KAPITEL 3 / *CHAPTER 3* [3]
A COMPREHENSIVE REVIEW OF EMERGING TECHNOLOGIES FOR FLASH FLOOD PREDICTION INCLUDING: AI, ML, IoT APPROACHES

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Introduction

The World Economic Forum (WEF) highlights that flash floods, driven by climate change, are destructive forces that can devastate infrastructure and property, particularly in arid desert regions. These floods have had a profound impact globally, affecting 761 locations and resulting in over 47 million deaths, with significant numbers attributed to cardiovascular (11 million) and respiratory (4.7 million) diseases. Between 2010 and 2016, 204 flash floods were estimated to have reduced global gross domestic product (GDP) by approximately 0.04%. Beyond the immediate economic losses, flash floods have far-reaching consequences on socioeconomics, the environment (such as waste generation, water pollution, and the spread of communicable diseases), and the mental health of affected communities.

Given the severe implications of flash floods, it is crucial for governments and communities to implement highly effective early warning systems and hazard assessment strategies to mitigate the damage. Traditional flash flood warning systems primarily depend on physically-based modeling approaches, including rainfall–runoff models, hydrological, hydrodynamic, and 1D/2D/3D numerical models. However, these models often struggle with challenges such as data resolution and the complexity of mountainous terrain. Additionally, their inability to accurately predict flow depth, velocity, and recurrence levels can limit their effectiveness in future flash flood prevention.

This study reveals that 1D hydrodynamic flood models may not be sufficient for predicting flash floods in urban areas because they oversimplify topographic and urban flow features. These models are also highly computationally intensive, requiring vast amounts of data, which complicates uncertainty analysis. To enhance the efficiency of traditional approaches, emerging technologies such as artificial intelligence (AI),

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machine learning (ML), and the Internet of Things (IoT) can be integrated into flash flood management systems.

Several studies have explored the role of these advanced technologies in predicting hydrological events, including floods. One study assessed the effectiveness of machine learning ensemble techniques for flood monitoring and found that these techniques are rapidly becoming essential in managing hydrological disasters due to their high performance. However, a systematic review of the literature suggests that the integration of machine learning and image processing techniques with flood management has not been extensively explored. Another review highlighted the contributions of emerging technologies, like AI, to creating flood-resilient built environments, but emphasized the need for future studies to incorporate comprehensive flood variables to achieve accurate predictions.

The unpredictability of flash floods, especially in highly impervious or impermeable landscapes, underscores the need for highly efficient early warning systems and precise susceptibility maps. Despite the growing interest in using advanced technological tools to improve flash flood management, few comprehensive reviews have thoroughly examined their application. This study aims to fill that gap by critically reviewing the current innovative technologies used in flash flood management and addressing key research questions, such as:

1. What are the trends and characteristics of studies on smart technologies like AI, ML, IoT, cloud computing, and robotics in flash flood early warning predictions?

2. How effective are AI/ML algorithms in predicting flash flood susceptibility?

3. What are the common indicators and influential factors in assessing flash flood susceptibility?

4. What are the strengths and limitations of current studies that could enhance future flash flood early warning and susceptibility predictions?

The findings from this review could lead to significant improvements in technologically-based flash flood early warning systems, offering valuable insights for policymakers, engineers, and scientists involved in future flash flood projects.

This review builds upon existing literature by providing more comprehensive coverage and a sharper focus. The key contributions of this study include:

1. A focus on current evidence of emerging technological tools applied in flash flood early warning and susceptibility predictions.

2. A thorough review of various emerging technologies used in flash flood management, including AI/ML, IoT, cloud computing, and robotics.

3. An examination of different AI/ML internet algorithms utilized for flash flood warnings and susceptibility predictions.

4. A detailed review of studies that have applied machine learning for flash flood susceptibility assessment, supported by model performance evaluations.

5. An analysis of temporal trends in flash flood-related technological studies, from older to more recent publications.

6. A synthesis of the findings and suggestions for future research priorities and strengths.

The study is organized into five main sections:

- Section 2 details the study methodology, including design, search strategies, and eligibility criteria.
- Section 3 presents the search results and a general bibliographic analysis.
- Section 4 provides a comprehensive review of AI, ML, IoT, cloud computing, and robotics in flash flood management.
- Section 5 offers a critical analysis of the findings.
- Section 6 summarizes the strengths, limitations, and future research directions.
- Finally, Section 7 concludes the study, offering insights for future advancements in flash flood management.

