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UAVs as a Tool for Optimizing Boat-Supported Flood Evacuation Operations

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Abstract: The frequency and intensity of flood events are increasing year by year as a result of climate change. This poses significant threats to human settlements and adversely affects biodiversity, agriculture, and infrastructure. One of the most prominent and traditional flood evacuation approaches is through the use of boats. Nonetheless, serious challenges exist with respect to determining the optimal deployment locations, routes, and timing. Given research advances in the Unmanned Aerial Vehicles (UAVs) sector—and their ability to offer real-time data and aerial monitoring services—we argue that their applications could help enhance boat-supported flood evacuation operations. In this opinion piece, we explore new opportunities for disaster management and underscore the advantages of integrating UAVs into flood evacuation methodologies, including areas of rapid field assessment, optimal route planning, and improved coordination between rescue boats. Notwithstanding the potential of UAVs, we emphasize several gaps to be explored in terms of large-scale data management/processing, regulatory limitations, and technological know-how. Furthermore, we provide recommendations for bolstering boat deployment protocols, disaster preparedness training programs, policy frameworks, and emergency response systems, which could maximize their efficacy in flood evacuation scenarios.

Keywords: flood rescue services; disaster management; climate change; Unmanned Aerial Vehicles; drones; remote sensing

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1. Introduction

Coastal flooding has increased within the last 20 years, primarily as a result of sea level rise (SLR), placing over 70 million people at increased risk of expanding floodplains [1]. Between 1980 and 2011, flood losses have increased globally from an average of $7 billion to $24 billion per year, with an increase in the average number of fatalities by 1000 per year. For instance, in 2010, a total loss of $51 billion in China was estimated. In 2011, more than 50 fatalities and high material damage were reported in different countries

worldwide (including Mozambique, Namibia, South Africa, Brazil, Columbia, Mexico, China, India, Korea, Pakistan, Philippines, and Thailand) [2]. Similarly, in the Mediterranean environment, floods are a serious threat to people, causing 458 flood fatalities in five Mediterranean sub-areas between 1980 and 2015, with these fatalities being caused by people being dragged by water when traveling, drowning, and suffering heart attacks [3].

Flooding causes a broad suite of short and long-duration impacts of moderate to high severity. Developing and implementing practical flood mitigation approaches and effective evacuation plans are vital to minimizing potential flood impacts on human health and lives, infrastructure, regional economy, natural resources, and the environment. Floods directly impact a wide variety of assets, including transportation infrastructure like roads, bridges, ports, and facilities like schools and hospitals. Floods also, directly and indirectly, damage human health by impacting water quality or food supply, causing loss of lives, and causing shorter- and longer-term degradation of natural resources, such as biodiversity, coastal habitats, and provisioned ecosystem services. Indirectly, floods can (i) alter the regional economy by damaging infrastructure and causing loss of jobs, (ii) disrupt agriculture by delaying the planting of spring crops, causing soil compaction, and increasing crop loss, and (iii) degrade the quality of ecosystems through erosion and permanent loss of habitats [2,4].

Emergency plans, created preemptively and with regard to local context, are crucial to protecting people's lives as well as to reduce the overall negative impacts possible from floods. Modern flood forecasting and early warning systems —which predict future water levels and flows— are frequently used in preparing flood evacuation plans, developing appropriate flood control approaches, and managing environmental and water resources systems [5]. Such systems are particularly useful when flood risks, hazards, and vulnerabilities have been understood and mapped for the area of interest [6]. Data-driven techniques/models —such as GIS-based hydrological water balance models, artificial neural network (ANN) models, and optimization algorithms— have become popular for flood forecasting in recent years, offering evidence-based evacuation plans [5,7,8]. Exacerbating the situation, poorly planned urban development also plays a role in flood mitigation by altering how much, where, and the speed of changes in water flows, as well as being related to how many people live in or near flood-prone areas [9].

