Research Paper

Main Leveraging Artificial Intelligence for Enhancing Flood Resilience in Urban Villages: A Case Study of Zhengzhou, China

A Comprehensive Framework Applied to Zhengzhou, China

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Abstract

In this paper, we present a conceptual framework for improving flood resilience in urban villages using saof Synthetic Aperture Radar (SAR) imagery and artificial intelligence. This theoretical exploration draws insights from the 2021 Zhengzhou flood event and proposes a methodological approach that combines the all weather imaging capabilities of SAR with deep learning models for flood detection and mapping. The framework addresses the special challenges of urban villages, where high density development is combined with inadequate infrastructure. This study is theoretical but lays the foundation for future empirical research and practical implementation in flood prone urban environments. The proposed framework adds to the growing discourse on urban resilience by providing a systematic approach to integrating advanced technology into disaster preparedness in vulnerable communities.

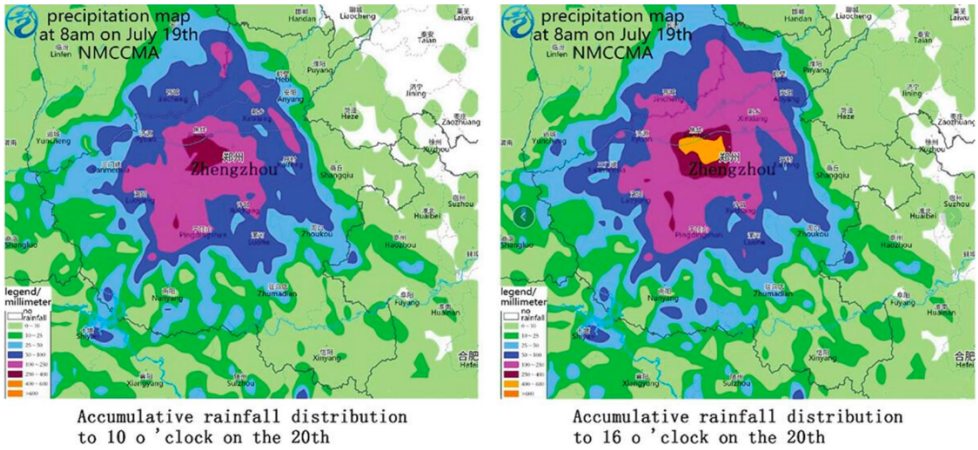
Keywords

Flood Resilience, Urban Villages, SAR Imagery

1. Introduction

1.1 Research Context

Anthropogenic climate change is driving increasing frequency and intensity of extreme precipitation events that present unprecedented challenges to urban flood management systems worldwide (He and Silliman, 2019). In particular, in informal settlements like the urban villages, where insufficient infrastructure and higher population density work as aggravating factors, this vulnerability is even pronounced (Mwalwimba, Manda and Ngongondo, 2024). In light of the catastrophic July 2021 Zhengzhou flood, with 302 fatalities and CNY 53.2 billion in economic losses, our results emphasize the need for improving flood monitoring and response functions now at these vulnerable urban areas.



Accumulative rainfall distribution to 10 o 'clock on the 20th

Accumulative rainfall distribution to 16 o 'clock on the 20th

Image 1: Zhengzhou real-time rainfall map. Image source: China Meteorological Administration

However, contemporary flood monitoring approaches are found to lack capabilities to resolve the challenging aspects of urban villages. Traditional methodologies, mostly developed for formal urban areas, generally fail to incorporate the specific spatial and social attributes of informal settlements (Abbott, 2002). However, existing systems often lack sufficient temporal resolution and accuracy in densely populated urban areas, where rapid flood dynamics require near real time monitoring. To bridge these gaps, this research develops an integrated framework that combines Synthetic Aperture Radar (SAR) technology with deep learning methods tailored to the unique requirements of urban villages in Zhengzhou.

