

Analyzing the Impact of Urbanization on Flood Vulnerability through Recent Floods and Socio-Economic Data

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Synopsis

This study examines the impact of urbanization on flood vulnerability by analyzing socio-economic indicators in conjunction with global flood datasets. Flood vulnerability is assessed using two key indicators: exposed population and displacement vulnerability. The analysis incorporates urbanization level, GDP per capita, the Gini coefficient, and the Human Development Index (HDI) to evaluate spatial and temporal trends in flood risk. The results show that both low- and high-urbanization areas can experience high flood exposure, but displacement vulnerability tends to decrease with increasing urbanization. Notably, lower-middle-income countries and regions with greater economic disparity exhibit higher displacement vulnerability, suggesting that rapid urban growth without adequate infrastructure amplifies flood risks. The findings underscore the importance of integrating socio-economic and hydrometeorological factors into urban flood risk assessments and call for improved disaster preparedness in rapidly urbanizing regions.

Keywords: Urbanization, Flood vulnerability, Socio-economic data

1. Introduction

Urbanization is advancing rapidly worldwide, reshaping human settlements and altering natural landscapes. Although urban development brings numerous socio-economic advantages, it also heightens exposure to environmental hazards, particularly natural disasters. Among these, flooding stands out as one of the most pressing risks in urban areas, with its frequency and severity increasing due to both climate change and the proliferation of impervious surfaces (IPCC, 2014). Flood events can severely disrupt urban systems by damaging infrastructure, displacing communities, and exacerbating existing social and economic inequalities. As such, understanding and managing

flood risk has become a critical priority for sustainable urban development and climate adaptation.

Flood risk is commonly understood as comprising three interconnected components: hazard, exposure, and vulnerability (Tellman et al., 2021; IPCC, 2014). Hazard refers to the probability and intensity of a flood event; exposure denotes the presence of people, infrastructure, or economic assets in flood-prone areas; and vulnerability reflects the susceptibility of these elements to damage and the capacity of communities to respond or recover. This framework, widely applied in disaster risk reduction efforts, provides a structured basis for evaluating the socio-economic and environmental drivers of flood risk.

Existing studies on flood risk assessment generally follow three methodological approaches. The first relies on remote sensing techniques, using satellite imagery to map flood extent and estimate exposed populations; for example, Tellman et al. (2021) overlaid flood maps with gridded population data, while Sejati et al. (2024) and Yildiz and Varol (2024) applied land-use change analyses in Indonesia and Turkey to explore urbanization's impact on flood exposure. The second approach uses hydrological models such as HEC-RAS and the Fathom Global Flood Model to simulate flood scenarios based on terrain and weather inputs; Devitt et al. (2023) and Rentschler et al. (2023) conducted global analyses using Fathom, and regional applications were demonstrated in Nepal (Mesta & Galasso, 2022) and Istanbul (Özer & Yalçiner Ercoşkun, 2024). The third approach employs statistical analyses—including regression and geographically weighted regression—to quantify the relationship between flood vulnerability and socio-economic indicators, as shown in Sauer et al. (2024), though these methods often depend on the completeness and resolution of available observational data.

While each methodological approach offers valuable insights, they also present limitations: remote sensing provides empirical flood observations but lacks socio-economic depth; flood models enable scenario simulations yet depend heavily on assumptions and infrastructure data; and statistical analyses are interpretable but sensitive to data quality. Observation-based datasets are particularly valuable for capturing real-world impacts, making them well-suited for assessing exposure and vulnerability.

However, prior studies have often prioritized economic indicators like GDP per capita, with limited focus on urbanization as a dynamic driver of flood vulnerability. Urban population growth not only increases exposure but also affects vulnerability through disparities in infrastructure, governance, and social conditions. To address this gap, the present study incorporates urbanization level—the proportion of a population living in urban areas—as a central socio-economic indicator, alongside GDP per capita, the Gini coefficient, and the Human Development Index (World Bank, 2024; Solt, 2024;

Kummu et al., 2020).

This study quantitatively examines how urbanization influences flood vulnerability by focusing on two key indicators: exposed population and displacement vulnerability. Utilizing spatial flood data from the Global Flood Database (Tellman, 2021) and FLODIS (Mester et al., 2023), combined with socio-economic variables, it conducts a comprehensive, multi-scale analysis of flood risk. Through this approach, the research addresses a notable gap in existing studies and aims to generate policy-relevant insights for improving flood resilience in rapidly urbanizing areas.