More recently, an effective approach is the development of a rapid-response flood evacuation model that utilizes public transportation to evacuate vulnerable populations. This model incorporates the minimum number of vehicles required, the sequence of trips, and also flood propagation data [10]. Also recently, a transit-based evacuation approach —distinct from traditional approaches— has been adopted, focusing on using public transit systems such as boats, trains, and ambulances to improve the efficiency of evacuation efforts [11]. Sea-air rescue, which utilizes helicopters, seaplanes, rescue boats, ships, and submarines, has also seen significant uptake in many countries within search and rescue (SAR) operations [12]. However, for larger floods with water depth exceeding 40 cm, boats can be highly effective in supporting evacuations as they reach flood victims using the shortest route—e.g., directly across the flooded area. In future development, by incorporating advanced distance sensors, boats can effectively detect obstacles and/or determine safe and rapid exit strategies, making them increasingly useful tools for both flood evaluation and evacuation [13].

Although several efforts have been made in order to tackle flood control implementation, many of the aforementioned approaches have failed during the actual event for different reasons. Challenges are mainly focused on flood predictions (i.e., depth, extent, and flow velocity) without considering other factors such as local social behavior, house security, and the dynamic nature of urban areas (i.e., construction, river and street modifications, etc.), and the hydrological uncertainties that might arise due to variability in climate and river morphology, among others. Additionally, land use changes in floodplains affect flood risk [14], but the impact of future land use changes is not factored into flood predictions. Similarly, for flood evaluation and evacuation, challenges associated with

transit-based evacuation arise due to data availability and accuracy limitations, model validation, stakeholder coordination, and the integration of uncertainty and dynamic factors [11]. Consequently, the effectiveness of evacuation plans is compromised by insufficient guidance on when and where to implement transit evacuation as well as which routes to take. Given the dynamic nature of cities and social behavior, it is essential to provide real-time data and regularly update baseline information to ensure the effective implementation and revision of emergency evacuation plans. Optimizing the modeling approaches within transit-based evacuation planning—in particular boats—will eventually enhance operational efficiency, optimize resource allocation, and ensure evacuee safety.

Unmanned aerial vehicles (UAVs) provide real-time surveillance capabilities for rapid decision-making which can overcome challenges associated with boat-based flood evacuation [11]. Integrating UAVs into flood disaster management and operations can provide efficient evacuation options [15]. UAVs assist primarily by gathering valuable/real-time first-responder information including passable roads, surface type of roads/paths, possible collection points, contamination results, and other information [16]. Additionally, UAVs can quickly survey the disaster area for an overall situational view (including people detection and critical locations), ultimately providing communications infrastructure and improving situational awareness of affected areas [17]. Nevertheless, to optimize disaster management efforts, UAVs can benefit from the integration of Wireless Sensor Networks (WSN), which are spatially dispersed sensors that can centralize data collection of recorded physical environmental conditions (e.g., temperature, sound, pollution levels, humidity, and wind) [17]. In general, UAVs can often be more efficient than humans, enter flooded areas, quickly search for victims/survivors, and greatly reduce the expense and risks of rescue missions [18].

Flood evacuation and flood rescue operations require critical and time-sensitive responses. While boats and unmanned surface vehicles (USVs) can provide critical advantages to flood evacuation operations, including victim recovery and delivering supplies, the integration between USVs and UAVs offers additional services that optimize flood rescue operations. These services overlap between (i) extracting flood-related features from the images of the disaster zone, (ii) assessing damage to local infrastructure in disaster zones, (iii) highlighting alternatives when traditional networks are unsafe and/or unusable, (iv) providing environmental monitoring and mapping, (v) offering situational awareness, and (vi) enabling supplies to unreachable areas [19,20].

2. UAVs and Boat-Supported Flood Evacuation

UAVs capture and deliver real-time flood environment maps and specific aerial imaging. The derived data can be used by rescue teams to organize their operations effectively, find near-optimal paths, and identify the most suitable locations for rescue operations. This will eventually support the rescuers and decision-makers in optimizing their plans and use of resources [20]. For instance, in Malaysia, where floods occur nearly every year due to heavy and regular rainfall, stakeholders found that using boats for victim rescue is costly and time-consuming [18]. Consequently, it was suggested that UAVs should be deployed during both disaster events and search operations for victims given their capacity to cover large areas and gather detailed images quickly within a short period [18]. UAVs hover over identified victims and transmit their location to rescuers through a GSM (Global System for Mobile communications) network, which reduces the number of rescuers required to find and rescue a lost person and eventually minimizes the expense and risks of the missions [18]. Malaysia's case study highlights the effectiveness of UAVs in flood-related rescue operations, demonstrating their capacity to enhance efficiency, minimize costs, and improve overall safety. Moreover, UAVs could effectively detect and locate suspected hazards, which mitigates safety risks while providing reliable data on hazard identification, flood control, and disaster reduction [21].