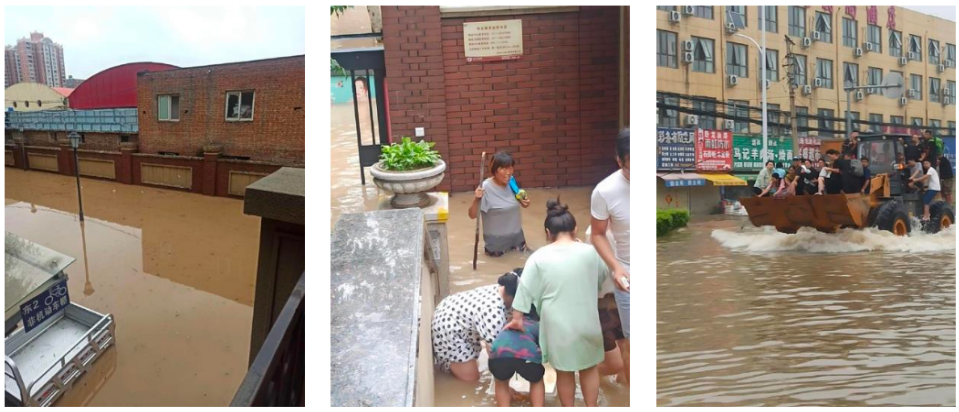


Image 2: Zhengzhou after the flood. Image source: Henan News Network

1.2 Research Objectives

This study addresses three primary research objectives:

1. To develop a comprehensive theoretical framework integrating SAR technology and deep learning methodologies for urban flood monitoring, with specific attention to:
    - Data acquisition optimization strategies
    - Processing algorithm adaptation requirements
    - Implementation pathway identification
2. To establish methodological approaches addressing urban village-specific challenges:
    - Morphological complexity considerations
    - Temporal resolution requirements
    - Spatial accuracy optimization
    - System integration protocols
3. To provide a theoretical foundation for future empirical research through:
    - Clear methodological guidelines
    - Testable hypotheses development
    - Validation criteria establishment
    - Implementation pathway identification

The significance of this research lies in its potential to:

- Advance theoretical understanding of technology integration in disaster management
- Establish methodological frameworks for future empirical studies
- Guide practical implementation strategies
- Contribute to urban resilience enhancement

2. Literature Review

Understanding that combines multiple theoretical perspectives and advanced technological solutions is essential for effective flood monitoring and management in urban villages (Jamshed *et al.*, 2020). However, current literature stresses the intricate interplay between urban morphological qualities, socio-technical systems, and adaptive flood dynamics that define a good monitoring approach (He and Silliman, 2019)(Evans, 2012). While technological solutions have been developed to a significant degree, the specific challenges of urban villages, with their high-density development, complex spatial arrangements, and limited infrastructure, require more sophisticated and integrated approaches to flood monitoring and management. Most of the existing research has been in conventional urban areas, and has paid very little attention to the particular context of urban villages (Cohen, 2004). (Fernández and Lutz, 2010) states that most flood monitoring studies focus on planned urban development, which leaves a big gap in the understanding of how monitoring systems can be adapted to the peculiarities of informal settlements. The limitations are particularly acute in the context of Chinese urban villages, where urbanization and informal development patterns result in unique challenges for flood management systems.

Urban form theory provides a theoretical foundation for understanding urban flood monitoring. This theoretical framework, pioneered by (Conzen, 1960), and offers fundamental insights into how urban form influences flood vulnerability. provides fundamental insights into how urban form affects flood vulnerability. He noted that the physical layout and structural characteristics of urban areas play an important role in determining their environmental risk profile. This theoretical framework was subsequently extended (Kropf, 2009) to explicitly link patterns of urban organization to flood risk, focusing on how complex morphology affects water flow dynamics, drainage patterns, flood propagation pathways, and accessibility for emergency response. These morphological considerations are particularly relevant to the case of urban villages, where high building densities, intricate spatial layouts, and limited permeable surfaces make it difficult to monitor and manage flood events.

