining near-total damage.

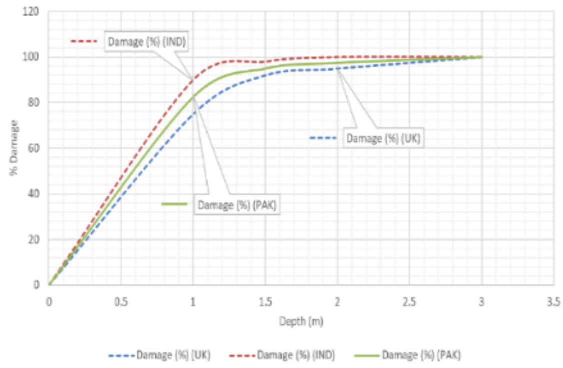

Fig. 1: Flood damage function for Pakistan based on Mud

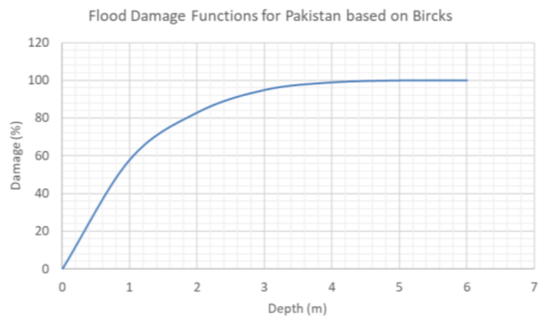

Fig. 2: Flood damage function for Pakistan based on bricks

3.1.3 Concrete Structures

- At 0.5 meters, only 3.5% damage was recorded [43]–[45].
- At 2 meters, damage rose to 32.5%, significantly lower than mud or brick buildings under similar conditions as shown in Fig. ***3*** [46].
- Maximum damage of 65.9% was observed at 3 meters, suggesting that reinforced concrete buildings maintain partial functionality even during severe flooding.

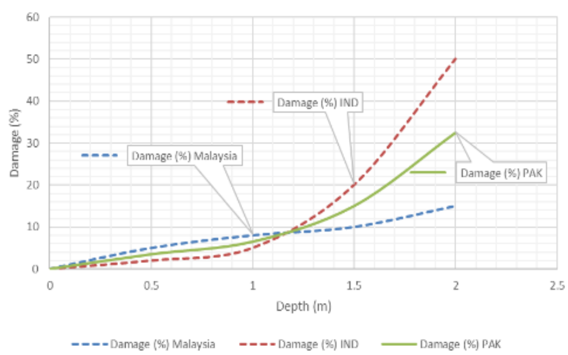

Fig. 3: Flood damage function for Pakistan based on concrete

3.2 Duration Impacts

Flood duration amplified damage across all building materials, with prolonged inundation (>10 days) resulting in substantial increases as shown in Fig. *4*:

- **Mud Structures**: Damage surged to 100% at depths as shallow as 0.25 meters, compared to 82.5% in short-duration floods [47].
- Brick Structures: Prolonged flooding increased damage by an average of 20%, with total structural compromise occurring at 2.5 meters [48]–[50].
- Concrete Structures: While generally resilient, prolonged exposure led to micro-cracking, water seepage, and eventual reinforcement degradation. Damage increased from 32.5% to 44.5% at 2 meters during extended flooding [51]–[53].

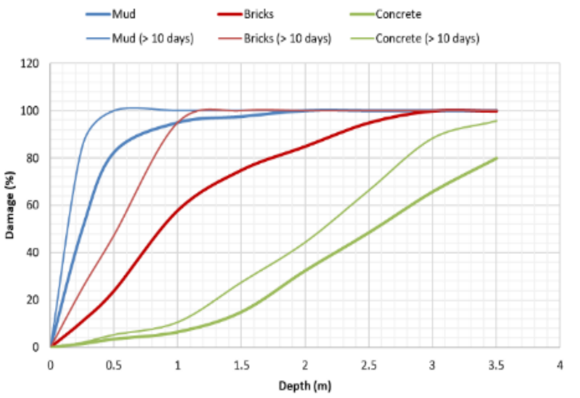

Fig. 4: Flood Damage Functions for Pakistan based on Duration for Mud, Bricks and Concrete

3.3 Velocity-Damage Relationships

Flood velocity was a critical factor in structural damage, particularly for mud and brick buildings as shown in Fig. *5*:

3.3.1 Mud Structures

- At velocities exceeding 1 m/s, 90% damage was recorded, even at shallow depths [54].
- Collapse occurred at velocities >1.5 m/s due to loss of cohesion in the mud [55].