This paper focuses on metals in traffic area runoff and their traffic-related emissions. The study's hypothesis is that it is possible to calculate mass balances for traffic-related metals (emissions and runoff loads) across all types of traffic areas (highways, roads, and parking lots) based on a literature review. The objectives of this paper are to summarize the distribution of annual metal loads in runoff from various traffic areas, identify relevant trends and factors, update and expand existing mass balances for heavy metal runoff loads and emissions in Germany, and determine the mass fluxes of traffic-related metals.

3.1. Materials and Methods

Using a gray literature search methodology, we manually gathered articles on flash flood technologies from various scientific databases, including Google Scholar, Scopus, and Web of Science. To find relevant articles, we employed search terms such as "flash flood," "flood technologies," "artificial intelligence," "machine learning," "internet of things," "deep learning," "robotics," and "cloud computing." The search primarily relied on Google Scholar and manual searches, beginning on September 15, 2023, and concluding on December 10, 2023, covering research articles published between 2010 and 2023.

The study's objective was to review emerging technologies specifically related to flash floods, so the search results were filtered to exclude studies focusing on other types of floods, such as river floods, coastal floods, or urban floods. Additionally, studies that addressed flash flood susceptibility or prediction but lacked clear methodologies for training and validating test datasets were not included. The selected papers had to evaluate the performance of models, such as those involving artificial intelligence (AI) and machine learning (ML).

No restrictions were placed on the publication year or the country of origin for the included studies. Only papers published in English were considered; those in other languages were not translated and, therefore, excluded from the review. The citations for all eligible articles were exported into EndNote 20 Software, and the full-length articles were uploaded for data extraction and bibliographic analysis. Detailed search strings used in the electronic databases can be found in Table S1 of the Supplementary Material.

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3.2. Analysis by Flash Flood AI/ML type

The current study initiated a comprehensive bibliographic analysis to quantify the extent of publications that have utilized AI and machine learning (ML) for flash flood susceptibility analysis and early warning predictions. As illustrated in Figure 1, flash flood-related publications over the past decade have been categorized by year and the type of technology employed. Among the 50 papers published between 2010 and 2023, 13 (26%) were released in 2021. However, there was a notable decline in publication numbers during 2022-2023, a trend partly attributed to the impact of the COVID-19 pandemic. The data reveal a period of stagnation in publication rates between 2010 and 2017, followed by a dramatic increase from 2018 to 2023.

The analysis of flash flood technologies by type indicated that a significant 64% of the publications focused on the application of AI and ML for predicting flash flood susceptibility and issuing early warnings. Other technologies, such as storm cell identification, video-based surveillance, interactive voice response systems, and digital image analysis, accounted for 9% of the total publications. The Internet of Things (IoT) was featured in 19% of the papers, cloud computing in 6%, robotics in 2%, with the remaining publications covering a variety of other technologies.

The traditional hydrological models have proven inadequate for accurately predicting early warnings for flash floods, underscoring the necessity of integrating AI and ML into future susceptibility assessments to enhance prediction accuracy. AI, in general, refers to the capability of computer systems to perform tasks typically associated with human intelligence. ML, a subset of AI, employs algorithms like random forests to predict outcomes by training and validating data sets.

In the context of flash flood assessments, AI and ML can leverage various algorithms, including random forests and logistic regression, using historical flood datasets to predict and validate flood events. Table 1 provides a detailed breakdown of AI/ML algorithms utilized for flash flood forecasting, categorized into two groups: (A) traditional AI/ML algorithms for early warning predictions and (B) AI/ML algorithms for susceptibility predictions, with associated model performance metrics. Among

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these, three AI/ML algorithms—support vector machines (SVMs), artificial neural networks (ANNs), and nearest neighbor classification (NNC)—were employed for early warning predictions, with coefficients of determination (r) of 0.88 for SVM, 0.79 for ANN, and 0.89 for NNC. It was also suggested that integrating computer vision could further enhance the accuracy of flash flood predictions.

One study conducted in Amman, Jordan, evaluated the efficacy of an ML-based ANN model in predicting flash flood early warnings for street drainage water levels. The study found that the ANN model achieved a forecasting accuracy of 93.5%, outperforming conventional forecasting models. Another study demonstrated that SVM could forecast flash flood events within 2.5 milliseconds, significantly faster than traditional numerical models, which take approximately 25 hours. This particular study was conducted in urban areas around the Jindong River basin in Hangzhou, China. Furthermore, an ANN model was able to forecast flash flood events with a 2-hour lead time and transmit warning information via telemetry systems or short message services (SMS) within 10 minutes in the Garang River region of Semarang, Indonesia.

In Leyte Island, Philippines, a study found that an ML-driven regression algorithm could send flash flood warnings, such as alerts for water level and velocity, via SMS when the flood reached a threshold level. However, the study also identified issues with SMS warnings exceeding memory capacity. Another study applied a neural network autoregressive model with an exogenous output (NNARX) to improve predictions of flash flood water levels, velocity, and ocean bottom pressure with over 80% accuracy, although false alarm rates and communication challenges were noted.