In addition to physical characteristics, the socio-technical systems perspective provides important insights into the implementation of flood monitoring. This theoretical approach stems from the research of (Trist and Bamforth, 1951) which emphasized the important relationship between technological solutions and their social context. Applying this theory to recent flood monitoring applications emphasizes the need to integrate technical capabilities with local social structures and institutional frameworks. (Yue Zhang *et al.*, 2023) show that the success of flood monitoring systems depends on coordination with local infrastructure capacity, integration with community social networks, adaptation to institutional governance structures, and the ability of communities to use the system. This realization is important in urban villages where social networks may be more important than formal institutional structures.

Complex Adaptive Systems (CAS) theory illuminates further the dynamic nature of urban flood processes. Further developed by (Batty2007) from(Holland, 1996) foundational work, further developed by (Batty2007), it is also adapted that urban flood systems show non-linear behavior patterns that necessitate adaptive monitoring approaches. Emergent properties of these systems require real time analysis capabilities, multi scale interactions requiring integrated monitoring solutions and self-organizing characteristics affecting response strategies. This theoretical perspective emphasizes the necessity for monitoring systems that can adapt to and capture the complexities of urban flood events in the urban village environment.

The recent technological improvements in remote sensing and computational methods have greatly improved flood monitoring capabilities. (A. Refice *et al.*, 2014) highlight the advantages of SAR technology in flood monitoring, particularly its ability to operate effectively in adverse weather conditions and provide

high-resolution imagery through cloud cover. Using large volumes of SAR data, extracting spatial features, analyzing temporal flood patterns, and predicting flood propagation, hybrid CNN-RNN architectures (Islam *et al.*, 2022) show their effectiveness in processing large volumes of SAR data. However, these technological advances provide promising solutions to the complex monitoring needs of urban village environments. However, there are still many significant gaps in current research. The current literature is insufficient in terms of integration between theoretical frameworks and practical monitoring solutions, especially in the context of urban villages.

While individual theories provide useful insights, there is still a need for integrated frameworks that combine multiple theoretical perspectives with technical solutions. In addition, current research has not adequately addressed the challenges of deploying flood monitoring systems in urban village environments, which have unique morphological and socio-technical characteristics. Current algorithms, while effective in traditional urban environments, may not be optimally adapted to the complexity and dynamics of flooding systems in urban villages, and thus optimizing deep learning algorithms for flooding systems in urban villages is an ongoing challenge.

3: Methodology

The objective of this study is to create a comprehensive theoretical framework that combines Synthetic Aperture Radar (SAR) technology with deep learning methods for flood monitoring in urban villages of Zhengzhou. The methodology section provides data acquisition optimization strategies, algorithm adaptation requirements, implementation pathway identification and a complete methodological framework construction. The scientific rigor and systemic coherence of the research design is ensured by the close alignment of each methodological component with Urban Morphological Theory, Socio-Technical Systems Theory, Complex Adaptive Systems (CAS) Theory, and the multi-level perspective on technological transitions.

3.1 Data Acquisition Optimization Strategies

Optimized data acquisition strategies are crucial to accurate and real time flood monitoring. With the complex spatial structures and diverse socio-economic characteristics of Zhengzhou's urban villages, this study employs a dual approach of SAR data acquisition and urban morphology analysis to formulate the detailed data acquisition optimization strategies.

The first step is to choose good SAR satellite data sources for data acquisition. For the flood monitoring needs of Zhengzhou's urban villages, this study uses high resolution SAR data from Sentinel-1, RADARSAT-2 and TerraSAR-X, from which high frequency coverage (every 12 days) and spatial resolution of up to 5 meters in C band is provided for large scale dynamic monitoring. The Canadian Space Agency (CSA) operated RADARSAT-2 which provides high resolution data (ranging from 1 meter to 100 meters) and multi polarization modes that are suitable for fine grained flood monitoring, such as delineating water boundaries and assessing variations in flood depth (Ramsay *et al.*, 2004). The 1 meter spatial resolution and high temporal resolution (Lobo and Garcia, 2014)of TerraSAR-X, operated by the German Aerospace Center (DLR), is ideal for real time detailed flood monitoring and data analysis.