UAV technology integrated with a communication system and live video streaming system allows direct communication with victims and real-time relief operations planning. For instance, two significant uses of UAVs in SAR operations and for victim rescue were reported in the United States. The first was in Dry Creek Canyon, Oregon, using a DJI Phantom 4 K quadrotor, and the second was in Wahclella Falls Trailhead, Oregon, using a SAR Bot [22]. This integration supported the rescuer in planning boat routes, moving efficiently to the correct location, assessing the situation and number of victims, and undertaking routine checks. This successful rescue planning and flood disaster management was achieved by adopting a computer vision library tool that allowed rapid detection of people by sending their location back to the control center via the GPS (Global Positioning System) [23].

Similarly, UAVs equipped with vertical take-off and landing (VTOL) can take off and land vertically like a helicopter, allowing them to operate in tight or confined areas, such as near flood zones where space is limited [22]. VTOL drones combine the agility of multirotor drones with the long-range and wide coverage of fixed-wing drones, making them ideal for flood evacuation operations where both precision (in smaller areas) and endurance (for broad surveillance) are needed [22]. In a further example within Saudi Arabia, UAVs equipped with a precise drop or release mechanism were assessed to carry inflatable boats to flooded areas, enhancing emergency response, saving people, and eventually supporting public health goods and disaster management operations [24].

UAVs could be widely used before, during, and after boat-supported flood evacuation, as follows:

- **Before floods:** UAVs can be used to locate evacuation routes, shelter points, and temporary barriers while estimating the extent, depth, and velocity of flooding in support of management and evacuation plans.
- **During floods:** UAVs support time-sensitive decisions by providing real-time information, enabling effective prioritization of emergency response actions, and determining gaps in existing flood emergency plans (e.g., location of shelter points, evacuation routes, knowledge about resistance and resilience measures).
- **After floods:** UAVs are primarily deployed to identify where best to deploy rescuers and resources still involved in rescue activities and recovery operations. Additionally, they assess the impact of floods on people, properties, and infrastructure.

Lastly, UAVs can advise on the need for additional flood evacuation measures by calibrating and comparing the data generated before and during the flood, assessing their compliance and synchronization.

A case study in Someșul Mic River, Romania, demonstrates the effectiveness of UAVs in obtaining useful information for flood prevention (before floods), by predicting events and offering topographical data. For rapid intervention (during floods), UAVs were used to provide real-time data for efficient coordination and damage assessment. As for flood monitoring (after floods), UAVs helped assess the affected areas and monitor changes in water levels and landscape damage. UAV integration allows good monitoring even on days with many clouds, by flying below the cloud ceiling, which is challenging for satellite images [25].

As shown in Figure 1, UAVs enhance boat-supported flood evacuations by providing comprehensive situational awareness and improving preparedness, response efficiency, and recovery effectiveness.

The following table (Table 1) demonstrates the main differences between traditional and UAV-supported boat evacuation in flood scenarios [18–23].