3.3.2 Brick Structures

- High-velocity floods caused significant scouring at the foundations, leading to 100% damage at depths exceeding 1 meter when combined with velocities >1.5 m/s [56]–[58].

3.3.3 Concrete Structures

- While more resilient, structural issues such as foundation scouring and lateral displacement were observed at velocities >1.5 m/s. However, collapse was not recorded in any case, indicating superior durability [59]–[61].

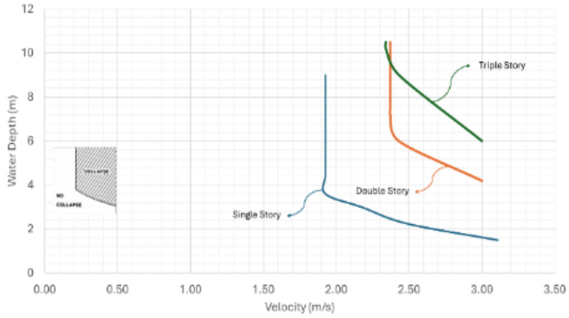

Fig. 5: Flood damage functions based on velocity and no. of stories

4. Discussion

The results confirm that flood depth is the primary determinant of damage severity, aligning with global studies [18]. Mud structures exhibited exponential damage escalation at shallow depths, with 100% damage occurring at 1.5 meters. This highlights the inadequacy of mud as a primary construction material in flood-prone regions.

Brick structures followed a more linear damage progression, but their reliance on mortar joints for structural integrity made them susceptible to degradation with increasing depth. Concrete structures, in contrast, demonstrated a non-linear but slower damage progression, emphasizing their utility in mitigating flood risks.

The implications are clear: construction practices in Pakistan must shift from vulnerable materials (mud, brick) to more resilient options (reinforced concrete) in flood-prone areas.

4.1 Role of Duration in Amplifying Damage

Flood duration exacerbated damage across all building materials [62], but the extent varied:

4.1.1 Mud Structures

- Completely failed under prolonged exposure, even at shallow depths. This vulnerability arises from the hydrophilic nature of mud, which dissolves and loses cohesion when saturated [63].

4.1.2 Brick Structures

- Suffered moderate increases in damage due to mortar degradation and water ingress. Prolonged flooding significantly impacted the structural integrity of walls and foundations [64], [65].

- Using hydraulic lime or water-resistant mortars can mitigate such vulnerabilities.

4.1.3 Concrete Structures

- The relatively minor impact of duration highlights the superiority of concrete. However, issues like water seepage and reinforcement corrosion under long-duration floods require attention, particularly in areas with poor drainage [66]–[68].

4.2 Velocity as a Secondary but Critical Factor

Velocity impacts structural stability through hydrodynamic forces, which can lead to scouring, lateral displacement, and collapse. The study revealed that:

- **Mud Structures**: Even low velocities (1 m/s) caused extensive damage due to erosion and foundation instability [69].
- **Brick Structures**: Moderate velocities (>1.2 m/s) scoured unreinforced foundations, leading to collapse when coupled with higher depths [70].
- **Concrete Structures**: Resisted collapse but required reinforcement at foundations to counter high-velocity impacts.

The findings underscore the importance of site-specific measures, such as embankments and riprap, to reduce velocity-related risks.

5. Conclusion

The study highlights the critical relationship between flood depth, duration, and velocity in determining structural damage across various building materials in flood-prone regions of Pakistan. The findings indicate that mud structures are particularly vulnerable, exhibiting rapid damage escalation with 82.5% damage at a flood depth of 0.5 meters, increasing sharply to 95% at 1 meter, and reaching complete failure (100% damage) at just 1.5 meters. Brick structures, while somewhat more resilient, show moderate damage of 58% at 1 meter, escalating to 83% at 2 meters and 95% at 3 meters, indicating significant susceptibility to deeper flooding. In contrast, concrete structures demonstrate a slower, non-linear progression of damage, with only 3.5% damage at 0.5 meters, rising to 32.5% at 2 meters, and a maximum of 65.9% at 3 meters, underscoring their superior resilience in flood conditions.

