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A Comprehensive Review of Flood Detection Innovations using IoT, GIS and Machine Learning

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Abstract

Floods are among the most devastating natural disasters, necessitating timely and accurate detection to mitigate damage to infrastructure, ecosystems, and human life. Traditional early flood warning systems, while valuable, are increasingly limited by their inability to provide real-time data essential for live flood detection. Live detection relies on continuous monitoring of dynamic data streams, including IoT sensor networks, satellite imagery, and camera footage, enabling immediate response capabilities. This paper presents a systematic review of flood detection techniques, contrasting traditional methods with modern technologies such as IoT, Artificial Intelligence (AI), and Machine Learning (ML). We examine the role of IoT sensors in capturing real-time environmental data, as well as the integration of satellite imagery and live NVR (Network Video Recorder) footage. Furthermore, this review addresses challenges in accessing live data sources, as many real-time video feeds remain unavailable to the public, impacting detection effectiveness. Our findings offer insights into the advantages, limitations, and future directions for enhancing live flood detection systems.

Keywords: Flood detection, real-time monitoring, Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), GIS, Disaster Management.

1. Introduction

Floods are one of the most destructive natural disasters, resulting in significant loss of life, property, and resources globally. The increasing frequency and intensity of floods make detection and monitoring essential, particularly in vulnerable areas, to minimize damage and improve emergency response. Traditional flood detection systems often rely on early warning methods based on weather predictions. However, these approaches are not always reliable due to the unpredictable nature of weather patterns, which can reduce the accuracy of early detections [1]. In contrast, real-time flood detection systems using IoT, machine learning, and remote sensing provide immediate assessments of flood conditions, enabling timely interventions in rapidly changing scenarios [4]. The May 2024 flood in Southern Brazil affected over 420,000 people, with 16% socially vulnerable, causing severe damage to croplands and infrastructure. The floodwater volume was estimated at 1.5 billion cubic meters, highlighting the urgent need for real-time flood monitoring systems to protect vulnerable communities [12].

A study in the Miraj, Palus, and Walwa tehsils of Sangli district revealed that most farmers faced complete crop losses, with sugarcane remaining the dominant crop post-flood. Rice cultivation and intercrops increased, while nearly one-third of the land became unsuitable for farming. The affected farmers had marginal landholdings, low livestock possession, and limited farming experience [9], [18].

Figure 1. Flood situation in Sangli, illustrating the river overflow and its destructive impact on local infrastructure and communities [20].

Severe flooding in the Sangli region caused river overflow, damaging infrastructure and communities. Figure 1 highlights the need for real-time monitoring systems to track water levels, improve emergency response, and reduce flood impact [20].

This review attempt and analyze various flood detection techniques, with a focus on real-time monitoring systems that have gained prominence due to technological advancements. IoT-based systems, for instance, enable continuous data collection on river levels, rainfall, and other key parameters, thus improving responses to flood risks [8]. Additionally, machine learning algorithms are being increasingly employed to detect flood occurrences based on historical data, offering a proactive approach to flood management [2], [5].

Remote sensing also plays a critical role, with satellite imagery aiding in flood mapping and risk assessment. Combining these technologies with artificial intelligence has led to more accurate and reliable methods for flood detection, particularly in real-time applications [3], [7]. This review highlights the latest advancements, comparing the strengths and limitations of these methods in terms of accuracy, response time, and scalability, and emphasizing the importance of real-time systems for effective flood management.

This paper is structured as follows: Section II provides an analysis of IoT-based flood detection systems combined with remote sensing technologies, highlighting their role in real-time flood monitoring. Section III discusses machine learning applications in flood detection, including various algorithms and GIS. Section IV reviews traditional flood detection methods, comparing their effectiveness against modern technologies. The findings underline the need for real-time systems to provide timely and accurate flood information, especially in high-risk areas like Sangli [8].

2. Integration of Iot and Remote Sensing for Flood Detection Systems

Flood detection and monitoring systems have significantly advanced with the integration of IoT-based sensors and remote sensing technologies. IoT plays a vital role in providing real-time data acquisition from various environmental sensors, such as water level, temperature, and rainfall sensors, enabling continuous monitoring and early warning systems [14]. These sensors, when connected to cloud-based platforms, allow seamless data transmission for flood detection and risk assessment.

On the other hand, remote sensing techniques leverage satellite imagery, drones, and SAR sensors to gather largescale geographical data, which helps in flood mapping and damage estimation [15]. Recent advancements in deep learning have further improved the accuracy of flood detection using remote sensing images by automatically identifying water bodies and flood-affected areas [16]. The combined use of IoT and remote sensing technologies enhances the efficiency and accuracy of flood detection systems, making them essential for early warning and disaster management.

Figure 2. Flood Monitoring System with IoT Sensor RTDS.