A frequency of data acquisition is chosen based on the dynamic characteristics of floods in urban villages. To capture the rapid flood evolution and expansion paths, the data acquisition frequency is increased to at least once a week, or during the rainy season or flood prone periods. On the other hand, the frequency is changed to once a month during non-flood seasons to monitor long-term flood risk trends and changes. In

addition, high SNR SAR images are selected to maintain stringent control on the SNR and to ensure clear visibility of flood features (Gersman *et al.*, 2008). Polarization modes (e.g., VV/VH) are selected to improve the discrimination of water bodies from the surrounding land surface. Geometric correction, radiometric calibration, and speckle noise reduction using Gaussian and median filters are performed during data preprocessing to improve SAR image quality and consistency and generate high quality data inputs for subsequent deep learning models.

Vector data on building footprints, road networks and land use types were collected through Geographic Information System (GIS) software (e.g., ArcGIS and QGIS) for spatial distribution analysis, mapping of urban villages and identification of flood-prone areas. In addition, the study developed quantitative indicators of morphological complexity including Land Use Diversity Index (LUDI), Building Height Variance (BHV) and Road Network Density (RND). These metrics are calculated using the Shannon Diversity Index of Land Use Diversity (LUDI), Building Height Variance (BHV), and Road Length per Unit Area (RND), which reflect land use complexity, building height variance, and road network density. The spatial data collection strategy is guided by these morphological complexity metrics to increase the density and resolution of data collection in areas of high morphological complexity to accurately capture the dynamics of flooding.

3.2 Algorithm Adaptation Requirements

To adapt deep learning algorithms to complex SAR data, we must understand how to carefully optimize for the multi-level and multi scale flood propagation patterns. This study approaches algorithm adaptation from two perspectives: It covers data preprocessing and feature extraction, deep learning model selection and optimization.

Deep learning algorithms must address the specific needs of flood monitoring, which is why model selection is critical. Based on Holland and Batty complex systems theories, this study chooses and optimizes suitable deep learning models, such as Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs), and their hybrid models (e.g., CNN–RNN hybrids). SAR images are adept at extracting spatial features (water body boundaries and expansion characteristics) (Wang, Zhang and Hao, 2019), while RNNs are good at dealing with time series data and capturing temporal dynamics of flood spread (B. Nagendra and G. Singh, 2023). The hybrid models combine the strength of CNNs and RNNs to process spatial features and temporal dynamics simultaneously, which improves the capability of dynamic flood monitoring.

Ongoing study optimizes model architecture for better model adaptability and predictive accuracy guided by complex systems theory. For instance, the flood features can be extracted at various spatial scales using introduction of multi scale convolutional layers in CNN component. Adding Long Short-term Memory (LSTM) units into the RNN component will help the model capture long term dependencies better and finally better predict flood expansion path. In addition, a multi level feature extraction mechanism is employed to combine different levels of features to improve the model's ability to adapt to the complex flood propagation patterns.

Deep learning models are good at what they do because data preprocessing and feature extraction are so important. A systematic preprocessing of SAR data is performed including noise filtering, data augmentation and normalization of the images. Then, to improve quality of the SAR images, Gaussian and median filters are used to filter speckle noise from them. Data augmentation is applied to the training data to increase the diversity of the training data and thereby, to improve the model’s generalization capability such as rotation, flipping, scaling etc. For image normalization, we scale SAR image pixel values to the range [0, 1] to stabilize and keep the model training consistent.

