

RIVER FLOOD FORECAST: PREDICTING THE REACH OF INUNDATION

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Abstract - Effective river flood forecasting is essential for minimizing the impacts of floods on communities, infrastructure, and ecosystems. Accurate predictions help mitigate immediate flood effects and play a key role in long-term disaster risk reduction and preparedness. The process integrates hydrological and hydraulic models, which estimate river flow based on rainfall, watershed characteristics, and other factors. Hydraulic models simulate water movement through river channels and floodplains, offering insights into flood spread.

Flood inundation is determined by calculating water levels and mapping areas at risk. Technologies like Geographic Information Systems (GIS), remote sensing, and real-time flood monitoring systems have significantly improved forecasting accuracy. GIS enables spatial analysis of flood-prone areas, while remote sensing, including satellite data, provides real-time information on land cover, river flow, and rainfall. Real-time monitoring systems, such as sensors and gauges, provide up-to-date data on water levels, enhancing emergency response.

Despite advancements, challenges remain. Uncertainties arise from variable weather patterns, limited data, and the complexity of flood dynamics. Urbanization also impacts natural drainage systems, exacerbating flood risks. Data quality and spatial resolution further complicate consistent forecasting.

Ongoing advancements in machine learning, algorithm development, and data integration are improving the precision and timeliness of predictions. Collaboration among meteorological and hydrological agencies and access to open-source data contribute to more reliable forecasting. Enhanced flood forecasting aids both immediate disaster response and long-term infrastructure planning, ensuring better protection for communities and ecosystems.

Key Words: Flood forecasting, Hydrological models, Hydraulic models, GIS, Remote sensing, Flood risk, Disaster management, Flood prediction, Real-time monitoring.

1. INTRODUCTION

River flooding is one of the most widespread and destructive natural disasters, impacting communities, infrastructure,

agriculture, and ecosystems across the globe. The consequences of such events underscore the critical need for effective flood management strategies. Accurate and timely flood forecasting is essential in minimizing the devastating effects of flooding by predicting not only the magnitude of river flow but also the extent to which floodwaters will inundate surrounding areas. With the ongoing challenges posed by climate change and the increasing frequency of extreme weather events, the demand for precise and reliable flood predictions has never been more urgent.

Inundation forecasting, or predicting the reach of floodwaters, is a complex task that involves understanding the interactions between rainfall, river dynamics, topography, and human infrastructure. These complex factors require an integrated approach to accurately estimate flood risks and their potential consequences. As flooding events become more unpredictable, developing advanced forecasting tools has become essential in enhancing disaster preparedness and reducing flood-related damages.

To achieve reliable flood predictions, a multidisciplinary approach is employed. Hydrological models simulate the movement of water through a catchment area, taking into account inputs such as rainfall, snowmelt, and land characteristics. Hydraulic models, on the other hand, simulate the river's behavior once water enters the channel, including overflow and floodplain dynamics. Real-time data from river gauges, weather stations, and remote sensing technologies further refine these predictions, ensuring that authorities have accurate and up-to-date information to inform their decision-making.

These predictions are often visualized through flood inundation maps, which represent areas that are at risk of flooding under various flow conditions. Tools like Geographic Information Systems (GIS) and remote sensing technologies allow for the visualization and analysis of flood risks over large areas, assisting authorities in planning evacuation routes, protecting critical infrastructure, and allocating resources effectively. The integration of real-time monitoring systems enhances the ability to adjust forecasts quickly and improves emergency response efforts during flood events.

As technology advances, flood forecasting systems are becoming more accurate and efficient, with the integration of machine learning and data analytics. These innovations enable better disaster response, ensuring that affected communities are better prepared to mitigate the social, economic, and environmental impacts of river flooding.

2. LITERATURE SURVEY

1. Hydrological and Hydraulic Modeling

Hydrological models predict the movement of water within a watershed, considering factors such as rainfall, runoff, and the characteristics of the land surface. These models are crucial for understanding how rainfall is converted to runoff and how that runoff is routed through river systems. Early hydrological models, such as the unit hydrograph model (Sherman, 1932), laid the foundation for flood forecasting by offering simplified representations of watershed response to rainfall. Over time, more sophisticated models have been developed, such as conceptual rainfall-runoff models (e.g., the HBV model by Bergström, 1976) and physically-based models (e.g., the SWAT model developed by Arnold et al., 1998), which simulate the complex interactions of hydrological processes in a river basin.