Figure 2 pictorially exemplifies a typical IoT-based flood monitoring setup, implemented by HDUG [19], where sensors such as RTDs (Resistance Temperature Detectors) and water level sensors are strategically positioned in critical river areas to continuously track water levels and other environmental parameters. This system also includes an alarming system that alerts nearby people when water levels rise. The collected data is transmitted via a GSM module to a cloud platform, where it is processed and made accessible to end-users. By analyzing this real-time data, users can detect potential flood conditions early, allowing for timely responses and preventive measures in flood prone regions. During the survey, one of these sensors was observed to be installed on the Krishna River basin bridge in Sangli.

Sensors in IoT and Remote Sensing-Based Flood Detection

IoT-based systems use various sensors such as water level sensors, rainfall sensors, temperature sensors, and flow velocity sensors for real-time monitoring [14]. These systems are cost-effective but limited to small areas. Remote sensing utilizes satellite sensors (SAR, Optical), drone-based imaging, and multispectral sensors for largescale flood mapping [15]. Though highly accurate, remote sensing is expensive and requires advanced processing techniques [16]. Google Flood Hub is one of the leading platforms that utilizes IoT sensors and remote sensing technologies to provide early flood warnings and real-time monitoring in flood-prone regions [21].

Importance of Real-Time Data

The primary advantage of remote sensing in flood monitoring is its ability to deliver real-time data, which is critical for issuing timely alerts and minimizing damage. High-resolution images combined with advanced data processing methods can accurately detect rising water levels, saturated soil conditions, and other indicators of imminent flooding. This capability is especially necessary in high-risk areas where rapid response is essential to safeguard lives and property [3], [7].

3. Machine Learning Applications in Flood Detection

Machine learning has significantly advanced flood detection by enabling both early detection and real-time monitoring. Live detection, in particular, offers an edge over early detection by leveraging real-time data from sensors and satellites, providing timely updates on changing environmental conditions. This continuous monitoring improves the accuracy and responsiveness of flood warnings, which is crucial for rapid response in high-risk areas [2].

Machine Learning Techniques for Flood Detection

Various machine learning methods, including deep learning and ensemble models, are instrumental in flood detection. These techniques process complex datasets, such as river flow metrics and satellite imagery, to identify patterns and predict flooding events with higher accuracy. Satellite-based models, for instance, analyze high-resolution images to monitor changes in water bodies and land saturation, enhancing early flood identification [5][7]. Deep learning models like *Long Short-Term Memory (LSTM)* and *Gated Recurrent Unit (GRU)* are particularly effective in time-series flood detection. These models excel at capturing temporal dependencies in sequential data, making them suitable for detecting water levels and flood occurrences based on historical data and weather patterns. The combination of deep learning and remote sensing data further improves the precision of flood forecasting systems.

Challenges and Data Limitations

Limited public access to real-time flood data restricts research and application [1]. High-frequency data collection needs costly infrastructure and technical skills, often unfeasible in remote areas. Data privacy and restricted access to governmental datasets further hinder collaboration. Promoting data sharing, standardized protocols, and open data initiatives is vital to enhance global flood detection systems.

Role of GIS in Flood Detection

Geographic Information Systems (GIS) play a vital role in flood detection and mapping by integrating spatial data, environmental parameters, and historical flood records. GIS enables the analysis of various Flood Controlling Factors (FCFs) such as elevation, slope, aspect, rainfall patterns, stream density, and land use [18].

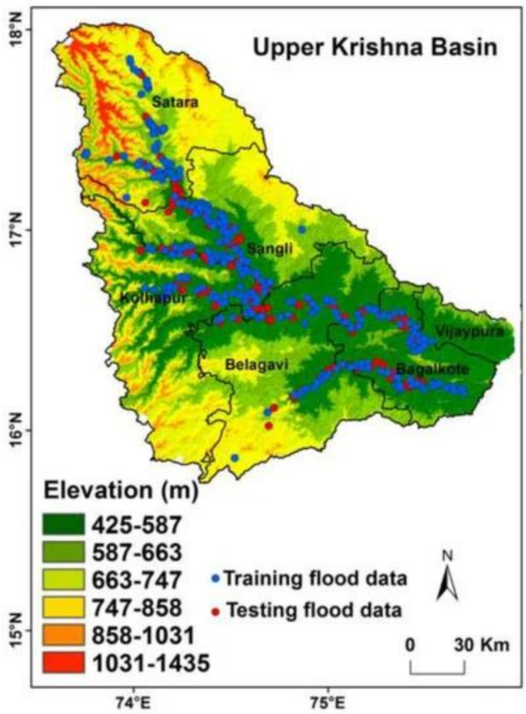

Figure 3. Flood Inventory Map of the Upper Krishna Basin showing Training and Testing Flood Locations [18].

In the Upper Krishna Basin (UKB), the flood inventory map (refer to Figure 3) was generated using 370 flood locations recorded during the August 2019 floods. These flood points were obtained from various government reports and were categorized into training sites (70%) and testing sites (30%). The selected FCFs were converted into raster format with a spatial resolution of 30×30 m for further analysis.

