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A SYSTEMATIC REVIEW OF URBAN FLOOD MODELING APPROACHES AND FREQUENCY ANALYSIS METHODS

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Abstract: Flooding is a growing global issue, particularly in urban environments where human activities and climate change have increased both the frequency and intensity of floods. Traditional methods of flood frequency analysis (FFA), while valuable, often fail to account for dynamic environmental changes and urbanization. This paper reviews contemporary approaches to FFA, focusing on the integration of hydrological modeling techniques with environmental considerations. It highlights the importance of green infrastructure and sustainable urban planning in reducing flood risks. The review also examines the application of soft computing models in flood prediction and their strengths and limitations.

Keywords: Flood Frequency Analysis, Urban Flooding, Hydrological Modelling, Environmental Sustainability, Climate Change, Soft Computing, Green Infrastructure.

1. Introduction

Floods remain one of the most destructive natural disasters, causing billions of dollars in damages and displacing millions of people globally. In urban areas, flooding is a particularly complex phenomenon due to the high variability in surface characteristics, drainage systems, and land use. Over the past few decades, rapid urbanization has not only increased the number of impervious surfaces but also altered natural waterways, exacerbating flood risks (Ozdemir et al., 2013). The combination of urbanization and climate change has had a profound impact on flood dynamics. As cities expand, natural landscapes are replaced with impermeable surfaces, reducing infiltration and increasing surface runoff. Simultaneously, climate change has altered precipitation patterns, leading to more intense storms, rising sea levels, and more frequent flash floods (Berndtsson et al., 2019).

According to the Intergovernmental Panel on Climate Change (IPCC), extreme precipitation events are projected to increase by 20-30% in many regions by 2050, further stressing urban drainage systems (IPCC, 2014).

In developing countries like Nigeria, urban floods are now a yearly disaster due to heavy rainfall, poor drainage systems, and unregulated settlements in flood-prone areas. In 2018, floods affected 34 of Nigeria's 36 states, displacing 210,000 people and damaging infrastructure and agricultural land (HKRC, 2018). By 2024, the situation worsened, with 1.7 million people impacted and 200,000 displaced across 31 states. The collapse of the Alau Dam submerged 70% of Borno State, displacing 419,000 people and heightening food security concerns (Center for Disaster Philanthropy, 2024). These challenges highlight the urgent need for improved flood management policies that integrate environmental and urban planning solutions. Therefore, this paper aims to review the current state of flood frequency analysis and urban flood modeling techniques.

2.0 Flood Frequency Analysis

Flood frequency analysis (FFA) has evolved significantly over the past few decades, particularly in response to increasing urbanization and climate change impacts. Traditional statistical methods, such as Extreme Value Type distributions, have been widely used for estimating flood risks based on historical flood data (Stedinger & Griffis, 2008). However, the assumption of stationarity— where past flood data are assumed to represent future events—has been increasingly challenged by the dynamic nature of urbanization and climate variability (Milly et al., 2008). Traditional FFA models often fail to account for the effects of land-use changes, such as deforestation and urban sprawl, which significantly alter watershed behavior and runoff patterns (Beighley & Moglen, 2003). For instance, urbanization leads to the creation of impervious surfaces that reduce natural infiltration and increase surface runoff, exacerbating flood risks in cities (Berndtsson et al., 2019). Additionally, climate change introduces further complexities, as extreme weather events—such as intense rainfall—become more frequent and severe, necessitating more adaptive and dynamic flood models (Saghafian et al., 2014).

In response to these challenges, non-stationary FFA models have been developed to better reflect the changing nature of flood-generating processes. These models incorporate variables such as rainfall intensity, land-use changes, and climate projections, providing more accurate predictions of flood events under dynamic conditions (Benameur et al., 2017). Hydrological models, such as HEC-HMS and WATFLOOD, have been widely adopted to simulate the rainfall-runoff process and estimate flood magnitudes under various scenarios, including those influenced by climate change (Fisaha, 2018).

To provide an overview of the key studies related to flood frequency analysis and urban flood modeling, **Table 1** presents a summary of the methodologies and findings of major studies in this field. This literature matrix highlights the diversity of approaches taken by researchers and demonstrates the increasing importance of incorporating environmental sustainability into flood management strategies. The studies demonstrate a clear trend towards the integration of nonstationary flood models, which account for dynamic factors such as climate change and urban expansion. Traditional statistical methods, while valuable, often fail to consider these changing conditions, as evidenced by studies such as Beighley & Moglen (2003) and Saghafian et al. (2014), which emphasize the limitations of stationary assumptions in flood risk estimation.