Finally, to extract important features for flood monitoring, the study makes use of the urban morphology analysis results. The areas covered are flood depth variations, and water body expansion speed and surface change detection. Water body expansion speed is calculated as flood propagation speed from time series SAR images. SAR images' scattering characteristics are used to estimate dynamic information on flood intensity through estimate of flood depth variations. Surface change detection compares pre and post flood SAR images to identify surface morphology changes (e.g. submergence of buildings and damaged roads). By extracting these features and using them to define input to the deep learning models, accuracy and real time capability of flood monitoring are increased.

3.3 Implementation Pathway Identification

The implementation pathways need to be identified to translate theoretical frameworks into practical applications. Through technical integration and system design, this study ensures the effective application of SAR technology and deep learning methods in flood monitoring of urban villages, and recognizing technology transition pathways.

Practical application is based on technical integration and system design. The study designs technical solutions based on socio technical systems theory, Trist and Bamforth, which accommodate the social structure and flood prevention needs of urban villages. It involves many rounds of communication with community residents, local governments and other stakeholders to understand their flood prevention requirements as well as their level of acceptance of technology, so that the technical solutions meet actual needs. The study collects community expectations and suggestions through surveys and in depth interviews and adapts the technical solutions to increase user satisfaction. In addition, the study provides protocols for system integration that support seamless interoperability between SAR technology and deep learning systems. It includes standardization of SAR data formats, design of real time data transmission protocols, and standardization of system interfaces to facilitate compatibility and scalability of the different technical components.

For the sustainable implementation, it is important to identify technology transition pathways. The study identifies macro, meso and micro level pathways to align the technology transition process with the social and environmental characteristics of urban villages, drawing on (Geels, 2004) multi level perspective on technological transitions. To achieve this at the macro level, collaboration with local governments is pursued to enhance policy support and funding for flood monitoring technologies, and to apply for government research project grants to secure policy incentives and resource allocation for flood management. On the meso level, the study collaborates with SAR data providers and deep learning technology suppliers to build stable technical support and data supply chains to ensure the successful deployment of SAR technology and deep learning systems. In addition, long term partnerships with technology suppliers are also established to ensure a continuous supply of technical resources and support. The study designs and implements training programs for technical operators and community residents to improve their operational capabilities and technology acceptance at the micro level. This would include organizing training workshops, developing operation manuals and establishing technical support teams to enable technical personnel and community members to operate and maintain the flood monitoring system, thus securing its operation and acceptance among the community.

Specific implementation steps include working with local governments to draft technical application proposals and secure policy and funding support, organizing technical training and education through training sessions, operation manuals and technical support teams to ensure that technical staff and

community residents have the necessary operational skills, conducting pilot projects by selecting a number of urban villages in Zhengzhou to deploy the flood monitoring system, performing field tests and optimizing the system according to pilot feedback, and optimizing and scaling the system through refining the system's performance and user experience based on pilot project

3.4 Construction of the Methodological Framework

The systematic and scientific nature of the research requires the building of a robust methodological framework. This study combines quantitative and qualitative research methods, with statistical analysis and deep learning techniques for quantitative assessment of SAR data, and interviews and surveys for qualitative assessment of the social adaptability of the technical solutions from the community resident and local government perspectives. In detail, the construction of the methodological framework is outlined below.

Flood monitoring is assessed for the accuracy and reliability through quantitative analysis. The relationship between SAR data and flood monitoring outcomes is evaluated using statistical methods, such as regression analysis and time series analysis. The study trains deep learning based flood monitoring models using collected SAR data and assesses their predictive performance using metrics such as cross validation, confusion matrices, accuracy, recall and F1 scores. Furthermore, historical flood event data are used to validate the models, to validate the models applicability and effectiveness for different flood scenarios.

The social adaptability of the technical solutions is assessed using qualitative research methods. The needs, expectations, and experiences of community residents, local government officials, and technical operators with the flood monitoring system are gleaned from in-depth interviews. The broader feedback from community residents about their perceptions and willingness to adopt the technology is gathered through surveys. Qualitative research findings are used to optimize the systems so that the technological advancements do not only come with technological advancements but also with the social needs of the communities resulting in a harmonious integration of technology and society.

