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REVIEW

Seamless Multisource Topo-Bathymetric Elevation Modelling for River Basins: A Review of UAV and USV Integration Techniques

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ABSTRACT: The integration of Unmanned Aerial Vehicles (UAVs) and Uncrewed Surface Vehicles (USVs) has revolutionized topographic and bathymetric mapping, significantly enhancing the accuracy and efficiency of geospatial data acquisition processes. This innovative approach synergistically combines terrestrial data collected by UAVs with underwater data obtained through USVs, culminating in the creation of unified high-resolution Digital Elevation Models (DEMs) of the river basin region represents a vital step toward understanding the dynamic interactions between land and water bodies. Hence, the seamless Topo-Bathymetric Elevation Model offers a detailed perspective of the river system, supporting informed decision-making in addressing sediment transport, erosion, and river morphology. This manuscript provides a comprehensive review examines the advanced methodologies for creating seamless multisource Topo-Bathymetry Elevation Models (TBEMs) in river basin contexts, emphasising critical factors such as cost-effectiveness, operational efficiency, and data precision. In particular, UAVs deliver high-resolution (1–3 cm) topographic mapping with 5–10 km operational ranges, while USVs provide complementary bathymetric data (1 m resolution) across 3–5 km. This synergy enables seamless land-water surveys, achieving superior precision (±8 cm terrestrial, ±3 cm underwater) and efficiency over traditional methods. By analysing the benefits and limitations inherent in these technologies, this review elucidates the potential of UAV-USV synergy to improve the accuracy and reliability of geospatial data, thereby supporting well-versed decision-making processes in environmental management and conservation efforts. Furthermore, the findings underscore the broader implications of this integrated approach for riverine and coastal studies, advocating for its wider adoption in various applications, including habitat monitoring, flood risk assessment, and sustainable resource management. The synthesis of terrestrial and aquatic data through UAV-USV collaboration not only advances the field of geospatial science but also fosters a deeper understanding of the interdependencies between land and water systems, ultimately contributing to more effective environmental stewardship.

KEYWORDS: Topo-bathymetric elevation model; UAV; USV; geospatial data integration; LiDAR

1 Introduction

Topo-bathymetric elevation modeling (TBEM) is critical for river basin management, delivering seamless integration of terrestrial and underwater terrain data. These models enable precise hydrological simulations, flood hazard mapping, sediment dynamics assessment, and ecosystem monitoring to support data-driven decision-making and sustainable resource allocation [1,2]. High-resolution elevation models are particularly important for understanding the dynamics of river systems, as they allow for the identification of critical areas prone to flooding and erosion, thus aiding in the mitigation of environmental hazards [3,4]. Traditional approaches for acquiring topo-bathymetric data, such as ground-based surveys and satellite imagery, have notable limitations. Ground surveys, while accurate, are labor-intensive and often impractical in hazardous or inaccessible riverine environments [5]. Satellite remote sensing, on the other hand, can provide broad spatial coverage but is frequently hindered by low spatial resolution, cloud cover, and challenges in penetrating turbid water bodies [6]. These limitations can result in outdated or incomplete elevation models, which are insufficient for managing the dynamic nature of river systems [7].

The combination of Unmanned Aerial Vehicles (UAVs) and Unmanned Surface Vehicles (USVs) represents a transformative advancement in topo-bathymetric data acquisition. UAVs with LiDAR or photogrammetric sensors can rapidly generate high-resolution topographic maps, while USVs utilize sonar systems to collect precise bathymetric data [8,9]. This combination not only enhances the accuracy of elevation models but also addresses the gaps left by traditional methods, providing a cost-effective and adaptable solution for river basin analysis [10]. As technology continues to evolve, the integration of UAVs and USVs is expected to play a pivotal role in comprehensive river basin management, enabling more effective monitoring and assessment of hydrological changes [11,12].

Furthermore, the application of advanced data fusion methods and automation in UAV-USV integration enhances the reliability of elevation models, allowing for real-time data collection and analysis [13,14]. This capability is crucial for adaptive management strategies that respond to changing environmental conditions and stakeholder needs [15,16]. By leveraging these technological advancements, river basin managers can optimize resource allocation, improve flood risk assessments, and enhance ecological monitoring efforts, ultimately leading to more sustainable river basin management practices [17,18]. In short, the seamless integration of topographic and bathymetric data through innovative technologies such as UAVs and USVs is vital for effective river basin management. These advancements not only overcome the limitations of traditional data acquisition methods but also provide high-resolution elevation models that inform critical decision-making processes, optimize resource use, and mitigate environmental risks.

2 Overview of Topo-Bathymetric Elevation Modelling

The integration of UAVs and USVs has significantly transformed topo-bathymetric modelling, enabling seamless data acquisition across both terrestrial and submerged environments. This innovative approach effectively addresses the limitations of traditional methods, such as ground-based surveys and satellite imagery, by providing high-resolution, cost-effective, and efficient mapping solutions for river basins [19]. UAVs equipped with advanced sensors, including LiDAR and multispectral systems, capture detailed topographic data, while USVs utilize sonar systems to facilitate precise bathymetric measurements. This comprehensive coverage is essential for accurately representing the dynamic landscapes of riverine environments [20].