2. Data and Methodology

2.1 Conceptual Framework

This study adopts the disaster risk framework established by the Intergovernmental Panel on Climate Change (IPCC), which defines flood risk as a function of three interrelated components: hazard, exposure, and vulnerability. Hazard refers to the probability and intensity of flood events, shaped by factors such as topography, weather patterns, and climatic variability. Exposure describes the presence and distribution of people, infrastructure, and assets in flood-prone areas. Vulnerability reflects the susceptibility of these exposed elements to harm and the capacity of communities to mitigate or adapt to flood impacts.

To translate this conceptual framework into empirical analysis, flood damage is understood as the result of flood intensity, the scale of population exposure, and underlying vulnerability conditions. Based on this understanding, the study uses two primary indicators to evaluate flood risk in relation to socio-economic factors: the number of people exposed to floods and the proportion of the exposed population that was displaced.

2.2 Vulnerability Indicators

(1) Exposed Population

The exposed population is estimated by overlaying observed flood extents with spatial population data. Specifically, flood inundation areas derived from remote sensing datasets are combined with gridded population distribution maps (e.g., GHSL) to estimate the number of individuals

residing within flooded zones. Although this indicator does not directly measure vulnerability, it serves as an indirect measure of flood impact that enables consistent cross-country comparisons across events of varying magnitude.

(2) Displacement Vulnerability

Displacement vulnerability is defined in this study as the proportion of the exposed population that was forced to evacuate due to flooding. This metric reflects the severity of flood impacts on human settlements and serves as a direct indicator of vulnerability. Since both the number of displaced individuals and the size of the exposed population account for the scale of the flood event, this proportion enables meaningful comparisons across events of varying magnitudes.

The displacement data are derived from the FLODIS dataset, which integrates satellite-observed flood extents from the Global Flood Database with human displacement records compiled by the Internal Displacement Monitoring Centre (IDMC), a leading global authority on disaster-induced population movements (Mester et al., 2023; IDMC, 2024).

2.3 Vulnerability Indicators

(1) Urbanization Level

Urbanization level is defined as the portion of urban population to the total population of a country. It reflects the concentration of populations in urban areas and serves as the primary indicator for assessing the effects of urban development on flood risk.

(2) GDP per Capita

GDP per capita measures a country's average economic output per person and is used here as a proxy for overall economic development. It is expected to be correlated with disaster management capacity, infrastructure investment, and resilience.

(3) Gini Coefficient

The Gini coefficient represents income inequality, ranging from 0 (perfect equality) to 1 (maximum inequality). It is used to assess the impact of socio-economic disparities on flood vulnerability, particularly in urban areas.

(4) Human Development Index (HDI)

HDI is a composite index that evaluates health (life expectancy), education (mean years of

schooling), and economic well-being (GNI per capita). It is used as a holistic indicator of development quality, and in this study, it supports the interpretation of urbanization trends and vulnerabilities.

2.4 Research Design and Analytical Steps

To examine the relationship between flood vulnerability and urban development, the study proceeds through the following analytical steps:

Correlation Analysis of Socio-Economic Indicators: Pearson correlation coefficients are computed among the four socio-economic indicators to assess multicollinearity and select appropriate variables for multivariate analysis. Highly correlated indicators are excluded to avoid redundancy.

Analysis of Exposed Population: Using the urbanization level as the primary independent variable, the relationship between urban development and flood exposure is analyzed. GDP per capita, the Gini coefficient, and HDI are included as covariates to investigate how various urban characteristics influence exposure levels.

Analysis of Displacement Vulnerability: Displacement vulnerability is analyzed using the same set of socio-economic indicators. The goal is to determine how urbanization and inequality influence evacuation outcomes. Events are categorized by income group and Gini level to allow for comparative analysis.

2.5 Data Sources

(1) Global Flood Database (GFD)

The Global Flood Database (GFD) contains spatially consistent records of 3,195 flood events worldwide from 2000 to 2018, compiled by Tellman et al. (2021). After quality control, 913 events matched with MODIS satellite imagery were retained. This dataset includes details on inundation extent, duration, fatalities, and estimated exposed populations, derived by overlaying flood extents with the Global Human Settlement Layer (GHSL).