Several studies, including Berndtsson et al. (2019) and Moradi et al. (2019), highlight the growing importance of incorporating green infrastructure—such as permeable pavements and rain gardens— into urban flood management strategies. These sustainable approaches not only help reduce flood risks but also offer additional environmental benefits, such as reducing urban heat islands and improving water quality. In the context of Nigeria, studies like Ibrahim & Isiguzo (2009) and Komolafe et al. (2015) provide valuable insights into the specific challenges faced by flood-prone regions. These studies underscore the need for location-specific models that account for both climatic and socio-economic factors. Furthermore, the limited capacity of drainage systems and the poor enforcement of land-use regulations are highlighted as major contributors to recurrent flooding in Nigerian cities.

Table 1: Literature Matrix

Author(s) & Year	**Objective**	**Methodology/Model Used**	**Key Findings**	**Environmental or Sustainability Aspect**	**Relevance to Current Study**
Berndtsson et al. (2019)	Assess flood risks due to climate change and urbanization.	Statistical FFA, HEC-HMS, and runoff models	Urbanization and climate change amplify flood risks. Green infrastructure (e.g., permeable surfaces) can help reduce runoff and manage stormwater.	Emphasizes sustainable flood management through green infrastructure.	Shows how climate change affects flood intensity; relevant for integrating sustainability into flood models.
Saghafian et al. (2014)	Develop flood frequency models with non-stationary conditions.	Rainfall-runoff models, nonstationary flood models	Non-stationary models better account for changes in land use and rainfall patterns, providing more accurate flood predictions.	Addresses climate-induced variability in hydrological processes.	Relevant for exploring advanced, dynamic flood prediction methods.
Ibrahim & Isiguzo (2009)	Analyze flood frequency for Gurara River catchment.	Extreme value distributions (e.g., Pearson Type III)	Pearson Type III provided the best fit for long-term flood forecasting in the region.	No specific environmental aspect mentioned.	Demonstrates practical application of statistical FFA, useful for flood-prone areas in Nigeria.
Benameur et al. (2017)	Examine flood frequency in an Algerian watershed.	Complete FFA using multiple statistical methods	Different statistical models produce varying levels of accuracy in flood prediction, with Pearson Type III being highly effective.	Limited discussion of environmental impacts.	Provides insights into the limitations of traditional statistical methods.

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Climate change will
Hydrological models Supports the need for
Assess the impact of significantly increase flood Highlights the role of
Moradi
incorporating climate climate-adaptive
climate change on et al. flood frequency, especially for climate adaptation in change
frequency in
projections hydrological modeling
(2019)
extreme events (1-in-100-year flood management.
Northern Iran.
(CMIP5) techniques.
floods).

Adjust measured Statistical flood Urbanization complicates Focuses on how
Beighley & Relevant for
peak discharges in quantile estimation flood prediction, as land urbanization
Moglen urbanizing alters flood understanding how urban using long-term use
(2003) watersheds. changes affect risk; advocates for expansion alters data
discharge patterns. adaptive modeling. hydrological processes.

Examine runoff Runoff models, flood Runoff models help assess flood risks Considers impacts
Useful for Rogger et models and flood frequency statistics in changing environments, emphasizing
of land-use changes improving flood risk al. (2012) frequency for design flood the
importance of considering both and natural assessments in urban statistics. estimation
natural and anthropogenic factors. variability. areas.

2D and 3D models are effective Highlights the Review flood Literature Encourages the use of
Teng et for simulating complex urban importance of using
inundation modeling review of 1D, high-resolution data for
al. flood scenarios. However, detailed, high-resolution
techniques and their 2D, and 3D sustainable urban flood
(2017) uncertainties in data (e.g., data for accurate flood uncertainties. models mitigation strategies.
topography) can reduce accuracy. risk modeling.

Recurrent floods in Nigeria are
Review flood risk Literature review Emphasizes the need Useful for contextualizing
due to poor urban planning and
Komolafe analysis in Nigeria of Nigerian flood for sustainable flood risks in Nigeria and
infrastructure. Proactive et al. and its associated risks and infrastructure
understanding the role of
management through early
(2015) socio-economic management development in flood- infrastructure in flood

warning systems and improved impacts. practices prone regions. mitigation. drainage is recommended.