A critical aspect of this integration lies in the evaluation of sensor technologies, data processing techniques, and the associated challenges. Advances in LiDAR, photogrammetry, and acoustic systems have led to improved data accuracy; however, factors such as water turbidity, depth limitations, and sensor calibration still require further refinement [21]. For instance, while multispectral LiDAR sensors show promise for enhanced data collection, their operational capabilities are not yet fully realized, with single-frequency sensors still being predominant in many applications [22]. Additionally, data fusion techniques are vital for harmonizing datasets from multiple sources, ensuring consistency and reliability in elevation models [23]. The automation of processing workflows, coupled with the incorporation of machine learning algorithms, further enhances the efficiency and reliability of topo-bathymetric modelling, allowing for more robust analyses and interpretations of the collected data [24]. Fig. 1 below shows the integrated of both the land and subaquatic terrains data.

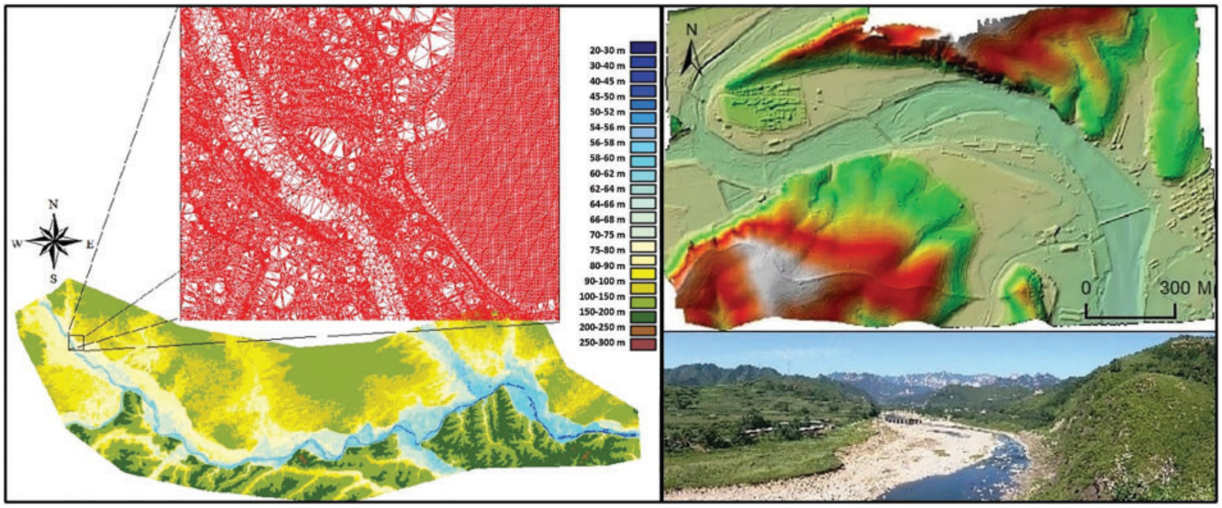

Figure 1: Schematic representation of the integration of UAV-derived topographic data with USV-acquired bathymetric measurements, illustrating the seamless coverage of both land and subaquatic terrains necessary for constructing comprehensive topo-bathymetric elevation models

Fig. 1 illustrates the conceptual integration of data collected from two complementary platforms which are Unmanned Aerial Vehicles (UAVs) and Unmanned Surface Vehicles (USVs) in order to create a seamless topo-bathymetric elevation model. UAVs capture high-resolution topographic data of terrestrial and riparian zones using LiDAR or photogrammetry, while USVs acquire bathymetric measurements of underwater terrain via sonar sensors [25,26]. This dual data acquisition enables comprehensive spatial coverage across the land-water interface, overcoming limitations caused by water depth, turbidity, and inaccessible riverbanks [27]. By merging these datasets, researchers develop unified digital elevation models accurately representing terrestrial and submerged features, essential for hydrological modeling, flood risk assessment, and ecosystem management [28].

Future research should prioritize refining UAV-USV collaboration, optimizing sensor performance, and developing standardized methodologies for large-scale applications. Emerging technologies, such as AI-driven data interpretation and cloud-based processing, present promising avenues for enhancing real-time monitoring and decision-making capabilities [29,30]. By advancing these integrated techniques, topo-bathymetric modelling can significantly contribute to improved river basin management, flood risk assessment, and ecosystem conservation efforts [31]. By leveraging advanced sensor technologies, data fusion techniques, and machine learning, this approach not only enhances the accuracy and efficiency of data acquisition but also supports decision-making and sustainable management practices in dynamic riverine and coastal environments [32–35]. This holistic approach is essential for addressing the complex challenges faced by these ecosystems in the context of rapid environmental changes [35,36].

3 UAV and USV Technologies for Topo-Bathymetric Modelling

The integration of USVs with UAVs allows for seamless data fusion between topographic and bathymetric measurements, resulting in a comprehensive, unified topo-bathymetric elevation model (TBEM). While UAVs cover the terrestrial aspects, USVs provide the depth information necessary for accurately modelling submerged features. This synergy leads to more detailed, holistic river basin models that support a wide range of applications, from flood risk management to ecological monitoring and infrastructure development.