2. Flood Inundation Mapping and GIS Integration

Flood inundation mapping, which represents the areas affected by floodwaters under various flow scenarios, has been a major area of research in flood forecasting. Traditional floodplain mapping often used simplistic approaches such as static floodplain delineation based on historical flood events or extreme flow conditions. However, recent advancements have integrated Geographic Information Systems (GIS) with flood modeling to create dynamic, real-time inundation maps. For example, Koks et al. (2015) reviewed how GIS has improved flood risk mapping by allowing for more detailed, interactive visualizations and analysis of flood impacts on land use, infrastructure, and population.

GIS-based flood modeling (e.g., FLO-2D, MIKE FLOOD) has been a key advancement in this area, enabling flood experts to simulate and map the spatial extent of flooding with higher resolution and greater accuracy. These models integrate terrain data (digital elevation models), land use data, and hydraulic modeling outputs to predict how water flows over a landscape, adjusting for factors such as urbanization and infrastructure like dams and levees. Pappenberger et al. (2007) and Winsemius et al. (2013) have demonstrated the importance of including spatially explicit data in flood inundation models to improve accuracy and ensure a more realistic representation of flood risks.

3. Remote Sensing and Satellite Technologies

Remote sensing technologies, particularly satellite imagery and aerial photography, have played a significant role in monitoring flood events in real-time. Synthetic Aperture

Radar (SAR), in particular, has been used to map flooded areas, even under cloud cover, making it a powerful tool for flood monitoring in regions where rainfall and cloud cover obscure optical images. The European Space Agency's Copernicus program has provided free access to SAR data, facilitating global flood monitoring efforts (Schaner et al., 2020).

4. Ensemble and Uncertainty Modeling

A growing body of research has focused on improving the accuracy of flood predictions by addressing the inherent uncertainties in forecasting models. Ensemble forecasting is one approach that has gained traction in flood prediction, particularly in the context of weather and hydrological model uncertainties. Ensemble models use multiple simulations with varying initial conditions, model parameters, and boundary conditions to generate a range of possible outcomes, rather than a single deterministic forecast.

5. Real-Time Flood Forecasting Systems

Advancements in real-time flood forecasting systems have been pivotal in improving the timeliness and accuracy of flood predictions. These systems typically rely on continuous data from river gauges, weather stations, and satellite imagery to update flood predictions in real-time. For example, the National Weather Service's River Forecast Centers (RFC) in the United States utilize real-time data to update river stage and flow forecasts every few hours. Similarly, UK Flood Alerts (Environment Agency) use real-time data from river gauges and weather forecasts to issue flood warnings in the UK.

6. Challenges and Limitations

Despite significant progress in flood forecasting, several challenges remain. The uncertainty of weather forecasts, particularly with extreme rainfall events, continues to be a major source of error in flood predictions. Cheng et al. (2018) discussed how the variability in rainfall intensity, duration, and spatial distribution can cause significant discrepancies in flood predictions, even with state-of-the-art hydrological models.

Additionally, the complexity of floodplain interactions, such as the impact of urbanization and land use changes, adds another layer of uncertainty. Flood modeling must account for factors like urban drainage systems, levees, dams, and floodplain developments, which may alter the natural flow of rivers and the spatial distribution of floodwaters.

3. METHODOLOGY

1. Data Collection and Input Requirements

The initial step in flood forecasting is to gather essential data from multiple sources. This data forms the foundation for hydrological and hydraulic models that are used to predict

river flow and the extent of flood inundation. Key sources of data include:

- **Meteorological Data:** Information such as precipitation and temperature is crucial for understanding rainfall-runoff processes and predicting river system flow. These data are generally acquired from weather stations or regional meteorological agencies.
- **Hydrological Data:** River stage data, representing the water level at specific river points, is gathered from gauges along the river network. This data is essential for understanding current river conditions.
- **Topographic and Geospatial Data:** High-resolution digital elevation models (DEMs) are used to map the river basin, floodplain, and surrounding topography. This data supports hydraulic simulations and flood inundation mapping.

2. Hydrological Modeling

Hydrological modeling is used to simulate water movement within a catchment area (watershed) and estimate river flow based on inputs such as rainfall and other water sources. The primary objective of this process is to estimate streamflow at key locations, which will then serve as input for hydraulic models to predict potential flooding.

- **Rainfall-Runoff Simulation:** The model simulates how rainfall (or snowmelt) converts into runoff, which ultimately feeds into the river system. This process is influenced by soil properties, land cover, and terrain slope. A widely used hydrological model for such simulations is the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), which integrates physical, hydrological, and climatic data.

