

Exploring the Synergistic Construction of Urban Stormwater Resilience in UAV Remote Sensing and Infrastructure

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Abstract. The process of urbanisation and extreme weathers has caused increased risk on pluvial flooding, while traditional monitoring methods shows obvious limitations on real-time dynamic response. This study systematically explores the application models and implementation pathways of UAV remote sensing and low-altitude infrastructure coordination technologies in enhancing urban flood resilience. By integrating low-altitude infrastructure networks, we establish a collaborative framework covering data acquisition, transmission, and analysis, with a particular focus on their integrated applications in water accumulation monitoring, disaster assessment, and emergency decision-making. The findings indicate that this technological framework significantly improves surface water accumulation detection accuracy through multi-source data fusion, achieves substantial breakthroughs in disaster assessment efficiency through computational advancements, and validates its effectiveness in emergency response during typical urban storm events. Additionally, the study identifies key constraints such as airspace management mechanisms and environmental adaptability of equipment, proposing directions for technology standardization and system resilience optimization. These findings provide methodological support and practical insights for the advancement of intelligent urban flood management systems.

Keywords: UAV remote sensing and low-altitude infrastructure synergy technologies; Multi-source data fusion; Intelligent Stormwater Management System.

1. Introduction

With urbanisation and climate change, there is a gradual upward trend in overall urban rain and flood disasters globally. According to the United Nations Office for Disaster Risk Reduction (UNDRR), over the past 20 years (2000-2020), global flood events accounted for 44 per cent of all natural disasters. The proportion of urban flooding has increased significantly, while flooding has caused very large economic losses and a large number of deaths. Therefore, the detection and emergency response of cities to floods is particularly critical.

Traditional monitoring and emergency response systems have certain limitations and technical bottlenecks. For example, traditional satellite remote sensing has insufficient spatial and temporal resolution; ground monitoring equipment has limited coverage; and emergency response is not sufficiently time-sensitive and dynamic. The synergistic approach of multiple technologies can make use of the high-resolution dynamic monitoring capability of drones, combined with low-altitude infrastructure (5G base stations, edge computing nodes) to support real-time data transmission, so as to achieve a closed loop of intelligent decision-making in air-ground synergy. Unmanned aerial vehicle (UAV) high-resolution dynamic monitoring can be used for rapid disaster assessment and real-time monitoring, through high-resolution images to monitor the spread of flooding, inundation depth and dynamic changes in real time, providing instant data support for emergency decision-making. Smith et al. point out that UAVs can generate high-definition orthophotos of inundated areas within 2 hours after flooding occurs, which can help the rescue team locate high-risk areas (such as underground passages, low-lying communities), and at the same time, UAVs can also help rescue teams locate high-risk areas (such as underground passages, low-lying communities) and low-lying

neighbourhoods, while high-resolution dynamic monitoring by UAVs can also flexibly respond to complex urban environments, where UAVs can fly at low altitude to avoid the obstruction of high-rise buildings, and flexibly enter areas difficult to be reached by vehicles and personnel (e.g., narrow alleys, underground garages) to obtain details of the localised disaster situation, Johnson et al. found that in typhoon-triggered urban flooding, a neighbourhood was found by UAVs to be The clogged entrance of an underground garage led to poor drainage, which was directed to be unblocked to significantly reduce the risk of flooding. The low-altitude infrastructure (5G base stations, edge computing nodes) to support real-time data transmission can guarantee the resilience of the communication network Flooding is prone to damage or power outages of ground-based base stations, and 5G base stations deployed in low-altitude (e.g., drone-carrying or temporary towers) can quickly restore communications to ensure stable transmission of emergency command and public distress signals Smith et al. proposed that drone-carrying mobile 5G base stations provides temporary network coverage in flooded areas, supporting rescue teams to share high-definition disaster images in real time and reducing communication recovery time by 70%. It also features low-latency and high-bandwidth data transmission. Tests by the European Union (EU) Flood Resilience Project show that the data upload speed of the drone under 5G network is 10 times faster than that of 4G, which meets the demand for real-time hydrological model updating.