In the data analysis phase, the study designs flood monitoring models using selected deep learning architectures (such as CNN-RNN hybrid models). The model architecture consists of input layers for processing multi-scale SAR data, hidden layers with multiple convolutional and recurrent units, output layers for predicting flood expansion paths and depths. The preprocessed SAR data is used to train the models with the help of hyperparameters (e.g. learning rate, batch size, and network depth) adjusted to optimize performance. We apply regularisation techniques such as Dropout and L2 to prevent overfitting and improve generalisation performance of the models.

Validation and evaluation of the model are critical to reliability. The models are validated using actual flood event data, using cross validation and confusion matrices to assess accuracy, recall and F1 scores, so that the models are reliable and effective in real world applications. The study further refines the model design based on validation results to improve the predictive capabilities and the adaptability.

The system integration and optimization aims at the effective operation of technical solutions in practical applications. A real time monitoring system is developed by integrating SAR data acquisition, deep learning analysis and flood early warning functionalities. To achieve efficient data flow and processing, the system architecture includes data reception modules, data processing modules, prediction modules and warning modules. It is a real time monitoring system with the capacity to transmit real time data, perform automated analysis and give instant flood warnings to enable quick responses during flood events. Pilot projects are continuously used to improve system performance and user experience by means of user

testing, performance evaluation and feedback mechanisms to ensure the effectiveness and user satisfaction of the system in practical applications. In addition, the system functionality is progressively expanded in the study to meet actual needs, e.g., multi-source data fusion capabilities and higher diversity and accuracy of warning information to ensure the system's adaptability to the changing flood monitoring requirements.

3.5 Research Outputs and Future Research

3.5.1 Research Outputs

This study is expected to achieve the following key outcomes:

1. Methodological Guide: This study will offer a detailed methodological guide of SAR data acquisition, deep learning model construction and optimization, system integration and implementation pathway design. This guide will provide future related research with specific data acquisition strategies, model selection and optimization methods, system design and implementation steps, which will help facilitate the advancement and application of future related research as a reference and replicable research method for subsequent researchers.

2. Testable Hypotheses: It will build a hypothesis framework for flood monitoring, e.g. 'There is a positive correlation between the spatial resolution of SAR data and the accuracy of flood monitoring,' and will validate these hypotheses through empirical research. These hypotheses will furnish a theoretical basis for future empirical studies on flood monitoring technologies and will contribute to the development and application of such technologies.

3. Validation Standards: The system will be validated to establish standards for accuracy, reliability and real time capability of the flood monitoring system. The accuracy of data processing, the reliability of model predictions, and the timeliness of system responses will be these standards, so that the scientific and practical validity of the research findings will be ensured. These standards will produce clear guidelines for the evaluation and optimization of flood monitoring systems.

4. Implementation Pathway Identification: This study will then define the implementation pathways for technological transitions, which will inform the application and dissemination of SAR technology and deep learning to different urban villages. The study will help identify macro, meso and micro level transition pathways for the effective use of technology in practical flood management, enabling widespread adoption and continuous improvement of flood monitoring systems.

3.5.2 Impact and Application Prospects

This study not only develops a systematic theoretical framework for application of SAR technology and deep learning in urban flood monitoring, but also provides innovative solutions for urban flood management in urban villages. The specific impacts and application prospects are as follows:

1. Enhanced Flood Monitoring Capability: This study optimizes data acquisition strategies and algorithm adaptation to significantly increase precision and real time capability of flood monitoring, thus improving urban village's response to flood risk in Zhengzhou. Real time dynamic flood changes are captured with high resolution and high frequency SAR data, and efficient deep learning processing is used to predict flood expansion paths and depths.

2. Increased Community Resilience: An efficient flood monitoring system gives timely warning information to communities to prepare for floods in advance, thereby reducing flood related losses and improving overall community resilience. Flood monitoring and warnings that are timely and accurate help communities execute emergency responses more effectively, minimizing casualties and property damage.