(2) FLODIS

FLODIS is an extended dataset based on the Global Flood Database (GFD) that enhances flood event records by integrating displacement, mortality, and economic loss data. It provides flood inundation maps at a 250-meter resolution and links these

spatial data with gridded socio-economic indicators such as population and GDP. The dataset is composed of two primary components: the displacement dataset, which includes 335 events based on records from the Internal Displacement Monitoring Centre (IDMC), and the mortality and damage dataset, which contains 695 events compiled from the Emergency Events Database (EM-DAT). In this study, the mortality and damage dataset is primarily used for analyzing flood-exposed populations due to its broader event coverage, while the displacement dataset is employed specifically to assess displacement vulnerability, as it directly records flood-induced evacuation figures.

(3) Socio-Economic Datasets

Urbanization Level: Sourced from the United Nations World Urbanization Prospects (WUP) and World Population Prospects (WPP), available in 5-year intervals at the national level. Adjustments are made to ensure consistency across definitions and administrative changes.

GDP per Capita: Extracted from the World Bank's World Development Indicators (2024), which provides annual national-level economic metrics.

Gini Coefficient: Taken from the Standardized World Income Inequality Database (SWIID v9.8), which compiles internationally comparable Gini estimates across countries and time.

HDI: Based on the gridded global dataset by Kummu et al. (2019), which offers HDI estimates from 1990 to 2015, including versions aligned with FLODIS data.

3. Results and Discussions

3.1 Interrelationships Among Socio-Economic Indicators

To assess the relationships among key socio-economic indicators used in this study, correlation analyses were conducted focusing on urbanization level, GDP per capita, the Gini coefficient, and the Human Development Index (HDI). The strongest correlation was observed between urbanization level and HDI, indicating that higher urbanization is generally associated with improvements in health, education, and income. In contrast, weaker correlations were found between urbanization level and GDP per capita, as well as between urbanization

and the Gini coefficient, suggesting that urbanization does not always align with economic growth or reductions in income inequality. These findings are visually illustrated in Figure 1, which highlights the strong link between urbanization and HDI.

Further analysis among GDP per capita, the Gini coefficient, and HDI revealed that GDP per capita and HDI are moderately correlated, while the Gini coefficient is negatively associated with both. Notably, Figure 2 shows that even countries with high GDP per capita can experience significant income inequality, reinforcing the importance of including both economic performance and equity measures in flood vulnerability assessments. Based on these results, GDP per capita and the Gini coefficient were selected as primary variables for multivariate analysis, while HDI was excluded to avoid multicollinearity with urbanization level.

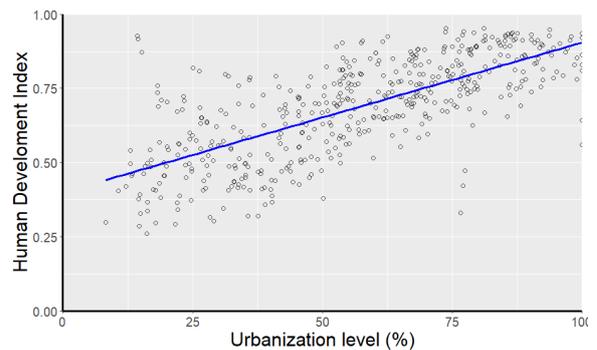


Figure 1 Urbanization level vs. Human Development Index (HDI). A strong positive correlation indicates that higher urbanization is associated with greater human development.

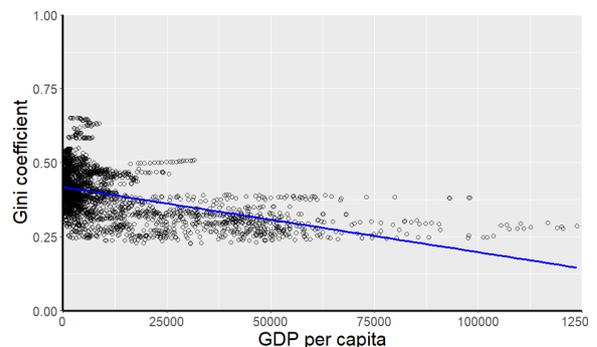


Figure 2 GDP per capita vs. Gini coefficient. A weak negative correlation suggests that higher income levels may relate to lower income inequality, though with variation.