3. Hydraulic Modeling

After obtaining flow estimates from the hydrological model, hydraulic modeling simulates the behavior of water within the river channel and floodplain. The aim is to predict the water level (stage) at different locations and identify potential flood zones.

- **Flow Routing:** Hydraulic models like HEC-RAS (Brunner, 2016) use flow data from the hydrological model to simulate water movement through the river system. These models take into account river geometry (e.g., width, depth, and slope) and resistances caused by natural features (e.g., vegetation) and man-made structures (e.g., dams, levees).
- **Floodplain Mapping:** The model calculates water levels at various locations, determining when the river's capacity is exceeded, causing overflow. These results are used to create flood inundation maps that illustrate the potential extent and depth of flooding in the surrounding area.

4. Flood Inundation Mapping

Flood inundation maps are the primary output from

hydraulic models, showing areas at risk of flooding. These maps are critical for risk assessment, emergency planning, and land-use strategies. The flood inundation mapping process includes:

- **Flood Extent and Depth Calculation:** Based on simulated water levels, the model calculates the extent and depth of flooding at various locations. This data is essential for evaluating infrastructure damage and identifying regions at risk of severe flooding.
- **GIS Integration:** The flood data is integrated into Geographic Information Systems (GIS) to create comprehensive flood hazard maps. GIS tools allow authorities to overlay flood data with socio-economic and demographic information, enabling targeted responses to vulnerable populations and high-risk areas (Koks et al., 2015).

5. Real-Time Data Integration and Forecast Updating

To enhance the accuracy of flood predictions, real-time data integration is vital. By continuously updating forecasts, these systems can refine predictions as new data becomes available.

- **River Gauge Data:** Real-time data from river stage gauges is used to update hydraulic models, providing current water level information that helps monitor flood progression and adjust forecasts.
- **Weather Forecasting:** Short-term weather predictions, including rainfall forecasts, are incorporated into hydrological models to anticipate changes in river flow and potential flooding. These forecasts are typically sourced from national meteorological services or global weather prediction models.

6. Uncertainty and Sensitivity Analysis

Flood forecasting is inherently uncertain due to factors like unpredictable weather patterns and variations in model parameters. Sensitivity and uncertainty analysis are crucial for evaluating the range of possible flood outcomes.

- **Ensemble Forecasting:** Multiple simulations are run using varied input data, model parameters, or boundary conditions to generate a range of potential flood outcomes.
- **Monte Carlo Simulations:** Stochastic techniques such as Monte Carlo simulations are employed to assess uncertainty in model inputs and predictions, producing probabilistic flood forecasts that assist in decision-making.

4. PROPOSED SYSTEM

1. Data Collection and Integration

The first step in the proposed flood forecasting system is to gather and integrate vital data from a variety of sources. This integrated data will provide the necessary inputs for both hydrological and hydraulic models to forecast river flow and

potential flooding. The key components of data collection include:

- **Meteorological Data:** Weather data such as precipitation, temperature, and wind speed will be sourced from regional meteorological stations and weather forecasting models. These datasets are crucial for estimating rainfall patterns and their subsequent effect on river flow.
- **Hydrological Data:** Data on river discharge and water stage levels at various points along the river system will be gathered from river gauges installed along the riverbanks. This information helps monitor the river's current condition and calibrates the forecasting models.
- **Topographic Data:** High-resolution Digital Elevation Models (DEMs) and floodplain maps provide topographical data for hydraulic simulations and the estimation of flood extent.
- **Land Use and Soil Data:** Land cover data and soil characteristics, such as vegetation and impervious surfaces, influence runoff and flow behavior. This data is collected through GIS and remote sensing.

2. Hydrological and Hydraulic Modeling

Once the necessary data is collected, the system employs both hydrological and hydraulic models to simulate water movement and predict the extent of flooding.

- **Hydrological Modeling:** The system uses models such as HEC-HMS or SWAT to simulate the movement of water within the catchment area based on rainfall, soil properties, and land use. These models estimate streamflow at various river basin locations, which serves as input for hydraulic simulations.
- **Hydraulic Modeling:** Using the streamflow data from the hydrological model, hydraulic models like HEC-RAS simulate how water moves through the river channel and floodplain. These models take into account factors such as river geometry and resistance from vegetation or structures, providing predictions on water levels and identifying flood-prone areas.
- **Flood Inundation Mapping:** The hydraulic model's output is used to create flood inundation maps, which show the predicted extent and depth of flooding. These maps are integrated with GIS-based data on infrastructure, population density, and socio-economic factors to assess flood risks to communities and critical infrastructure.