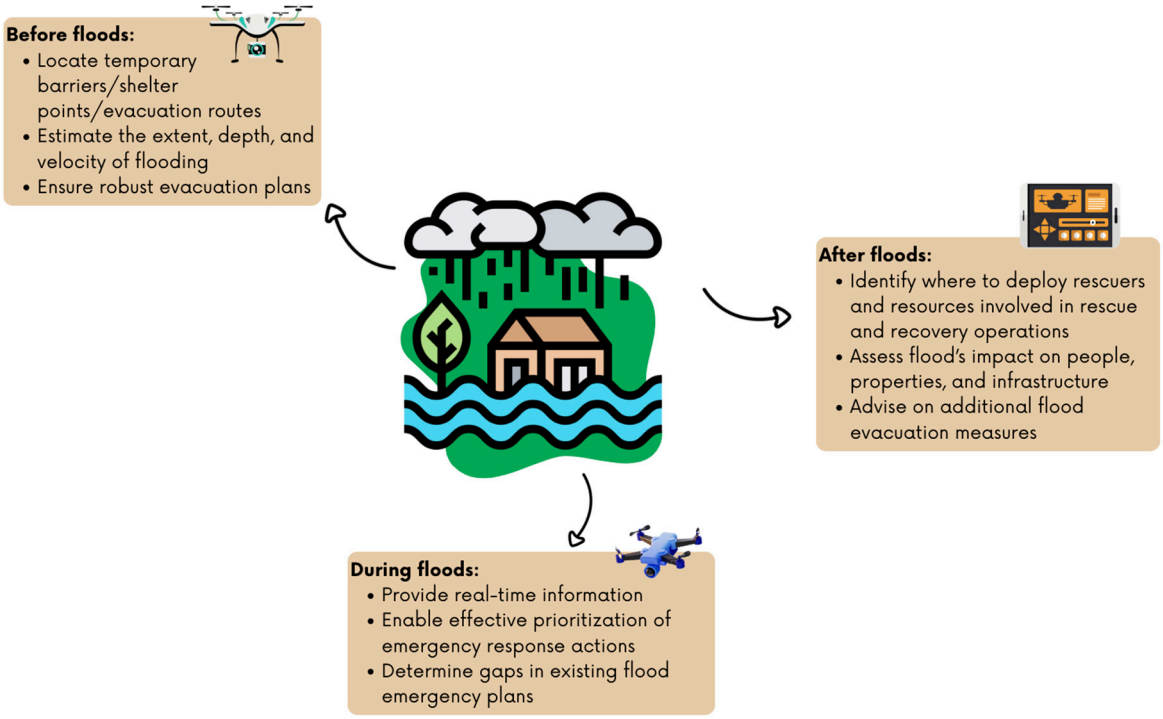


Figure 1. UAV implementation during different stages of boat-supported flood evacuation.

Table 1. Difference between traditional boat evacuation and UAV-supported boat evacuation.

Traditional Boat Evacuation	UAV-Supported Boat Evacuation
Slow because it needs extensive coordination among teams.	Rapid and immediate aerial surveillance and assessment, offering quicker assessment of larger areas and faster decision-making.
Relies on ground actions with limited access and visibility conditions.	Provides real-time data and wider coverage for larger areas.
Higher risk for rescuers who need to enter dangerous areas.	Remote operation reduces the risk to rescuers.
Basic and manual communication tools and navigation methods.	Advanced sensors (thermal, infrared) for improved detection and mapping capabilities.
Higher personnel costs due to larger teams required with continuous fuel and maintenance costs.	Initial investment in UAV technology and training is needed, which ensures lower ongoing operational costs and reduced personnel requirements.

3. Challenges and Limitations

Several challenges related to the timing, location, and routing of UAV deployments could limit the application of UAVs in search and rescue operations, particularly for boat-supported flood evacuation. These roadblocks could be associated with the limited knowledge and familiarity with technological advancement and the need for a standardized approach for UAVs to reach their full potential in flood evacuation operations. There are some specific challenges affecting where to deploy UAVs, route planning, and timing of deployment [26] that include the following:

- **Coverage, connectivity, and mobility:** where infrastructure and internet connectivity could be destroyed due to floods, eventually affecting the ability of victims to seek help.
- **Scalability, reliability, and robustness:** which could be affected by the vast number of UAVs in the region and mainly depend on the level of UAV autonomy.
- **UAV placement and resource constraint:** UAV cloud placement, mobility, and trajectory require adequate research to achieve effective performance. In addition, energy

constraints should be considered to ensure network performance in the design of scheduling algorithms.

- **Unreliable communication:** This could be a result of the growing number of connected devices (such as IoT) affecting the reliability and transparency of UAV data and results. For instance, as more devices collect and connect to wireless networks, bandwidth becomes increasingly crowded, thus affecting data transmission, privacy, quality, and reliability [27].

More concretely, to overcome these challenges, the following could be addressed: (i) assignment of resources, task planning management of key control functions, and interfacing with other systems, (ii) connectivity, communication, and placement of UAVs, (iii) data collection, processing, and integration, (iv) generation of outputs, and (v) need for trained pilots and specified sensors [26,28,29].