3. Facilitated Integration of Technology and Society: The study applies socio-technical systems theory to guarantee that the technical solutions have technological developments and social needs of the community, which results in a harmonious integration of technology and society. This integration increases the social acceptance and sustainability of the technical solutions, which is important for their effective and long-term application in real settings.

4. Promotion of Scientific and Intelligent Urban Flood Management: This study provides the theoretical framework and implementation pathways to transition urban flood management from traditional empirical approaches to scientific and intelligent approaches for the overall improvement of flood prevention and management in cities. Urban flood management becomes more precise, efficient and intelligent, and the city's capacity for flood risk management improved by using advanced SAR technology and deep learning methods.

3.5.3 Future Research Directions

Despite the construction of a complete theoretical framework, further exploration and validation in practical applications is necessary. Future research can expand in the following areas:

1. Conducting Empirical Studies: Based on the theoretical framework, future research should conduct empirical studies on flood monitoring in certain urban villages to verify the effectiveness and applicability of the framework. Evaluation of the framework's suitability and impact across different environmental and socio-economic contexts can be achieved through the application and testing of the framework in different types of urban villages. Theoretical framework will be refined and optimized with the empirical studies that will provide valuable data support.

2. Technological Optimization and Innovation: The intelligent level of flood monitoring can be continuously optimized and more technological innovations can be explored that are appropriate for complex urban environments, based on deep learning algorithms. For instance, by studying more complex neural network architectures, or through the combination of transfer learning and reinforcement learning, the model's predictive power and flexibility can be enhanced. Further, the precision and comprehensiveness of flood monitoring can be improved by exploring multi source data fusion techniques (as combining SAR data with other remote sensing data, for example, optical imagery and LiDAR data).

3. Interdisciplinary Collaboration: The theoretical framework will be further enriched by strengthening interdisciplinary collaboration with urban planning, sociology, and environmental science, which will further improve the study's comprehensiveness and applicability. Theoretical robustness and completeness of the theoretical framework can be advanced by adopting interdisciplinary perspectives and researchers can deeply investigate the complex relationships between urban morphology, social structures, and flood risks. For example, collaborating with urban planning experts allows us to integrate city development planning data to examine the effects of urban expansion on flood risks, and collaborating with sociology experts can explore the relationship between community flood awareness and behavior and the acceptance of flood monitoring systems.

4. Integration of Policy and Practice: The integration of research findings with local government flood prevention policies will promote the dissemination and application of technology in practical flood

management. The study collaborates with policy makers and practitioners to ensure that research outcomes can be translated to practical flood management strategies that improve the flood prevention capabilities of urban villages. Furthermore, policy recommendations and technical guidance can help local governments develop scientific and effective flood prevention policies and promote systematization and standardization of urban flood management.

4. Conclusion

Based on this work, we successfully develop a comprehensive theoretical framework that integrates Synthetic Aperture Radar (SAR) technology with deep learning methodologies to improve flood monitoring in Zhengzhou's urban villages. The research addressed the challenges of capturing accurate flood dynamics in high density, complex spatial environments by optimizing data acquisition through the selection of high-resolution SAR sources and detailed urban morphology analyses.

Yet, the implementation of the practical version was hindered by technical and resource related challenges, including the high costs and licensing restrictions of SAR data, the need for large computational power to train deep learning models, and the complexities of integration of new systems with existing urban infrastructure. The study then proposed to address these obstacles by using cloud based computing resources to handle computational demands, partnering with satellite data providers to gain access to low cost data, and using transfer learning techniques to reduce the amount of training data required. Furthermore, phased pilot projects were suggested to iteratively test and refine the system, and to guarantee scalability and adaptability. By solving these particular challenges with targeted solutions and comprehensive resource planning, this framework not only advances the theoretical understanding of technology integration in disaster management, but also makes it practically feasible and sustainable, thereby enhancing the resilience and safety of vulnerable urban communities.

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