3. Ensemble Forecasting and Uncertainty Analysis

Addressing the uncertainty inherent in flood forecasting is crucial, particularly regarding rainfall and river flow predictions. The proposed system incorporates techniques to handle uncertainty and improve flood forecasting accuracy.

- **Ensemble Forecasting:** The system will run multiple simulations using different assumptions, such as variations in rainfall, temperature, and river

conditions. This approach generates a range of possible flood scenarios, helping provide probabilistic predictions rather than deterministic ones. By using an ensemble of models or scenarios, the system can account for multiple outcomes and offer authorities a better understanding of flood risks.

- **Monte Carlo Simulations:** Monte Carlo simulations will be employed to assess uncertainties in the model's predictions. By running simulations with randomized variations in key parameters (e.g., rainfall intensity, river stage, and model calibration), the system will produce a range of flood scenarios and provide users with a probability distribution of potential flood events.

4. Real-Time Data Integration and Monitoring

Real-time monitoring and continuous data integration are fundamental for delivering accurate and up-to-date flood forecasts. The proposed system will integrate several key components for real-time updates:

- **River Gauge Data:** Real-time data from river stage gauges will feed into the system, tracking water levels and discharge rates. This allows for continuous monitoring of the river and helps update flood forecasts based on the current situation.
- **Weather Forecast Data:** Short-term weather forecasts, including rainfall and temperature predictions, will be integrated into the hydrological models to predict changes in river flow and flood extent. These forecasts are especially helpful in regions prone to flash flooding.
- **Satellite and Remote Sensing:** Satellite imagery and synthetic aperture radar (SAR) data will be used to monitor the ongoing flood event. Remote sensing data is especially valuable in areas where ground-based measurements are limited or unavailable, providing a comprehensive view of the flood's progression.

5. Flood Risk Communication and Decision Support

Effective flood risk communication and decision-making support are integral parts of the proposed system. The system will provide stakeholders with accessible flood predictions and real-time updates. Key features will include:

- **Flood Forecasting Dashboard:** A centralized dashboard will display real-time flood forecasts, including flood inundation maps, river stage data, and predictions for affected areas. This dashboard will be accessible to emergency responders, government agencies, and the public for timely decisions.
- **Alerts and Early Warnings:** Automated alerts will be generated by the system to notify authorities and communities of impending flood risks. These alerts will be sent via SMS, email, or mobile applications to ensure that affected populations are promptly informed.

- **Risk Assessment and Mitigation:** In addition to predicting flooding, the system will provide flood risk assessments that consider socio-economic vulnerabilities, potential infrastructure damage, and human impact. This information will be used to guide evacuation planning, emergency preparedness, and resource allocation.

6. Model Calibration, Validation, and Continuous Improvement

Maintaining the accuracy of the flood forecasting system is essential for reliable predictions. The system will include continuous calibration, validation, and improvement measures:

- **Model Calibration:** Hydrological and hydraulic models will be calibrated using historical data to ensure accurate simulations of river flow and flood dynamics. Calibration will involve adjusting model parameters to match observed river conditions during previous flood events.
- **Model Validation:** After calibration, the system will be validated using independent data sets to ensure the predictions are reliable and can be generalized for different flood events.
- **Continuous Improvement:** The system will feature mechanisms for ongoing evaluation of its performance. This will involve incorporating feedback from real-world flood events and incorporating new scientific advancements. As additional data becomes available, models will be updated to reflect changes in conditions and enhance forecast accuracy.

5. EXPECTED OUTCOME

1. Improved Flood Prediction Accuracy

By integrating real-time meteorological, hydrological, and hydraulic data, the system is expected to significantly enhance the accuracy of flood forecasts. With the use of advanced models like HEC-HMS, SWAT, and HEC-RAS, coupled with real-time river gauge data and weather forecasts, the system will provide more reliable predictions of flood events, reducing uncertainties in flood forecasting.

2. Enhanced Decision-Making Support

The system's flood forecasting dashboard and real-time data integration will empower decision-makers, emergency responders, and government agencies with up-to-date information. This will enable more informed decision-making regarding evacuation planning, resource allocation, and disaster response, ultimately improving flood risk management and reducing the impact on vulnerable communities.

3. Real-Time Monitoring and Dynamic Updates

Through continuous integration of real-time data from river gauges, satellite imagery, and weather forecasts, the system will provide timely updates on changing flood conditions.