3.2 Interrelationships Among Socio-Economic Indicators

This section analyzes the relationship between urbanization level and flood-exposed population using data from the Global Flood Database (GFD), with countries categorized by GDP per capita and the Gini coefficient. A general trend is observed in which regions with lower urbanization levels (below 50%) tend to exhibit larger exposed populations, particularly in low- and lower-middle-income countries. As urbanization increases, exposed populations tend to decrease, with a noticeable reduction in high-income countries where urbanization levels exceed 75%. This pattern likely reflects the presence of more robust flood mitigation infrastructure in wealthier, highly urbanized regions. However, a small upward trend is also observed around 80% urbanization, possibly due to the high population density in cities where a single flood event can affect a large number of people even with protective infrastructure in place. These patterns are clearly shown in Figure 3(a).

In contrast, Figure 3(b), which categorizes countries by Gini coefficient, reveals a more scattered distribution with no consistent trend between income inequality and exposed population. Nonetheless, a considerable number of high-exposure events are observed in countries with relatively high Gini coefficients, suggesting that income inequality may be associated with increased flood exposure, even if the relationship is not linear or strong. The broader dispersion in this figure highlights the complex and context-dependent role of inequality in shaping flood risk. Together, these findings underscore the importance of considering both economic development and social inequality when analyzing the impacts of urbanization on flood exposure.

3.3 Analysis with FLODIS Mortality and Damage Dataset

This section analyzes the relationship between urbanization level and flood-exposed population using the FLODIS mortality and damage dataset, with categorization by GDP per capita and Gini coefficient. As shown in Figure 4(a), countries with low to moderate urbanization levels (25%–50%)

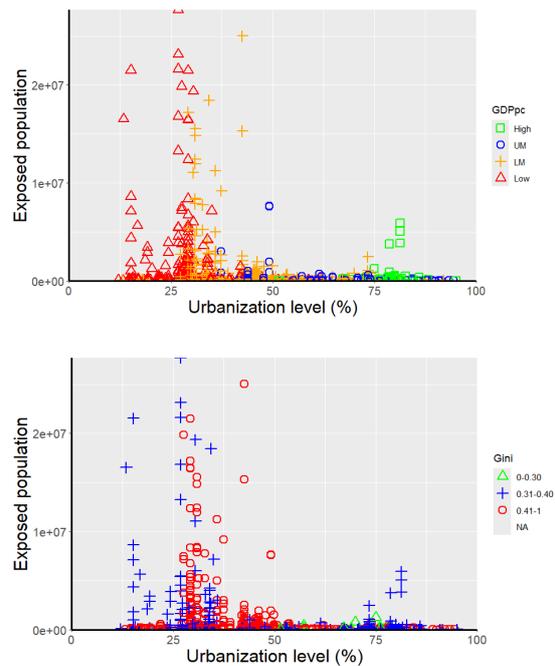


Figure 3 Exposed population vs. urbanization level categorized by (a) GDP per capita (up) and (b) Gini coefficient (down). Larger exposed populations are seen in low-income, low-urbanization countries (a), while exposure in high-inequality countries (b) is widely distributed with no clear trend.

generally experience larger exposed populations, particularly among low- and lower-middle-income groups. A smaller peak is also observed around the 80% urbanization level, likely reflecting the concentration of people in densely populated urban centers where flood mitigation infrastructure may be in place but can still be overwhelmed by extreme events. Compared to the GFD-based results, the FLODIS data shows a broader distribution of events across income groups, especially within the upper-middle-income category, due to the spatially disaggregated nature of the GDP data in FLODIS.

In contrast, Figure 4(b), which categorizes countries by Gini coefficient, reveals a more dispersed pattern. No clear trend is observed across levels of income inequality; however, a significant portion of flood events with high exposed populations occur in countries with moderate to high Gini coefficients (above 0.30). This suggests that income inequality may be associated with elevated flood exposure, though the relationship is not as structured or strong as the one observed for GDP per capita. The comparison between the two figures

highlights the importance of considering both economic capacity and social inequality when evaluating flood exposure across urbanization levels.

3.4 Analysis of Displacement Vulnerability

This section examines how displacement vulnerability varies with urbanization level, using the FLODIS displacement dataset, and categorizing events by GDP per capita and Gini coefficient. As shown in Figure 5(a), countries with lower GDP per capita, particularly lower-middle-income countries, tend to exhibit higher and more variable displacement vulnerability, especially at urbanization levels below 50%. These findings suggest that in less economically developed countries, rapid urban growth often outpaces the development of disaster mitigation infrastructure and evacuation systems, increasing the likelihood of large-scale displacement during flood events. In contrast, high-income countries predominantly show low displacement vulnerability, indicating stronger institutional and infrastructural capacities for flood preparedness and response.