Considering a case Study conducted in the Gurara River catchment in Kaduna State, Nigeria, four different probability distribution models were applied, visa viz: Extreme Value Type I, Normal, Exponential, and Pearson Type III—to analyze daily discharge data. The Pearson Type III distribution provided the best fit for predicting long-term flood risks, demonstrating the need for location-specific calibration of FFA models to account for regional hydrological variability (Ibrahim & Isiguzo, 2009).
However, Despite the progress made in integrating environmental sustainability into flood management practices, there is still a gap in the application of non-stationary models in developing countries. Many of the reviewed studies focus on developed regions with access to high-quality data and advanced flood modeling technologies. This gap highlights the need for further research that tailors advanced flood modeling techniques to the context of developing countries, where infrastructure and resources may be limited.
In conclusion, flood frequency analysis and hydrological modeling are essential tools for understanding and mitigating flood risks in urban areas. As demonstrated in this review, the shift towards non-stationary models and the incorporation of green infrastructure offer promising solutions for addressing the challenges posed by climate change and urbanization. However, further research is needed to adapt these models to the specific conditions of developing countries, where the socio-economic impacts of flooding are often more severe

2.2 Method of Flood Frequency Analysis

The two main methods of flood frequency analysis are analytical and graphical methods which the Institution of Engineers Australia (IEA) 2013, recommended that both procedures are used in complementary manner. The analytical method of flood frequency analysis usually involves fitting a probability distribution function to model the observed peak flow data from which the probability of exceedance of flow-discharge of a particular magnitude flood may then be calculated. Although, this method is widely used, there is little theoretical basis in the choice of distribution and despite extensive research. no particular distribution has emerged as the best fitted across and most uniform across different site.
According to Garg (2010), the methods used for determining flood flows can be classified as follows; Rational method, Empirical method, Determination by envelop curves, Determination by statistical probability method and Unit hydrograph method. However, Subramanyo (1994) stated that the use of a particular method depends upon the desired objective, the available data and the importance of the project.

3.0 Hydrological Modelling

Hydrological modeling plays a critical role in understanding flood dynamics and developing effective flood management strategies. By simulating the movement of water through a watershed, hydrological models help researchers and urban planners predict how different environmental factors—such as rainfall, land use, and soil characteristics—affect flood risks. In the context of urban flooding, these models are particularly useful for assessing the impact of human activities, such as deforestation, urban sprawl, and climate change.

3.1 Hydrological Models

Several hydrological models are commonly used for flood simulation. The HEC-HMS model, developed by the U.S. Army Corps of Engineers, is one of the most widely used tools for simulating rainfall-runoff processes in both rural and urban watersheds. HEC-HMS allows for the integration of various environmental factors, such as land use changes and climate variability, making it particularly useful for assessing flood risks in rapidly urbanizing areas (USACE-HEC, 2016).

Other widely used models include WATFLOOD, which is designed for distributed hydrological modeling, and HSPF (Hydrologic Simulation Program–Fortran), which simulates water quantity and quality in watersheds over long periods. These models are essential for evaluating the effectiveness of flood mitigation strategies, such as green infrastructure and floodplain restoration, under different climate change scenarios (Fisaha, 2018).

3.2 Green Infrastructure in Flood Mitigation

One of the most promising approaches to urban flood mitigation is the integration of green infrastructure. Green infrastructure includes natural and engineered systems designed to manage stormwater and reduce surface runoff. Examples include permeable pavements, green roofs, rain gardens, and constructed wetlands, all of which help to increase infiltration and reduce the volume of water entering urban drainage systems during storms (Ahmad et al., 2018).

By incorporating green infrastructure into hydrological models, urban planners can simulate the potential benefits of these systems in reducing flood risks. For example, studies have shown that green roofs can reduce peak runoff by up to 75%, while permeable pavements can increase infiltration rates by 50-60%, significantly reducing the burden on urban drainage systems (Berndtsson et al., 2019). These systems also provide additional environmental benefits, such as improving water quality, enhancing biodiversity, and reducing the urban heat island effect.

3.3 Environmental Impact of Climate Change

Climate change has significantly altered hydrological cycles, leading to more frequent and intense floods in many regions. Rising temperatures increase the rate of evaporation, while more intense rainfall events lead to flash floods and river flooding. Hydrological models must account for these changes by incorporating climate projections into their simulations. For example, studies in the Murray-Darling Basin of Australia have shown that climate change could increase the frequency of 1-in-100-year flood events by up to 40% by the end of the century (Moradi et al., 2019). This highlights the need for adaptive flood management strategies that can respond to both current and future flood risks.

4.0 Conclusion

Flood frequency analysis and hydrological modeling are essential tools for managing flood risks in urban environments. However, the increasing influence of climate change, urbanization, and environmental degradation requires a shift away from traditional methods that assume stationarity. Instead, flood models must incorporate dynamic environmental variables, such as land use changes, rainfall variability, and temperature fluctuations, to provide more accurate and reliable flood predictions.

The integration of green infrastructure into urban flood management offers a promising solution for reducing flood risks while promoting environmental sustainability. By enhancing infiltration and reducing surface runoff, green infrastructure can help mitigate the impact of urbanization on flood risks. Future research should focus on improving the accuracy of hydrological models and developing more robust, adaptive flood management strategies that can respond to the complex and evolving challenges posed by climate change.

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