Stormwater resilience refers to the ability of an urban or natural system to effectively resist, adapt and quickly recover from extreme hydrological events such as heavy rainfall and flooding through sound planning, design and management measures, including the enhancement of rainfall absorption and buffering capacity through infrastructure and ecosystems to reduce the probability and intensity of flooding. Dynamic adaptation of urban planning and management strategies (e.g. resilient embankments, permeable pavements) to respond flexibly to uncertainties arising from climate change, such as increased intensity or frequency of rainfall. Rapidly repairing critical functions (e.g. transport, water supply, electricity) after a disaster to reduce economic losses and human casualties, e.g. through smart drainage systems, emergency response mechanisms and community collaboration. Combination of engineering measures (e.g. river training) and non-engineering measures (e.g. early warning systems, disaster insurance) to coordinate natural and man-made systems for collaborative multi-scale and multi-sectoral management.

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2. Key Technological Analysis

2.1. UAV Technological Support

The core technology of UAV systems lies in multi-modal sensor integration and intelligent collaborative control. Functioning as "aerial eyes," UAV-mounted cameras and infrared sensors can penetrate rainfall interference to achieve accurate water depth identification.

The sensor suite constitutes the core tool for flood monitoring. Light Detection and Ranging (LiDAR) enables precise topographic measurement for identifying waterlogged areas, while thermal infrared cameras detect abnormal temperature variations in drainage networks. During the 2023 Zhengzhou rainstorm event, a UAV swarm successfully completed 3D disaster zone modeling under complex meteorological conditions through autonomous obstacle avoidance algorithms, demonstrating the practical applicability of this technology. Furthermore, collaborative UAV operations enhance coverage efficiency; for instance, reinforcement learning algorithms dynamically optimize flight paths to minimize redundant scanning [1].

2.2. Ground Infrastructure Coordination

The ground support system establishes the foundational architecture for a three-dimensional monitoring network. 5G communication base stations provide high-speed, low-latency transmission channels, significantly improving video data transfer efficiency compared to conventional 4G networks, thereby ensuring real-time acquisition of high-definition imagery by command centers.

Intelligent streetlights equipped with water level sensors form distributed monitoring nodes. As exemplified by a Shanghai pilot project, these nodes establish cross-validation mechanisms with UAV data to enhance monitoring reliability. For energy replenishment, dedicated charging stations integrated with solar charging technology have been deployed above drainage infrastructures in selected cities, effectively extending UAV operational endurance.

Edge computing nodes serve as distributed data processing units, substantially reducing cloud transmission latency and completing the "perception-transmission-processing" technological loop [2].

2.3. Data Processing Framework

Multi-source data fusion technology forms the core architecture for intelligent flood prevention decision-making. The system integrates UAV aerial imagery with ground sensor data through spatiotemporal registration algorithms, automatically generating high-precision real-time waterlogging heatmaps. An Artificial Intelligence (AI) early-warning module employing deep learning models analyzes multi-dimensional data characteristics to identify hazardous road segments and disseminate alerts via mobile terminals.

A virtual urban model constructed through digital twin technology enables simulation of diverse disaster scenarios, supporting dynamic optimization of emergency response plans.

UAV aerial surveying technology facilitates rapid acquisition of comprehensive multi-source data from open-pit mining sites, enabling cross-disciplinary situational awareness for rational planning and decision-making. This approach enhances inter-departmental collaboration, improves production efficiency, and mitigates safety risks. The technology demonstrates capabilities in rapid generation of true 3D models and excavation volume calculations, meeting requirements for daily production management and digitalized smart mine construction.

Additionally, it produces diverse digital outputs including orthophoto maps, 3D models, digital line graphs, and point cloud models. These deliverables support long/short-term open-pit mine planning, transport route optimization, and rational spoil yard design, providing an intuitive technical foundation [3].

3. Use Cases Analysis

Regarding the application scenarios of UAV remote sensing and low-altitude infrastructure coordination in the construction of urban storm resilience, we analyze two main aspects: storm monitoring and early warning and disaster assessment and decision-making.