Figure 5(b), which categorizes the same data by Gini coefficient, reveals a more dispersed pattern but provides additional insight into the role of income inequality. Countries with high Gini coefficients (above 0.40) are more frequently associated with flood events involving high displacement vulnerability, suggesting that social inequality contributes to greater flood risk, even in some urbanized contexts. In contrast, countries with low-income inequality and higher urbanization levels consistently exhibit low displacement vulnerability, reinforcing the importance of equitable development in enhancing resilience. Together, these findings highlight that both economic capacity and social equity are critical in shaping a population's vulnerability to displacement during flood events.

4. Concluding Remarks

This study quantitatively examined the relationship between urbanization and flood vulnerability by analyzing two key indicators: exposed population and displacement vulnerability.

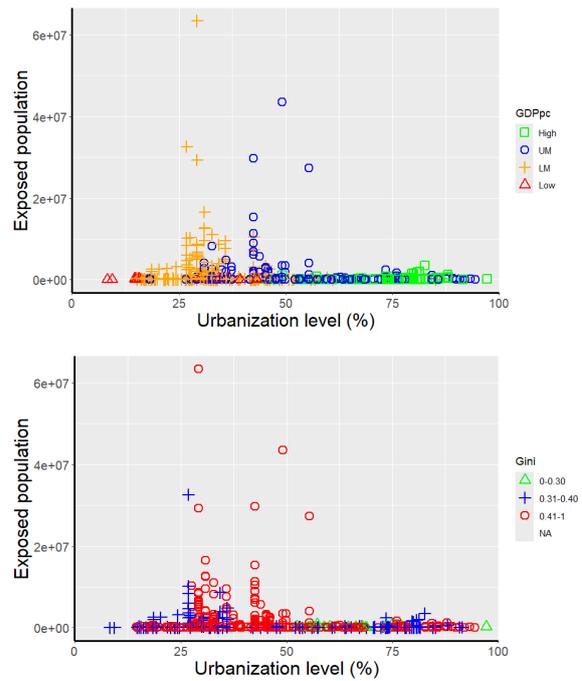


Figure 4 Exposed population vs. urbanization level by (a) GDP per capita and (b) Gini coefficient (FLODIS). High exposure is seen in low-income, moderately urbanized countries (a), while exposure is more dispersed under high inequality (b).

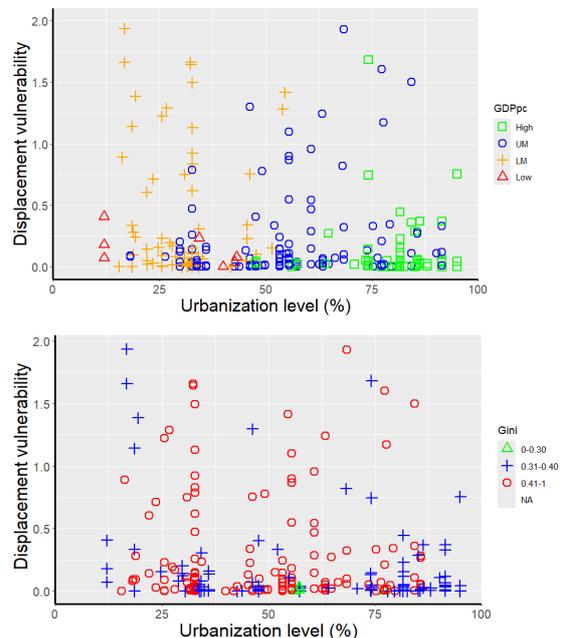


Figure 5 Displacement vulnerability vs. urbanization level categorized by (a) GDP per capita and (b) Gini coefficient (FLODIS). Higher displacement vulnerability is observed in lower-middle-income countries with low urbanization (a), while countries with high income inequality (b) tend to show more frequent and dispersed high-vulnerability events.

By integrating socio-economic data with spatial flood observations from the Global Flood Database (GFD) and FLODIS, the study provided a multi-dimensional assessment of how urban development and socio-economic conditions shape flood risk at the global scale.