Further, a neural network (NN) was used to forecast water levels with a one-hour lead time for a watershed in Campos do Jordão, Brazil, utilizing 3 years of rainfall and water level data from 11 hydrometeorological stations. The study achieved 100% accuracy in classifying true positives in both training and test sets, indicating the reliability of NN models in enhancing early warning systems, though the presence of false positives suggested room for algorithmic improvement. Another study utilizing the long short-term memory (LSTM) approach successfully predicted one-day flash flood warnings with a false alarm rate of 0.09 and two-day warnings with a false alarm rate of 0.21, achieving a critical success index of 0.75.

Addressing the issue of false alarms, an intelligent sensor network (ISN) demonstrated the potential to reduce false alarms and diagnose health data of affected populations via alerts. In Uttarakhand, India, gradient boosting (GBT) and recurrent neural network (RNN)-based warnings were assessed for varying alert levels, such as danger and warnings. The accuracy of these predictions, measured by the coefficient of regression (R^2), was 0.98 for RNN and 0.92 for GBT. However, the study highlighted challenges in predicting water discharge levels due to frequent changes in the area's hydrogeological features.

Another application of the LSTM method in Daqin, China, resulted in improved flash flood predictions, with reduced flood peak flow and volume errors within a range of 3.02-57.4% and 6.3-39.3%, respectively, when coupled with hydrological models. These findings underscore the potential of emerging AI/ML technologies in enhancing the accuracy and efficiency of flash flood predictions and early warning systems.

3.3. Analysis by Flash Flood by IoT type

The Internet of Things (IoT) has significantly advanced the management of flash floods, offering innovative solutions for real-time monitoring and early warning systems. At its core, the IoT is a network of interconnected technologies, including electronic devices, that communicate through the internet to deliver services based on sensor-generated data. This network comprises sensors, software, and computing systems that work in unison to collect, process, and transmit data in real-time, ultimately improving human life quality. For instance, the IoT can be leveraged to issue early warnings for flash floods, providing communities with timely information to mitigate potential disasters.

Integrating IoT into flash flood management systems enables real-time monitoring of flood-related conditions across both rural and urban areas. Although the incorporation of IoT in flash flood warning and monitoring systems is still emerging, recent studies underscore the critical role these smart technologies play in disaster preparedness. Table 3 highlights various studies that have applied IoT to flash flood monitoring and early warning prediction.

One study developed an intelligent flash flood management system using a network of water flow sensors, rain gauge sensors, long-range radios (LoRas), subscriber identity modules (SIMs), warning systems, monitoring systems, and mobile applications. This system allowed communities in flood-prone mountainous regions to receive continuous flash flood warnings via short message service (SMS). However, the study identified challenges in accurately reading and transmitting warning information due to fluctuations in steep slopes and water levels.

Another study examined fault tolerance by implementing the System for detecting and Forecasting Natural Disasters based on the IoT (SENDI) alongside an ns-3 simulator. The findings revealed that the system's overall accuracy in issuing flash flood alerts was over 65%, with red alerts achieving 80% accuracy and yellow alerts 61%. These results were obtained even under adverse conditions, demonstrating the robustness of the IoT system. However, the study also recommended further testing under system failure scenarios to enhance the reliability of such technologies in critical situations.

An innovative flash flood IoT system, known as the Gen1 On-Prem IoT, demonstrated remarkable reliability in delivering early warnings to targeted communities. This system, which operates on a 3G network protocol and incorporates various technologies such as flood level sensors, Linux, Apache, MySQL, PHP, Java, and an email trigger, was effective in issuing flash flood alerts. Despite some internet connectivity challenges and minor issues with performance and support for multiple users, the system proved successful in its primary function.

Another IoT-integrated early warning system, utilizing components such as Arduino microcontrollers, Raspberry Pis, a database server, a web server, and smartphones, enabled users to receive real-time updates on flood conditions and alerts. This setup allowed for continuous monitoring and timely dissemination of warnings, enhancing the community's preparedness for flash flood events.

Further advancements in IoT technology led to the development of a network comprising distance measurement ultrasonic sensors, rain sensors, message queuing telemetry transport (MQTT), Arduino microcontrollers, ThingsSpeak, and WiFi. This system effectively transmitted flash flood alert messages, detailing the type of flood threat. However, experts recommended that the system's monitoring capabilities could be significantly improved by integrating cameras and drones. Additionally, there has been a push to couple IoT systems with artificial intelligence and machine learning (AI/ML) to optimize their operations, particularly in processing and analyzing flood-related data.