Moreover, the duration of flooding exacerbates damage across all materials. For mud structures, damage surged to 100% at depths as shallow as 0.25 meters during prolonged exposure, compared to 82.5% in short-duration floods. Brick structures experienced an average damage increase of 20% due to prolonged flooding, with total structural compromise occurring at 2.5 meters. Concrete structures, while generally resilient, saw damage increase from 32.5% to 44.5% at 2 meters during extended flooding, highlighting the need for ongoing maintenance and reinforcement.

Velocity also plays a crucial role, particularly for mud and brick buildings. At velocities exceeding 1 m/s, mud structures recorded 90% damage, even at shallow depths, while brick structures experienced 100% damage at depths exceeding 1 meter when combined with velocities greater than 1.5 m/s. Although concrete structures showed resilience, issues such as foundation scouring and lateral displacement were observed at velocities above 1.5 m/s, necessitating reinforcement at foundations to counter high-velocity impacts.

6. Recommendations

To enhance structural resilience in flood-prone areas of Pakistan, several key recommendations should be implemented. First, reinforced concrete should be prioritized as the primary construction material due to its superior performance, with only 3.5% damage at 0.5 meters and a maximum of 65.9% at 3 meters. For brick structures, using hydraulic lime or water-resistant mortars can improve durability against water ingress. Additionally, all new structures should be elevated above expected flood levels, particularly in historically flood-prone areas.

Reinforcing foundations is crucial to prevent scouring and lateral displacement during high-velocity floods, and regular maintenance protocols should be established to address issues like water seepage and reinforcement corrosion. Local governments must develop comprehensive flood risk management plans that include zoning regulations and community awareness programs to minimize construction in high-risk areas.

1. Investing in flood mitigation infrastructure, such as drainage systems and levees, is vital for managing floodwaters effectively. Community education programs focused on flood preparedness should also be implemented. Finally, ongoing research into innovative building materials and techniques, as well as the long-term impacts of climate change on

flood patterns, should be supported. By adopting these recommendations, stakeholders can significantly improve structural resilience and enhance community safety during flood events.

7. References

[1] Manzoor, Z., Shabbir, R., Abbas, A., Rehman, H. ur, Ahmad, R., & Hassan, M. (2022). Floods and flood management and its socio-economic impact on Pakistan: A review of the empirical literature. *Frontiers in Environmental Science*, 10, 2480. https://doi.org/10.3389/fenvs.2022.1021862

[2] Khayyam, U. (2020). Floods: Impacts on livelihood, economic status and poverty in the north-west region of Pakistan. *Natural Hazards*, 102(3), 1033–1056. https://doi.org/10.1007/s11069-020-03944-7

[3] Government of Pakistan. (2022). *Pakistan Monsoon Floods 2022 (Post-Disaster Needs Assessment)*. Financial Tracking Service, UNOCHA. https://fts.unocha.org/multiyear/2313/summary

[4] Alabbad, Y., Yildirim, E., & Demir, I. (2022). Flood mitigation data analytics and decision support framework: Iowa Middle Cedar Watershed case study. *Science of The Total Environment*, 814, 152768. https://doi.org/10.1016/j.scitotenv.2021.152768

[5] Heinzlef, C., Becue, V., & Serre, D. (2020). A spatial decision support system for enhancing resilience to floods: Bridging resilience modelling and geovisualization techniques. *Natural Hazards and Earth System Sciences*, 20(4), 1049–1068. https://doi.org/10.5194/nhess-20-1049-2020

[6] Leal, M., Reis, E., Pereira, S., & Santos, P. P. (2021). Physical vulnerability assessment to flash floods using an indicator-based methodology based on building properties and flow parameters. *Journal of Flood Risk Management*, 14(3). https://doi.org/10.1111/jfr3.12712

[7] Englhardt, J., De Moel, H., Huyck, C. K., De Ruiter, M. C., Aerts, J. C. J. H., & Ward, P. J. (2019). Enhancement of large-scale flood risk assessments using building-material-based vulnerability curves for an object-based approach in urban and rural areas. *Natural Hazards and Earth System Sciences*, 19(8), 1703–1722. https://doi.org/10.5194/nhess-19-1703-2019

[8] Rasmussen, K. L., Hill, A. J., Toma, V. E., Zuluaga, M. D., Webster, P. J., & Houze, R. A. (2015). Multiscale analysis of three consecutive years of anomalous flooding in Pakistan. *Quarterly Journal of the Royal Meteorological Society*, 141(689), 1259–1276. https://doi.org/10.1002/qj.2433