Moreover, evolving coordination between local and federal response agencies could limit the implementation of UAVs during boat evacuation, where adopting UAVs into emergency and disaster management operations is subject to a wide range of regulations and laws. For instance, several countries require flight permissions, remote pilot certifications, registration of UAVs, requests for necessary approval, and craft operation under restrictions that aim to ensure data privacy and safety. These regulatory and legal issues can also limit access to data and locations, which often limits the success and outcome of evacuation operations [30]. To overcome these challenges, support for a UAV program at the highest levels of organizations, decision-making parties, and legal authorities, should be considered. Nevertheless, the maintenance of data privacy and adherence to security regulations should also be followed to protect the privacy and confidentiality of individuals and businesses.

The time required to obtain permission for UAV flights in controlled areas in the United States varies based on the availability of the Low Altitude Authorization and Notification Capability (LAANC), a collaborative system between the Federal Aviation Administration and industry partners. LAANC availability streamlines authorization procedures. Additional factors that influence the timeline/process include having a registered UAV, completing the Recreational UAS Safety Test (TRUST), and following the requirements of the Exception for Limited Recreational Operations of Unmanned Aircraft. These factors can shorten or extend the permission process [31].

Similarly, several technical limitations can also affect the integration of UAVs and boats for flood evacuation, as follows:

- **Limited range:** UAVs are limited in their ability to fly long distances or to maintain a strong signal connection with the controller or base station, which affects the total area covered especially for areas with poor signal coverage. Additionally, related legal regulations may arise due to the necessity of maintaining a visual line of sight with the UAV.
- **Weather conditions:** UAVs are generally impacted by bad weather conditions—such as rain, high winds, and extreme temperatures—which make it difficult or unsafe to fly UAVs and impact the ability to obtain timely and accurate data.
- **Limited access:** UAVs could have limited ability to access certain areas with limited visibility or signal interference.
- **Poor data quality:** UAVs can capture data from different perspectives at different times, but this could be influenced by various technical aspects—such as camera resolution, sensor accuracy, and data processing capabilities—which can lead to inaccurate or incomplete assessments of flooded areas.
- **Large datasets:** UAVs generate and capture high-resolution images, video, and other data, which result in large datasets requiring significant storage and specialized software tools for data management and analysis.
- **Data processing and interpretation:** UAVs require a complex and time-consuming process for large data processing and management, which influences the accuracy and usefulness of the data obtained, as well as the time for data analysis. This does not

always align with flood evacuation operations where immediate and critical responses are required.

- **Airspace permissions and risk assessment:** UAV operations often require flight permissions from the local civil aviation authorities, which could take a long time to obtain. Moreover, for specific UAV operations, airspace permission also requires a full risk assessment to identify and limit the risks, such as the Predefined Risk Assessment (PDRA) or the Specific Operations Risk Assessment (SORA) in the European Union.

Not considering the aforementioned limitations could detrimentally impact the effectiveness of evacuation operations, the safety of rescue teams, and the accuracy of decision-making. Therefore, rescue teams, decision-makers, and stakeholders should carefully consider the technical capabilities of UAVs, as well as potential weather conditions and other environmental factors, when planning UAV inspections. High-quality cameras and sensors such as Light Detection and Ranging (LiDAR) should also be considered to ensure effective and sufficient analysis and interpretation of data and landscape changes [32,33].

Case Studies: UAV Deployment and Challenges Faced

In 2018, during the Kerala floods in India, rescue teams used aerial drones to survey affected areas and locate stranded individuals. While this was useful, rescuers did encounter many challenges, specifically related to communication issues due to damaged cellular infrastructure and signal interference from heavy rainfall. These issues caused the UAV to lose its connection with its ground control station while surveying a severely flooded village, which eventually resulted in a temporary loss of real-time imagery that delayed rescue efforts for several hours [29].

Similarly, in Texas, during the response to Hurricane Harvey in 2017, UAVs were used for damage assessment and search operations. However, there were challenges with network congestion as too many affected residents were simultaneously using cellular networks. This led to slower data transmission rates from the drones, impacting the ability to quickly process and again slowing evacuation response times [34].