Taking the stormwater monitoring and early warning system in Guangming District, Shenzhen, as an example, the core needs and objectives of this scenario are as follows: In the process of urbanization, traditional ground monitoring networks have coverage blind spots (e.g., under overpasses, underground passages), and low-altitude infrastructure (e.g., 5G base stations, smart streetlights, traffic cameras) has not been fully integrated. As a national sponge city pilot area, Guangming District aims to achieve real-time UAV response to extreme weather conditions, dynamic full-air-space perception of surface water accumulation and pipeline anomalies, and the construction of an "air-ground-pipeline" collaborative monitoring network by leveraging low-altitude infrastructure (e.g., sensor-mounted streetlights, edge computing nodes at 5G base stations) for multi-facility interaction [4].

3.1. UAV Remote Sensing Combined with Simultaneous Localization and Mapping (SLAM) 3D Modeling[5]

SLAM technology enables real-time 3D modeling and dynamic updates, offering superior adaptability to complex urban environments, high-precision terrain and hydrological analysis, and multi-sensor fusion with automated processing capabilities. The integration of UAV remote sensing and SLAM 3D modeling provides several advantages: real-time dynamic monitoring and rapid modeling, high-precision hydrological simulation and risk assessment, and multi-source data fusion with intelligent analysis.

In practice, the DJI M300 RTK UAV, equipped with a Livox Avia LiDAR sensor (450-meter detection range, 40% improved penetration through rain and fog), operates in a coordinated mode. During heavy rainfall, three to five UAVs are deployed in a pre-defined grid-based scanning pattern (e.g., Guangming District is divided into eight grid zones). These UAVs transmit real-time data via 5G base stations and perform SLAM-based real-time modeling optimization using LiDAR point clouds, visible light imagery, and meteorological radar reflectivity. This approach enables multi-source data fusion for centimeter-level precision flood accumulation models and edge computing acceleration by deploying lightweight SLAM algorithms (e.g., LOAM-Livox) at 5G base stations, reducing modeling latency from 10 seconds to under 2 seconds.

As a result, the system can identify high-risk areas where water depth exceeds 20 cm (e.g., Guangming Avenue–Songbai Road intersection), generate a 30-minute flood risk heatmap, and provide emergency route planning for rescue vehicles, ensuring safe navigation by avoiding waterlogged areas.[6]

3.2. Rapid Identification of Damaged Infrastructure Using Deep Learning and Hyperspectral Imaging[6].

Equipped with hyperspectral imaging systems, UAVs can capture high-resolution multispectral imagery of disaster-affected areas. Hyperspectral imaging, which captures continuous narrow-band spectral signatures of ground objects, combined with deep learning models (e.g., 3D residual convolutional networks), enables multi-scale feature extraction while avoiding information loss associated with traditional dimensionality reduction methods, thereby improving identification accuracy.

For instance, 3D convolutional networks can directly process hyperspectral data cubes, extracting both spatial and spectral features, making them suitable for small-sample training scenarios.

The damaged infrastructure identification process follows two main approaches:

3.2.1 Pre-Disaster and Post-Disaster Data Comparison

By comparing pre-disaster water body masks (e.g., derived from SAR imagery) with post-disaster hyperspectral imagery, deep learning models (e.g., deep convolutional networks) integrate multi-source data to generate flood distribution maps, rapidly identifying inundated roads, bridges, and buildings.

3.2.2 Feature Fusion and Classification

By analyzing the texture and spectral characteristics of post-disaster hyperspectral images, a feature-level fusion approach generates flood probability distribution maps, assisting decision-makers in locating damaged areas. For example, in the 2020 Poyang Lake flood (Jiangxi, China), multi-source satellite remote sensing data (e.g., Planet optical imagery, RADARSAT-2 radar data) were used to analyze flood extent and accurately assess infrastructure damage. Similarly, during the 2020 heavy rainfall in Hunan Province, UAV aerial imagery was integrated with high-resolution satellite data to rapidly interpret flood extent and water depth distribution, providing critical baseline data for post-disaster reconstruction.