[9] Rana, I. A., & Routray, J. K. (2018). Multidimensional model for vulnerability assessment of urban flooding: An empirical study in Pakistan. *International Journal of Disaster Risk Science*, 9(3), 359–375. https://doi.org/10.1007/s13753-018-0179-4

[10] Nazeer, M., & Bork, H. R. (2019). Flood vulnerability assessment through different methodological approaches in the context of North-West Khyber Pakhtunkhwa, Pakistan. *Sustainability*, 11(23), 6695. https://doi.org/10.3390/su11236695

[11] Shrestha, B. B., Kawasaki, A., & Zin, W. W. (2021). Development of flood damage functions for agricultural crops and their applicability in regions of Asia. *Journal of Hydrology: Regional Studies, 36*, 100872. https://doi.org/10.1016/j.ejrh.2021.100872

[12] USACE. (1992). *USACE-Catalog of Res Flood-Depth Functions*. U.S. Army Corps of Engineers.

[13] FEMA. (1998). *Hazus-MH Technical Manual Flood Model*. Washington, D.C.: Department of Homeland Security.

[14] Wing, O. E. J., Pinter, N., Bates, P. D., & Kousky, C. (2020). New insights into US flood vulnerability revealed from flood insurance big data. *Nature Communications, 11*, 1–7. https://doi.org/10.1038/s41467-020-15264-2

[15] Maiti, S. (2007). Defining a flood risk assessment procedure using community-based approach with integration of remote sensing and GIS: Based on the 2003 Orissa. *International Institute for Geo-information Science and Earth Observation*. Retrieved from http://scholar.google.com

[16] Balasbaneh, A. T., Abidin, A. R. Z., Ramli, M. Z., Khaleghi, S. J., & Marsono, A. K. (2020). Vulnerability assessment of building material against river flood water: Case study in Malaysia. *IOP Conference Series: Earth and Environmental Science, 476*(1), 012004.

https://doi.org/10.1088/1755-1315/476/1/012004

[17] Miroshnikova, T. (2021). Economic assessment of flood damage. *E3S Web of Conferences, 244*, 10055. https://doi.org/10.1051/e3sconf/202124410055

[18] Frank, E., Ostan, A., Coccato, M., & Stelling, G. S. (2001). Use of an integrated one dimensional modelling approach for flood hazard and risk mapping. In *Flood Risk Management and the European Community* (Vol. 50). https://doi.org/10.2760/16510

[19] Islam, M. Z., & Wang, C. (2024). Cost of high-level flooding as a consequence of climate change driver?: A case study of China's flood-prone regions. *Ecological Indicators, 160*, 111944. https://doi.org/10.1016/j.ecolind.2024.111944

[20] Kreibich, H., Thieken, A. H., Petrow, T., Müller, M., & Merz, B. (2009). Is flow velocity a significant parameter in flood damage modelling? *Natural Hazards and Earth System Sciences, 9*(5), 1679–1692. https://doi.org/10.5194/nhess-9-1679-2009

[21] Lonetti, P., & Maletta, R. (2018). Dynamic impact analysis of masonry buildings subjected to flood actions. *Engineering Structures, 167*, 445–458. https://doi.org/10.1016/j.engstruct.2018.03.076

[22] Maiwald, H., Schwarz, J., Kaufmann, C., Langhammer, T., Golz, S., & Wehner, T. (2022). Innovative vulnerability and risk assessment of urban areas against flood events: Prognosis of structural damage with a new approach considering flow velocity. *Water, 14*(18), 2793. https://doi.org/10.3390/w14182793

[23] Xiao, S., Li, N., & Guo, X. (2021). Analysis of flood impacts on masonry structures and mitigation measures. *Journal of Flood Risk Management, 14*(4), e12743. https://doi.org/10.1111/jfr3.12743

[24] Shah, A., Khan, H. M., & Qazi, E. U. (2013). Damage assessment of flood affected mud houses in Pakistan. *Journal of Himalayan Earth Sciences, 46*(1), 99–110. Retrieved from https://consensus.app/papers/damage-assessment-of-flood-affected-mud-houses-in-pakistan-shah-khan/56f118ffa242565698804b391767ffda/