These examples highlight how technical challenges such as signal disruption and network congestion can have tangible impacts on the effectiveness of UAV-supported rescue operations in real flood scenarios. They underscore the importance of developing robust communication systems and contingency plans to ensure reliable data transmission in challenging environments.

4. Potential Solutions

Flood evacuation will benefit from emerging hardware and software technologies to facilitate the deployment and scale-up operations. In terms of hardware, UAVs have seen a drastic improvement in their capabilities in the recent past, allowing them to be more energy efficient, sport more equipment, and reach more remote areas. We envisage that the advances in drone technology will continue and we will see more specialized models suited for this task. Also in the hardware realm, assisted boat operations will benefit from advances in the IoT domain. UAVs equipped with appropriate sensors for location (e.g., GPS), remote sensing technology (e.g., LiDAR, infra-red/broad spectrum cameras), and environmental sensors (e.g., temperature, chemical) assist with timely and accurate data collection on the ground. Complementary advances in wireless sensor networks allow an energy-efficient connectivity of the edge network (i.e., field-deployed IoT devices), to a resilient cloud computing engine ready to process the incoming data in real-time [35].

In terms of software developments, new advances in the field of Artificial Intelligence (AI) will allow faster data extraction and presentation. Machine Learning (ML) models have been used with historical weather and flood data, alongside real-time sensor inputs to predict flood behavior and identify the safest evacuation routes efficiently and accurately [36,37]. ML models based on decision trees (e.g., Random Forests) have the benefit that once pre-trained, they are efficient and suitable for deployment on edge devices. Emerging advances in Large Language Models (LLMs) render the data more accessible and

are particularly suitable to enable operators on the ground to extract timely and valuable information using natural language. Many applications of UAV integration with AI/ML methods have proven to be applicable and efficient in flood disasters. For instance, an unsupervised semantic segmentation method utilizing color images from UAVs was applied for successful, fast, and accurate flood area detection [38]. Likewise, an automated flood monitoring system called flood detection structure (FDS) was developed to detect and analyze the flood severity while monitoring flooded and non-flooded areas [37]. Additionally, a study shows that an AI-based approach coupled with an optimized GPU-based edge computing platform built into UAVs allows immediate analysis of images on the spot, without needing to send large files to the cloud. This speeds up the process and reduces the amount of data being sent and data uncertainty, making the whole operation more reliable, quicker, and more efficient [39].

In general, given their affordability, efficiency, and cost-effectiveness in gathering information, UAVs have considerable potential to become a crucial and invaluable tool to be integrated with boats for modern disaster management strategies. Therefore, stakeholders and decision-makers should benefit from UAV deployments in boat-supported flood evacuation plans [17]. Figure 2 summarizes the advantages, challenges, and added features of using UAVs in flood disasters and management.