Key GIS-based factors such as Digital Elevation Models (DEM) and Topographic Wetness Index (TWI) were used to identify areas with high flood susceptibility, as lower elevations tend to have a higher likelihood of flooding [18]. Furthermore, GIS supports the statistical analysis of environmental conditions, enabling the creation of flood susceptibility maps through machine learning models.

4. Traditional Methods

In many regions, flood monitoring relies on traditional methods, such as manual observation of water levels using Non-Volatile Recorder (NVR) cameras installed near river bridges. These cameras are typically positioned to focus on white scales marked along the riverbanks to indicate water levels. However, this method requires continuous human intervention, where officials manually observe the live footage and update water level readings through applications like the SMKC (Sangli, Miraj & Kupwad City Municipal Corporation) Seva App [22]. This approach is not scalable, especially during largescale floods, as it depends heavily on human availability and consistent observation.

Another conventional method for flood detection is the *pipe and ball technique*, where a floating ball inside a vertical pipe rises with the water level, providing a visual indication of the water height. However, this method is impractical in flood situations, as the high river flow can damage the system. Additionally, debris and sediment from floodwaters can accumulate inside the pipe, obstructing the ball's movement and rendering the system ineffective.

Furthermore, flood detection approach involves early warning systems installed in dams. The *HERO: Hybrid Effortless Resilient Operation Stations for Flash Flood Early Warning Systems* provides automated flood detection by continuously measuring water levels and transmitting real-time data to control centers. These systems improve response time and reduce human intervention, enhancing flood monitoring efficiency [23].

Moreover, NVR camera access is restricted to authorized personnel, keeping the live footage hidden from the public. Additionally, most systems do not store historical video footage due to storage limitations, making it challenging to perform post-event analysis or develop predictive models based on past flood patterns.

5. Research Gap

Despite notable advancements in flood detection technologies, several gaps persist in the existing literature and current systems.

- **Underutilization of Deep Learning:** While traditional machine learning methods and satellite data are widely used in flood detection, the application of deep learning remains limited. The integration of advanced deep learning models could significantly enhance the accuracy and responsiveness of flood detection [1], [5].
- **Real-Time Data Accessibility:** Flood monitoring systems frequently rely on satellite data, which can be costly and may lack the granularity required for local studies. The lack of access to live river data restricts the capacity of flood management strategies to provide timely alerts [7].
- **Regulatory Constraints on Data Access:** Government restrictions on the availability of real-time river monitoring data and video footage present barriers for researchers. Limited open access to such data hinders the development of robust flood detection models that could benefit from real-time data integration.
- **Reliance on Manual Data Collection:** Traditional systems, such as SMKC, often depend on manual data collection and uploading, which introduces delays in data availability and response. This highlights the need for automated, real-time monitoring to improve situational awareness during flood events.
- **Lack of Localized Detection Systems:** Much of the current research focuses on large-scale areas, overlooking the need for localized flood detection systems that can address specific challenges faced by regions such as Sangli. Localized systems would enable more accurate and context-sensitive predictions, improving preparedness and response for at-risk communities [11].

The proposed study aims to develop a flood monitoring system using deep learning and real-time data to improve predictive accuracy and disaster response.

Future enhancements may include real-time flood detection for better early warnings.

6. Future Directions

IoT and remote sensing technologies are among the best solutions for flood detection, but they are not entirely reliable due to high costs and limited public accessibility. Government branches like HDUG have already invested in installing IoT and remote sensing devices for flood monitoring, but the general public remains unaware of such systems and their data. Making this valuable data publicly accessible can greatly improve disaster management systems and help in building community-based flood detection systems. However, privacy and security concerns often restrict data sharing, which needs to be addressed by developing a secured data-sharing platform where data remains in safe and trusted hands.

Floods are natural phenomena that cannot be entirely predicted, but by integrating dam discharge levels, rainfall patterns, and other environmental parameters with deep learning algorithms and GIS-based models, the detection accuracy can be significantly enhanced. Deep learning techniques offer cost-effective, automated, and reliable solutions compared to traditional methods. Future advancements should aim to utilize existing technologies to reach as many people as possible, helping communities receive early warnings and ultimately preventing disasters. Technology should not only improve detection systems but also serve humanity by saving lives.

7. Conclusion

Flood detection systems play a crucial role in minimizing the devastating impact of floods on infrastructure, ecosystems, and human life. This systematic review highlights the evolution of flood detection techniques from traditional methods to advanced technologies involving IoT, Artificial Intelligence (AI), and Machine Learning (ML). The integration of IoT sensors, satellite imagery, and live NVR footage has significantly improved the accuracy and efficiency of real-time flood detection. However, the lack of accessibility to live video feeds and the complexity of real-time data processing present notable challenges. Based on the comprehensive analysis of more than 20 research papers, it is evident that hybrid approaches combining IoT networks with AI-based image analysis offer promising solutions for enhancing live flood detection systems. Future research should focus on developing open-access live data platforms and optimizing AI algorithms to improve detection accuracy and response time in various regional flood scenarios

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