[25] Song, Y., Zhang, J., Zhang, S., Yan, J., Wang, Y., Liu, Q., & Cheng, X. (2023). Study on uniaxial mechanical behavior and damage evolution mechanism of water-immersed mudstone. *Sustainability, 15*(16), 12499. https://doi.org/10.3390/su151612499

[26] Keshmiry, A., Hassani, S., Dackermann, U., & Li, J. (2024). Assessment, repair, and retrofitting of masonry structures: A comprehensive review. *Construction and Building Materials, 442*, 137380. https://doi.org/10.1016/j.conbuildmat.2024.137380

[27] El-Hachem, R., Rozière, E., Grondin, F., & Loukili, A. (2012). Multi-criteria analysis of the mechanism of degradation of Portland cement based mortars exposed to external sulphate attack. *Cement and Concrete Research, 42*(10), 1327–1335. https://doi.org/10.1016/j.cemconres.2012.06.005

[28] Marvila, M. T., Azevedo, A. R. G., Monteiro, S. N., Vieira, C. M. F., Xavier, G. C., & Vieira, C. M. F. (2020). Durability of coating mortars containing açaí fibers. *Case Studies in Construction Materials, 13*, e00406. https://doi.org/10.1016/j.cscm.2020.e00406

[29] Yu, X. T., Chen, D., Feng, J. R., Zhang, Y., & Liao, Y. D. (2018). Behavior of mortar exposed to different exposure conditions of sulfate attack. *Ocean Engineering, 157*, 1–12. https://doi.org/10.1016/j.oceaneng.2018.03.017

[30] Wang, W., Lin, H., Liu, Y., Zhang, H., Luo, J., Zhu, L., & Zhang, S. (2024). A case study of pavement foundation support and drainage evaluations of damaged urban cement concrete roads. *Applied Sciences, 14*(5), 1791. https://doi.org/10.3390/app14051791

[31] Neumann, C., Faria, E. F., & dos Santos, A. C. P. (2021). Concrete leaching of a hydroelectric powerhouse due to 40 years of exposure to river water. *Construction and Building Materials, 302*, 124253. https://doi.org/10.1016/j.conbuildmat.2021.124253

[32] Rosenqvist, M., Bertron, A., Fridh, K., & Hassanzadeh, M. (2017). Concrete alteration due to 55 years of exposure to river water: Chemical and mineralogical characterisation. *Cement and Concrete Research, 92*, 110–120. https://doi.org/10.1016/j.cemconres.2016.11.012

[33] Ismail, M., Muhammad, B., & Ismail, M. E. G. (2010). Compressive strength loss and reinforcement degradations of reinforced concrete structure due to long-term exposure. *Construction and Building Materials, 24*(6), 898–902. https://doi.org/10.1016/j.conbuildmat.2009.12.003

[34] Paulik, R., Mclean, G., Elwood, K., & Ingham, J. (2019). Tsunami hazard and built environment damage observations from Palu City after the September 28 2018 Sulawesi earthquake and tsunami. *Pure and Applied Geophysics, 176*(8), 3305–3321. https://doi.org/10.1007/s00024-019-02254-9

[35] Jing-Ming, W. (1985). Distribution of earthquake damage to underground facilities during the 1976 Tang-Shan earthquake. *Earthquake Spectra, 1*(4), 741–757. https://doi.org/10.1193/1.1585291

[36] Igwe, O., & Umbugadu, A. A. (2020). Characterization of structural failures founded on soils in Panyam and some parts of Mangu, Central Nigeria. *Geoenvironmental Disasters, 7*(1), 1–26. https://doi.org/10.1186/s40677-020-0141-9

[37] Milanesi, L., Pilotti, M., Belleri, A., Marini, A., & Fuchs, S. (2018). Vulnerability to flash floods: A simplified structural model for masonry buildings. *Water Resources Research, 54*(10), 7177–7197. https://doi.org/10.1029/2018WR022577

[38] Ahamed, T., Duan, J. G., & Jo, H. (2021). Flood-fragility analysis of instream bridges – Consideration of flow hydraulics, geotechnical uncertainties, and variable scour depth. *Structure and Infrastructure Engineering, 17*(11), 1494–1507. https://doi.org/10.1080/15732479.2020.1815226

[39] Hung, C. C., & Yau, W. G. (2017). Vulnerability evaluation of scoured bridges under floods. *Engineering Structures, 132*, 288–299. https://doi.org/10.1016/j.engstruct.2016.11.044