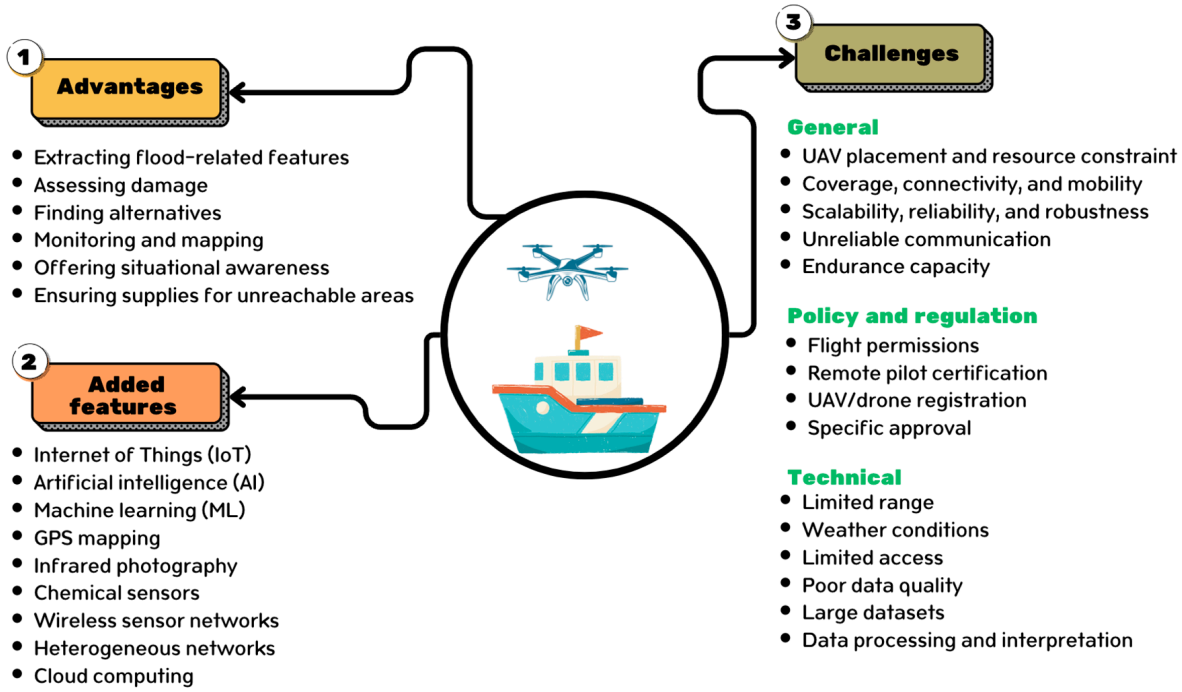


Figure 2. Summary of the core advantages of UAVs, challenges to address, and potential solutions to consider.

5. Future Insights and Recommendations

Future steps and actions could consider the following to optimize the integration of UAVs and boat-supported flood evacuation:

- **Boosting UAV capacities:** combining different types of UAVs to overcome single-use UAV limitations such as shorter flight times, smaller payloads, and reduced operating range.
- **Training programs:** developing and offering specific training to UAV operators and rescuers to ensure adequate performance and application of UAVs in boat-supported flood evacuation.
- **Simulation and testing:** evaluating the effectiveness and success of suggested/adopted approaches and techniques by conducting simulations and tests using images and data from past floods.

- **Standard manuals and guidelines:** creating manuals and guidelines to support and educate the public, ensuring the safe and effective use of UAVs, especially since regulations on UAVs have started to become more relaxed.
- **Policy and regulations:** ensuring a continuous update and review of regulations and policies related to UAV use in boat-supported flood evacuation, including national and international aviation authorities (e.g., International Civil Aviation Organization, Federal Aviation Administration, and European Union Aviation Safety Agency) regulations, legal frameworks for UAV use in disaster relief, data privacy/protection policies, and coordination policies between UAVs and rescue teams.
- **Research and development:** Investing in research and development will result in accurate and evidence-based UAV implementation for coordinating boat-supported flood evacuation.

6. Conclusions

To conclude, this opinion paper examined the effectiveness of boat-supported flood evacuation by introducing UAVs as a novel and efficient tool that enhances the overall flood response strategy. Integration of UAVs with traditional boat evacuation would significantly improve response times, accuracy in locating victims, and overall situational awareness. To reiterate, UAVs show efficiency in (i) optimizing the deployment of emergency response by providing real-time aerial imagery, ultimately allowing informed decisions on where to allocate resources and prioritizing the most vulnerable areas, (ii) enhancing route planning and increasing the safety of rescuers and evacuees by identifying the safest and most effective routes for evacuation boats while avoiding obstacles, and (iii) enabling timely interventions by ensuring continuous monitoring of flood conditions and parameters, eventually optimizing resource utilization and rescuers efforts. UAVs also play a key role in post-evacuation and flood events, where they have the potential to evaluate the damage and use the data for future evacuation planning and management. Through this work, we expect to assist stakeholders, managers, and rescuers by offering ideas for developing robust and enhanced conceptual frameworks for maximizing flood evacuation planning by integrating UAVs into their disaster management plans. We encourage policymakers, organizations, and those responsible for evacuation planning to work collaboratively to combine UAVs and boats for boat-supported flood evacuation operations. Furthermore, continuous research and development, training, and clear guidelines will essentially foster the full potential of UAVs to enhance robust preparedness for future floods.

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UAVs as a tool for optimizing boat-supported flood evacuation operations

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