The current IoT systems, which include components like Arduino microcontrollers, mobile phones, cloud services, water flow sensors, and ultrasonic distance measurement sensors, have proven effective in transmitting real-time flash flood alerts. However, integrating these systems with remote sensing technologies and geographical information systems (GISs) could further enhance their spatial and temporal accuracy. In one instance, a system successfully communicated flash flood alerts every five minutes, showcasing its efficiency in maintaining continuous communication during flood events.

A more sophisticated IoT system was also developed, incorporating TensorFlow, Raspberry Pi, a Telegram Channel, a camera, and a soft design document (SDD). This system successfully disseminated flash flood alerts via the Telegram Channel, demonstrating its capability in leveraging modern communication platforms for hazard management. Another system, featuring a combination of Raspberry Pi, Synology Network Access Storage, a modem, a web server, an Android mobile phone, and a web browser like Google Chrome, was designed to perform multiple functions, further highlighting the versatility and potential of IoT in enhancing flash flood management systems.

Conclusion

The progression of traditional models for predicting flash floods has certainly yielded significant benefits, but it has also been plagued by numerous technological limitations. These limitations necessitate the integration of advanced smart technologies such as artificial intelligence (AI), machine learning (ML), the Internet of

Things (IoT), cloud computing, and robotics to enhance the accuracy of flash flood assessments and early warning systems. While traditional models, including hydrological and hydrodynamic frameworks, have been instrumental in early warning predictions and impact mitigation, they struggle with challenges like issuing alerts in complex terrains, high computational demands, and less precise forecasts.

To address these shortcomings, it is essential to adopt innovative technological tools, including AI/ML, IoT, cloud computing, and robotics, to thoroughly assess flash flood susceptibilities and develop more reliable early warning systems that can better protect communities and properties. This critical review study highlights several key findings:

1. **Current Technologies and Their Challenges:** Emerging technologies, particularly AI/ML, IoT, and cloud computing, have demonstrated the capability to issue real-time flash flood early warnings. However, they are not without challenges, such as the occurrence of false alarms, internet connectivity issues, and data loss. Future research should explore the inclusion of aerial robotics and computer vision to enhance the performance of these technologies.

2. **Optimization of AI/ML Methods:** The existing AI/ML techniques require optimization to boost their prediction accuracy. While random forests and support vector machines (SVMs) have proven to be the most accurate AI/ML methods, there is potential to further enhance their capabilities by integrating them with other technologies like computer vision.

3. **Inclusion of Diverse Variables:** Present AI/ML approaches employ a broad range of topographical, geological, and hydrological variables. However, future studies should expand this scope by including sociodemographic, health, and housing data variables. This broader approach would help generate more realistic and comprehensive flood susceptibility maps.

4. **Inconsistencies in Variable Selection:** There are inconsistencies and limited information regarding the rationale behind the selection of susceptibility variables. Additionally, potential multicollinearity among these variables poses a challenge that needs to be addressed in future research.

5. **Integration of Health Data:** Current flash flood susceptibility prediction models have not been evaluated against health data, such as flash flood-related mortality cases. Incorporating this data would be crucial in testing the reliability of models in predicting areas most vulnerable to flooding.

6. **Climate Change Considerations:** Future AI/ML-based studies on flash flood prediction should project susceptibility maps and issue early warnings under various climate change scenarios. This would help in understanding the impact of changing climate patterns on flood risks.

7. **Quantification of Health Impacts:** Quantifying flash flood-associated deaths, morbidity, and healthcare costs in susceptible communities could significantly improve future research and help in designing more effective flood management strategies.

The review emphasizes that the predictions for flash flood susceptibility and early warnings serve as critical guidelines for emergency response planning, adaptability, and policy implementation in preparation for future flood events. The study aims to provide a thorough evaluation of the current innovative technologies, such as AI/ML, IoT, cloud computing, and robotics, for early flood warning predictions and susceptibility assessments.

These technologies are capable of disseminating early warnings to targeted communities through electronic media, including SMS and social media platforms, in real time. However, the effectiveness of these systems is often hampered by internet connectivity issues and data loss. While random forests and support vector machines are the most commonly used AI/ML methods for warnings and susceptibility predictions, they still require optimization and could benefit from integration with other emerging technologies like computer vision.

Currently, AI/ML methods utilize several topographical, geometric, and hydrological variables for predicting susceptibility, but there are inconsistencies and a lack of clear theoretical foundations for the selection of these variables. Consequently, future flood risk assessment maps should incorporate additional factors, such as sociodemographic, health, and housing data, to ensure a more holistic approach to flood risk management.