[40] Meaza, H., Abera, W., & Nyssen, J. (2022). Impacts of catchment restoration on water availability and drought resilience in Ethiopia: A meta-analysis. *Land Degradation & Development, 33*(4), 547–564. https://doi.org/10.1002/ldr.4125

[41] Baho, D. L., Drakare, S., Johnson, R. K., & Angeler, D. G. (2020). Phytoplankton size- and abundance-based resilience assessments reveal nutrient rather than water level effects. *Science of the Total Environment, 746*, 141110. https://doi.org/10.1016/j.scitotenv.2020.141110

[42] Elshaer, M., Ghayoomi, M., & Daniel, J. S. (2019). Impact of subsurface water on structural performance of inundated flexible pavements. *International Journal of Pavement Engineering, 20*(8), 947–957. https://doi.org/10.1080/10298436.2017.1366767

[43] Balasbaneh, A. T., Abidin, A. R. Z., Ramli, M. Z., Khaleghi, S. J., & Marsono, A. K. (2020). Vulnerability assessment of building material against river flood water: Case study in Malaysia. *IOP Conference Series: Earth and Environmental Science, 476*(1), 012004. https://doi.org/10.1088/1755-1315/476/1/012004

[44] Nanayakkara, K. I. U., & Dias, W. P. S. (2016). Fragility curves for structures under tsunami loading. *Natural Hazards, 80*(1), 471–486. https://doi.org/10.1007/s11069-015-1978-1

[45] Nasim, M., & Setunge, S. (2022). Damage estimation of a concrete pier when exposed to extreme flood and debris loading. *Journal of Marine Science and Engineering, 10*(5), 710. https://doi.org/10.3390/jmse10050710

[46] Işık, E., Topkaya, B., Atmaca, B., Güneyisi, E. M., & Genç, A. F. (2024). Seismic performance and failure mechanisms of reinforced concrete structures subject to the earthquakes in Türkiye. *Sustainability, 16*(15), 6473. https://doi.org/10.3390/su16156473

[47] Paulik, R., Wild, A., Zorn, C., & Wotherspoon, L. (2022). Residential building flood damage: Insights on processes and implications for risk assessments. *Journal of Flood Risk Management, 15*(4), e12832. https://doi.org/10.1111/jfr3.12832

[48] Xiao, S., Li, N., & Guo, X. (2021). Analysis of flood impacts on masonry structures and mitigation measures. *Journal of Flood Risk Management, 14*(4), e12743. https://doi.org/10.1111/jfr3.12743

[49] Obuzor, G. N., Kinuthia, J. M., & Robinson, R. B. (2011). Enhancing the durability of

flooded low-capacity soils by utilizing lime-activated ground granulated blastfurnace slag (GGBS). *Engineering Geology, 123*(3), 179–186. https://doi.org/10.1016/j.enggeo.2011.07.009

[50] Wang, S., Zheng, H., Huang, E., Liu, X., & Luo, M. (2023). Experimental analysis on impact load of flash flood against a passable structure. *PLoS ONE, 18*(8), e0287848. https://doi.org/10.1371/journal.pone.0287848

[51] Sen, R., Shahawy, M., Rosas, J., & Sukumar, S. (1999). Durability of aramid fiber reinforced plastic pretensioned elements under tidal/thermal cycles. *ACI Structural Journal, 96*(1), 95–104. https://doi.org/10.14359/600

[52] Alhuthali, A., & Low, I. M. (2013). Mechanical properties of cellulose fibre reinforced vinyl-ester composites in wet conditions. *Journal of Materials Science, 48*(18), 6331–6340. https://doi.org/10.1007/s10853-013-7432-4

[53] Zhu, G., Xu, J., Wang, D., Zhang, Y., Du, B., Wang, X., & Zhang, B. (2023). The coupling effects of seawater aging and fatigue micro-crack on mechanical degradation of carbon fiber/epoxy plain woven composites. *Textile Research Journal, 93*(13–14), 3217–3227. https://doi.org/10.1177/00405175231154828

[54] Postacchini, M., Zitti, G., Giordano, E., Clementi, F., Darvini, G., & Lenci, S. (2019). Flood impact on masonry buildings: The effect of flow characteristics and incidence angle. *Journal of Fluids and Structures, 88*, 48–70. https://doi.org/10.1016/j.jfluidstructs.2019.04.004