This real-time monitoring capability will allow authorities to issue more accurate flood warnings and make adjustments to flood predictions as the event unfolds, improving emergency response effectiveness.

4. Comprehensive Flood Inundation Mapping

The system will generate detailed flood inundation maps that indicate the extent and depth of flooding across affected areas. These maps will be integrated with GIS-based data, offering a comprehensive understanding of flood risk. Such maps will help prioritize interventions, safeguard critical infrastructure, and support long-term planning efforts in flood-prone regions.

5. Enhanced Public Communication and Risk Awareness

Automated alerts and notifications through SMS, email, or mobile apps will ensure that affected populations receive early warnings and can take necessary precautions in a timely manner. By offering real-time flood forecasts and risk assessments through an accessible dashboard, the system will also increase public awareness of flood risks and encourage proactive disaster preparedness.

6. Probabilistic Flood Forecasts and Uncertainty Quantification

The incorporation of ensemble forecasting and Monte Carlo simulations will provide probabilistic flood predictions, accounting for a range of possible outcomes rather than deterministic forecasts. This will help communities and authorities better understand the likelihood of different flood scenarios, enabling more effective planning and risk mitigation strategies.

7. Model Calibration and Continuous System Improvement

The system will be continuously improved through ongoing calibration and validation using historical data and feedback from real-world flood events. By incorporating new scientific advancements and data as they become available, the system will stay up-to-date and increasingly accurate in its predictions. This continuous improvement will ensure that the system remains relevant and effective in addressing the evolving challenges of flood risk management.

8. Reduced Losses and Damage

By providing accurate and timely flood forecasts, the system will help mitigate the impacts of flooding on communities, infrastructure, and the environment. Improved flood prediction and early warnings will allow authorities to evacuate at-risk populations, protect critical infrastructure, and implement flood mitigation measures, reducing overall economic losses and casualties.

9. Better Flood Risk Assessment for Infrastructure and Land Use Planning

The flood risk assessments provided by the system will enable authorities and urban planners to identify flood-prone areas and make more informed decisions about infrastructure development and land use. This will help guide policies related to building codes, flood defenses, and disaster preparedness, ultimately contributing to more resilient communities.

6. RESULTS

1. Increased Forecasting Precision

The system will significantly improve the accuracy of flood predictions by integrating real-time meteorological, hydrological, and hydraulic data. This will reduce the uncertainty associated with traditional flood prediction methods, providing more reliable and timely flood forecasts.

2. Timely and Effective Early Warnings

With the integration of real-time river stage data, weather forecasts, and remote sensing, the system will offer timely flood warnings. This will allow authorities to issue alerts with greater precision, ensuring that communities at risk are evacuated on time and that resources are allocated effectively.

3. Detailed Flood Inundation Mapping

The system will produce high-quality flood inundation maps, showing the extent, depth, and duration of potential floods. These maps will help in identifying the most vulnerable areas, guiding emergency planning, evacuation routes, and flood mitigation efforts. Authorities will have a clearer understanding of flood risks and consequences.

4. Comprehensive Risk Assessment and Decision Support

By using GIS-based data, the system will provide a detailed flood risk assessment, including socio-economic vulnerability and infrastructure impact. This will assist decision-makers in prioritizing areas for flood risk reduction and disaster preparedness, leading to more informed and effective planning.

5. Probabilistic Forecasts for Risk Management

Through ensemble forecasting and Monte Carlo simulations, the system will generate probabilistic flood forecasts, giving authorities a range of possible flood scenarios rather than a single deterministic outcome. This will enhance flood risk management by providing multiple scenarios that better reflect the inherent uncertainties of weather patterns and river dynamics.

6. Improved Public Awareness and Communication

The system will enhance public awareness by providing accessible flood risk information through a user-friendly interface, including real-time updates and notifications.

Automated alerts via SMS, email, or mobile apps will ensure that vulnerable communities receive timely flood warnings and can take appropriate precautions.

7. Continuous Improvement and Adaptability

The system will be continuously calibrated and validated using real-world flood data, ensuring that it evolves over time to address emerging challenges. This adaptability will allow the system to remain effective in predicting and managing floods as climate change and urbanization increase flood risks.