The analysis of exposed population revealed that countries with low to moderate urbanization levels—particularly those with low or lower-middle income—tend to experience the highest flood exposure. A secondary increase in exposure was observed in highly urbanized regions, likely due to the concentration of population in dense urban centers where a single flood event can affect a large number of people. While GDP per capita showed a relatively clear relationship with exposure—where higher-income countries generally exhibited lower flood exposure—income inequality, as measured by the Gini coefficient, showed a more complex and dispersed pattern, suggesting that inequality may influence exposure in context-dependent ways.

Displacement vulnerability analysis further highlighted socio-economic disparities. Countries with lower economic capacity, especially those with urbanization levels below 50%, exhibited higher and more variable displacement vulnerability. Moreover, high income inequality was associated with a greater frequency of flood events involving large-scale displacement, reinforcing the idea that both economic development and social equity are crucial for reducing vulnerability to floods.

Overall, the findings underscore that urbanization alone does not reduce flood risk—its effects depend strongly on underlying socio-economic conditions. While wealthier and more urbanized countries tend to benefit from better flood protection and planning, areas with rapid but unequal urban development remain highly vulnerable. These results emphasize the need for integrated urban planning and social policy that address both infrastructure development and inequality reduction to build long-term flood resilience. Future research should further explore the interaction between socio-economic dynamics and physical flood hazards, including climate-driven changes in rainfall extremes, to inform more adaptive and inclusive disaster risk management strategies.

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References

- Devitt, L., Neal, J., Coxon, G., Bevacqua, E., Alfieri, L., Bates, P.D. (2023): Flood hazard potential reveals global floodplain settlement patterns. *Nature Communications*. 14, 2801.
- Internal Displacement Monitoring Centre (IDMC) (2024): Global Internal Displacement Database. <https://www.internal-displacement.org>
- IPCC, 2014. *Climate Change (2014): Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the IPCC*. Cambridge University Press.
- Kummu, M., Taka, M., Guillaume, J.H.A. (2020): Gridded global datasets for Gross Domestic Product and Human Development Index over 1990–2015. <https://doi.org/10.5061/dryad.dk1j0>
- Mesta, C., Galasso, C. (2022): Urban growth modelling and social vulnerability assessment for a hazardous Kathmandu Valley. *Scientific Reports*. 12, 6152.
- Mester, B., Frieler, K., Schewe, J. (2023): Human displacements, fatalities, and economic damages linked to remotely observed floods. *Scientific Data*. 10, 482.
- Özer, B., Yağciner Ercoşkun, Ö. (2024): Assessing the impact of urbanization on flood risk by RS and GIS: A case study on Istanbul-Esenyurt. *Journal of Contemporary Urban Affairs*. 8(1), pp. 57–78.
- Rentschler, J., Avner, P., Marconcini, M., Ranzoni, A. (2023): Global evidence of rapid urban growth in flood zones since 1985. *Nature*. 622, pp. 87–92.
- Sauer, I.J., Mester, B., Frieler, K., Willner, S.N., Otto, I.M. (2024): Limited progress in global reduction of vulnerability to flood impacts over the past two decades. *Communications Earth & Environment*. 5, 239.
- Sejati, A.W., Buchori, I., Lakshita, N.M., Kusumo, B.H., Widyastuti, R.D., Nurrahmawati, N. (2024):

- The spatial analysis of urbanization dynamic impacts in a 50-year flood frequency in Java, Indonesia. *Natural Hazards*. 120, pp. 2639–2659.
- Solt, F. (2024): Measuring income inequality across countries and over time: The Standardized World Income Inequality Database. *Social Science Quarterly*. 101(3), pp. 1183–1199.
- Tellman, B., Sullivan, J.A., Kuhn, C., Kettner, A.J., Doyle, C.S., Brakenridge, G.R., Erickson, T.A., Slayback, D.A. (2021): Satellite imaging reveals increased proportion of population exposed to floods. *Nature*. 596, pp. 80–86.
- Tellman, B. (2021): Global Flood Database. <https://doi.org/10.4211/hs.6461528501c14f7c9d6b10d20dd4f657>
- Yildiz, Ç.M.K., Varol, N. (2024): An approach to vulnerability indexing standardization to assess flood vulnerability for Vakfikebir, Trabzon. *Environmental Earth Sciences*. 83, 678.
- World Bank (2024): GDP per capita (current US\$). World Development Indicators. Available at: <https://data.worldbank.org/indicator/NY.GDP.PC.AP.CD>

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