[55] Fang, Q., Liu, S., Zhong, G., Zhang, H., Liang, J., & Zhen, Y. (2021). Nonlinear simulation and vulnerability analysis of masonry structures impacted by flash floods. *Shock and Vibration, 2021*, 6682234. https://doi.org/10.1155/2021/6682234

[56] Hung, C. C., & Yau, W. G. (2014). Behavior of scoured bridge piers subjected to flood-induced loads. *Engineering Structures, 80*, 241–250. https://doi.org/10.1016/j.engstruct.2014.09.009

[57] Ghani, A. A., & Mohammadpour, R. (2016). Temporal variation of clear-water scour at compound abutments. *Ain Shams Engineering Journal, 7*(4), 1045–1052. https://doi.org/10.1016/j.asej.2015.07.005

[58] Bento, A. M., Gomes, A., Viseu, T., Couto, L., & Pêgo, J. P. (2020). Risk-based methodology for scour analysis at bridge foundations. *Engineering Structures, 223*, 111115. https://doi.org/10.1016/j.engstruct.2020.111115

[59] Zaky, A., Özcan, O., & Avşar, Ö. (2020). Seismic failure analysis of concrete bridges exposed to scour. *Engineering Failure Analysis, 115*, 104617. https://doi.org/10.1016/j.engfailanal.2020.104617

[60] Zhang, C., Zhang, X., Huang, M., & Tang, H. (2019). Responses of caisson-piles foundations to long-term cyclic lateral load and scouring. *Soil Dynamics and Earthquake Engineering, 119*, 62–74. https://doi.org/10.1016/j.soildyn.2018.12.026

[61] Guan, D., Chiew, Y. M., Melville, B. W., & Zheng, J. (2019). Current-induced scour at monopile foundations subjected to lateral vibrations. *Coastal Engineering, 144*, 15–21. https://doi.org/10.1016/j.coastaleng.2018.10.011

[62] Win, S., Zin, W. W., Kawasaki, A., & San, Z. M. L. T. (2018). Establishment of flood damage function models: A case study in the Bago River Basin, Myanmar. *International Journal of Disaster Risk Reduction, 28*, 688–700. https://doi.org/10.1016/j.ijdrr.2018.01.030

[63] Chang, S., Dong, X., Liu, X., Zhang, H., & Huang, Y. (2024). Experimental study on the evolutionary law of transient saturation zones in a red mud dam under rainfall conditions. *Sustainability, 16*(10), Article 3903. https://doi.org/10.3390/su16103903

[64] Yang, J., Cheng, Y., Cui, D., Zhang, Z., Zhang, B., & Chai, J. (2024). Experimental study on the effect of environmental water on the mechanical properties and deterioration process of underground engineering masonry mortar. *Sustainability, 16*(12), Article 5186. https://doi.org/10.3390/su16125186

[65] Van Belleghem, B., Schutter, G. D., Wouters, H., & Boel, V. (2016). Capillary water absorption in cracked and uncracked mortar – A comparison between experimental study

and finite element analysis. *Construction and Building Materials, 110*, 154–162. https://doi.org/10.1016/j.conbuildmat.2016.02.027

[66] Ojo, O. M. (2019). Effect of water quality on compressive strength of concrete. *European Scientific Journal (ESJ), 15*(12), 172–184. https://doi.org/10.19044/esj.2019.v15n12p172

[67] Dogan, M. (2015). Corrosion failure in concrete reinforcement to damage during seismic. *Engineering Failure Analysis, 56*, 275–287. https://doi.org/10.1016/j.engfailanal.2015.01.015

[68] El-Dieb, A. S., & El-Maaddawy, T. A. (2018). Assessment of reinforcement corrosion protection of self-curing concrete. *Journal of Building Engineering, 20*, 72–80. https://doi.org/10.1016/j.jobe.2018.07.007

[69] Kadhim, J., Waheed, M. Q., Hussein, H. A., & Al-Wakel, S. F. A. (2024). Experimental study on the effect of flow velocity and slope on stream bank stability (Part I). *Civil Engineering Journal, 10*(8), 2631–2644. https://doi.org/10.28991/CEJ-2024-010-08-013

[70] Lin, Z., Hu, Y., Zhang, C., Liu, P., Liang, D., & Zhang, H. (2017). Investigation of nonlinear wave-induced seabed response around mono-pile foundation. *Coastal Engineering, 121*, 197–211. https://doi.org/10.1016/j.coastaleng.2017.01.002