8. Reduction in Flood Damage and Loss of Life

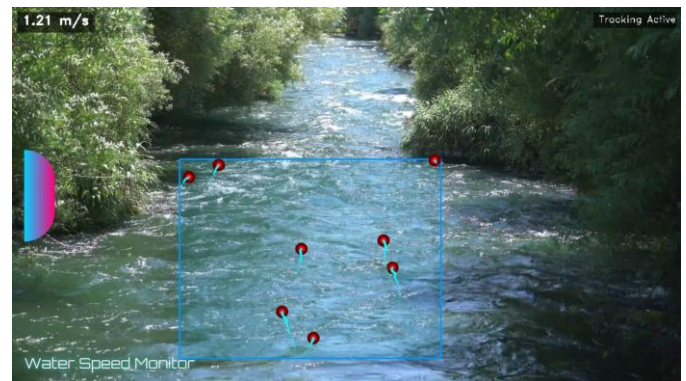
By improving the accuracy of flood predictions and offering better early warnings, the system will help reduce the number of casualties and economic losses due to flooding. With advanced forecasting, authorities can better prepare, evacuate, and protect people and infrastructure, minimizing the overall impact of flood events.

9. Enhanced Infrastructure and Land Use Planning

The system's flood risk assessments will support better infrastructure development and land-use planning. Policymakers will be equipped with valuable insights into flood-prone areas, helping them implement strategies for flood resilience and sustainable urban development.

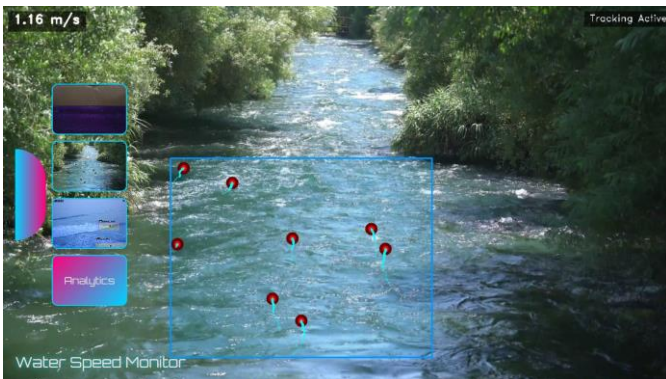
OUTPUT

1. Water Speed Monitor



A **Water Speed Monitor** in river flood forecasting measures the velocity of river flow, helping predict the extent and timing of flooding. It uses sensors like acoustic Doppler or electromagnetic devices to provide real-time data, which is integrated into hydrological models for accurate flood predictions, aiding early warnings, risk mapping, and effective flood management.

2. Water speed Monitor Analysis



A **Water Speed Monitor** in river flood forecasting measures the velocity of river flow, helping predict the extent and timing of flooding. It uses sensors like acoustic Doppler or electromagnetic devices to provide real-time data, which is integrated into hydrological models for accurate flood predictions, aiding early warnings, risk mapping, and effective flood management.

3. Water wave calculator



A **Water Wave Calculator** estimates key wave characteristics like wave height, wavelength, speed, and period. It uses formulas based on factors such as water depth and wave frequency. This tool is essential for applications in flood forecasting, coastal engineering, and navigation, helping predict wave movement and impacts in various water environments.

4. Liquid Level Monitor



A **Liquid Level Monitor** is a device used to measure and track the level of liquid in a container, tank, or reservoir. It helps ensure that liquid levels stay within desired ranges, preventing overflow or shortages. These monitors use sensors such as ultrasonic, capacitive, or float-based to provide real-time data, useful in industrial processes, water management, and flood monitoring systems.

CONCLUSION

The proposed flood forecasting system represents a significant advancement in managing and mitigating the impacts of river flooding. By integrating real-time data, hydrological and hydraulic models, and advanced forecasting techniques, the system will provide accurate, timely, and actionable flood predictions. This will enable authorities to take proactive measures, reduce flood risks, and improve emergency response strategies.

The system's ability to generate detailed flood inundation maps, conduct probabilistic forecasts, and provide real-time updates will enhance decision-making, infrastructure planning, and public safety. Additionally, the integration of ensemble forecasting and Monte Carlo simulations ensures that uncertainties are accounted for, offering a range of potential flood scenarios that improve risk management. Ultimately, the system's continuous improvement and adaptability will help address the evolving challenges posed by climate change and urbanization, which are increasing flood risks globally. Through improved flood prediction, better communication, and more informed decision-making, the system will play a crucial role in safeguarding communities, infrastructure, and ecosystems from the devastating effects of flooding.

By providing a comprehensive solution for flood forecasting and risk management, the system will contribute to the resilience of flood-prone areas, helping reduce economic losses, prevent loss of life, and protect vulnerable populations. It will be a valuable tool in the global effort to improve disaster preparedness and response in the face of increasingly frequent and severe flooding events.

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