This technology can also be extended to pluvial flooding scenarios, where hyperspectral imaging can detect hidden issues such as underground pipeline blockages or road collapses.

4. Collaborative Mechanism Innovations

4.1. Air-Ground System Integration

The air-ground collaborative monitoring system achieves efficient coordination of multi-source heterogeneous devices through a hierarchical architecture. The system comprises three organically integrated layers:

Perception Layer: Utilizes UAVs and ground sensors to collect spatial multidimensional data (e.g., water depth, flow velocity), forming a three-dimensional monitoring network.

Transmission Layer: Establishes high-speed communication links via 5G networks and mesh networks, ensuring real-time data transmission to command centers.

Decision Layer: Performs multimodal data fusion analysis using AI algorithms to generate early warnings and emergency plans.

To enable interoperability among heterogeneous devices, the system incorporates standardized protocols (e.g., Open Geospatial Consortium), functioning as a cross-platform "universal translator" by unifying data formats and interface specifications.

4.2. Intelligent Collaboration Paradigms

Digital twin technology enables dynamic mapping between physical and digital spaces through virtual urban models. For instance, the flood digital twin platform developed by Delft University of Technology simulates inundation scenarios under varying rainfall intensities, providing visual decision support for emergency planning [7].

Future advancements in IoT-physical engine integration may empower digital twin systems to achieve minute-level dynamic simulations of disaster evolution, with automated comparative analysis of multiple contingency plans. Federated learning technology innovatively addresses cross-departmental data-sharing challenges through distributed training mechanisms, allowing meteorological and transportation agencies to collaboratively optimize AI models without exchanging raw data.

With the integration of edge computing and blockchain, federated learning frameworks could expand to transnational river basin flood management scenarios while ensuring privacy protection, fostering the development of global-scale disaster prediction networks[8].

4.3. Management Mechanism Optimization

The "peacetime-emergency integration" management model dynamically allocates resources for seamless transitions between routine maintenance and emergency response. As demonstrated by Shanghai's implementation, UAVs conduct regular drainage network inspections during non-flood seasons and rapidly switch to emergency monitoring modes during floods for real-time flood tracking[9].

Future AI-driven adaptive scheduling algorithms may enable autonomous monitoring strategy adjustments based on real-time meteorological data, transitioning from manual to intelligent decision-making.

Public-private partnerships (PPPs) enhance technological ecosystems through social capital integration, exemplified by Tokyo's government-enterprise collaborative UAV monitoring network. With the maturation of sharing economy models, blockchain-based distributed resource trading platforms may emerge, allowing governments to dynamically lease enterprise-owned UAV resources and construct more resilient disaster response systems. These institutional innovations provide sustainable governance frameworks for urban flood prevention while pioneering new pathways for smart city paradigm transformation.

5. Innovative mechanisms for synergies

5.1. Technical Challenges

The integration of UAV remote sensing and low-altitude infrastructure for urban flood resilience faces several key technical challenges:

5.1.1 Sensor Reliability in Adverse Weather Conditions

Environmental Interference: Heavy rainfall degrades the performance of optical sensors (e.g., visible-light cameras, LiDAR), causing image blurring and point cloud data loss due to raindrop occlusion and water mist scattering. Strong winds destabilize UAV posture, leading to data distortion or vibration. Additionally, electromagnetic interference (e.g., lightning) may affect radar and communication signal stability.

Sensor Adaptability Limitations: Existing sensors are primarily designed for standard environments and lack specialized calibration algorithms for flood scenarios (e.g., detection of turbid water bodies and penetrative sensing in submerged areas). Furthermore, multi-sensor data fusion (optical, infrared, SAR radar) becomes challenging under extreme weather conditions, potentially generating conflicting information.

Hardware Protection Constraints: Waterproofing and dust resistance ratings (IP standards) may be insufficient for heavy rainfall. Miniaturized sensors also face durability and self-cleaning limitations in harsh environments.

5.1.2 Low-Altitude Airspace Management Conflicts

Dynamic Airspace Coordination Issues: UAVs share low-altitude airspace with manned aircraft (e.g., emergency helicopters, general aviation), yet real-time conflict avoidance mechanisms are lacking. In dense urban environments, Global Positioning System (GPS) multipath effects compromise UAV positioning accuracy and airspace safety margins.

Interoperability Bottlenecks: Existing air traffic management systems (e.g., ADS-B) are not fully compatible with low-altitude, small UAV operations, making unified monitoring difficult. Additionally, emergency response scenarios lack well-defined temporary airspace release and recovery mechanisms, potentially delaying flood monitoring missions.

Regulatory and Standardization Gaps: Low-altitude flight regulations (<300m) remain ambiguous regarding UAV and manned aircraft priority. Moreover, there are no dedicated regulatory exemptions for flood emergency UAV operations (e.g., nighttime flights, beyond-visual-line-of-sight operations).

5.2. Management Challenges

The integration of UAV remote sensing and low-altitude infrastructure for urban flood resilience also presents significant management challenges:

5.2.1 Cross-Sectoral Data Sharing Barriers

Urban flood management involves multiple departments, including meteorology, water resources, emergency response, and urban planning. However, differences in data standards, collection frequencies, and sharing mechanisms hinder efficient UAV remote sensing data integration. For instance, rainfall prediction data from meteorological agencies and hydrological monitoring data from water authorities may not be directly interoperable due to format discrepancies, reducing the timeliness of flood risk assessment. Additionally, unclear departmental responsibilities and concerns over data security further impede data-sharing efforts [10].

5.2.2 Inadequate Investment and Return Mechanisms for Low-Altitude Infrastructure

The construction and maintenance of low-altitude infrastructure (e.g., UAV landing sites, communication relay stations) involve high costs, yet clear revenue distribution mechanisms are lacking. For example, the value of UAV-generated flood monitoring data is difficult to quantify, leading to unclear return expectations in public-private partnerships (PPP). Moreover, the public

nature of such infrastructure conflicts with market-driven operations, discouraging private sector participation [11,12].

5.3. Future Research Directions

Future research on UAV remote sensing and low-altitude infrastructure collaboration for urban flood resilience should focus on the following areas:

Development of AI-driven real-time risk modeling based on UAV remote sensing data. Integration of urban flood dynamics models and historical disaster records to construct dynamic risk maps, enabling minute-scale predictions of inundation areas and vulnerable infrastructure. Reinforcement learning-based optimization of communication coverage and energy supply node layouts to support large-scale UAV swarm coordination during disasters. Integration of UAV multimodal data (visible-light, thermal infrared, LiDAR) with expert knowledge to quantify reliability thresholds in hybrid decision-making chains.

6. Conclusion

This study systematically constructs a framework for the collaborative application of UAV and low-altitude infrastructure technologies in urban flood management through an interdisciplinary research approach.

Three key findings are highlighted:

1) Deep integration of UAV swarms with ground-based infrastructure overcomes the spatiotemporal limitations of traditional monitoring, significantly enhancing disaster detection accuracy and response efficiency.

2) Federated learning and digital twin technologies address the conflict between cross-sectoral data sharing and privacy protection, providing a new paradigm for intelligent flood forecasting.

3) Despite advancements, practical applications still face challenges such as environmental adaptability limitations and rigid management frameworks, necessitating coordinated efforts in technological innovation and regulatory optimization.

Looking forward, technological advancements should prioritize enhancing edge computing-enabled autonomous decision-making and developing lightweight sensors resilient to extreme weather. Meanwhile, governance mechanisms should focus on establishing flexible resource allocation platforms to facilitate cross-regional and multi-level collaborative flood management. Notably, the deep integration of low-altitude sensing networks with urban digital twins has the potential to reshape disaster prevention and mitigation strategies in smart cities. Future research should explore human-machine collaborative decision-making mechanisms and strengthen socio-economic impact assessments of technological applications to provide more resilient solutions for sustainable urban development globally.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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