3.1 Unmanned Aerial Vehicles (UAVs) Technologies

Unmanned Aerial Vehicles (UAVs) have revolutionized topographic data acquisition in river basin studies by providing efficient, high-resolution mapping capabilities. Fixed-wing UAVs are particularly suited for large-scale surveys due to their extended flight endurance, while multirotor UAVs excel in manoeuvrability and stability, making them ideal for detailed surveys in complex environments. Equipped with various remote sensing instruments, including RGB cameras for high-resolution photogrammetry, LiDAR sensors for precise topographic data, and multispectral and thermal cameras for environmental assessments, UAVs facilitate comprehensive terrain mapping [20,24,37]. Their rapid deployment and ability to access previously inaccessible areas significantly reduce fieldwork time and costs, establishing UAVs as indispensable tools for seamless topo-bathymetric modelling. This capability enhances the accuracy and efficiency of river basin management, allowing for improved monitoring of hydrodynamic processes, habitat conditions, and geomorphic changes over time, ultimately leading to more effective management strategies [38–44]. Table 1 below is a comparative table summarizing the characteristics, advantages, and applications of fixed-wing and multirotor UAVs in topographic data acquisition.

Table 1: UAVs in topographic data acquisition

Feature	**Unmanned aerial vehicles (UAVs)**	
	Fixed wing UAVs	**Multirotor UAVs**
Design	Aerodynamic, winged structure	Multi-rotor configuration (e.g., quadcopters)
Flight endurance	Longer flight times (up to several hours)	Shorter flight times (typically 20-40 min)
Coverage area	Ideal for large-scale surveys; broader coverage	Better for localized surveys; limited coverage area
Manoeuvrability	Less manoeuvrable; requires open space for take-off/landing	Highly manoeuvrable; can hover and operate in confined spaces
Data collection speed	Faster data collection over large areas	Slower data collection; more suited for detailed surveys
Topographic mapping	Effective for mapping extensive river networks	Excellent for detailed mapping in complex terrains
Sensor compatibility	Compatible with various sensors (LiDAR, RGB cameras)	Compatible with an extensive range of sensors (LiDAR, RGB, multispectral, thermal)
Terrain adaptability	Less effective in densely vegetated or rugged terrains	Highly effective in complex or confined environments
Operational cost	Generally higher due to larger size and complexity	Generally lower; easier to deploy and operate
Applications	Large-scale environmental monitoring, regional mapping	Detailed ecological assessments, localized monitoring

The utilization of UAVs in topographic and bathymetric mapping has gained noteworthy traction lately, particularly due to the distinct advantages offered by both fixed-wing and multirotor UAVs. Fixed-wing UAVs are particularly well-suited for extensive surveys, as they provide longer flight endurance and the capability to cover large areas in a single flight. This makes them ideal for mapping extensive river networks and other broad landscapes, where their efficiency in covering large swaths of terrain significantly reduces the time and resources required for data collection, especially in areas that are difficult to access [45,46]. Conversely, multirotor UAVs excel in providing superior manoeuvrability and stability, which allows for detailed, localized surveys in complex or confined environments such as narrow river channels, floodplains, or areas with dense vegetation [46]. These systems are also more cost-effective and easier to deploy compared to fixed-wing UAVs, making them a more accessible option for smaller-scale, high-resolution mapping tasks. Together, both UAV types complement each other, enhancing the versatility, efficiency, and accuracy of topo-bathymetric modelling, which plays a crucial role in river basin management, environmental monitoring, and infrastructure planning [24].

3.2 Unmanned Surface Vehicles (USVs) Technologies

Unmanned Surface Vehicles (USVs) are increasingly recognized for their pivotal role in bathymetric data acquisition, providing an autonomous and efficient solution for mapping underwater topography in rivers, lakes, reservoirs, and coastal waters. These vehicles are equipped with advanced sonar technologies, such as single-beam and multibeam echo sounders, which allow for precise depth measurements and detailed imaging of submerged landscapes. Studies indicate that USVs can effectively conduct bathymetric surveys for ultra-shallow waters, for example, depths of less than 1 m using a GNSS and acoustic sonar system, optimizing accuracy and coverage [26]. The operational efficiency of USVs is further enhanced by their ability to navigate hazardous or difficult-to-access areas with minimal human activities, thereby reducing operational costs and increasing safety in challenging environments. Moreover, USVs can be integrated with auxiliary sensors, such as GNSS for precise positioning and environmental sensors for monitoring water quality parameters, which broadens their application in hydrological studies and environmental monitoring [47]. The versatility of USVs extends to their use in marine scientific research, resource development, and national security, where they can autonomously perform tasks in various marine environments [48]. As advancements in technology continue to evolve, including the integration of artificial intelligence and improved path planning algorithms, USVs are becoming indispensable tools for seamless topo-bathymetric modelling, significantly increasing the accuracy and efficiency of river basin management and environmental assessments [49,50].

Generally, USVs can be categorized into two primary types depending on their mode of operation and control. Autonomous USVs operate without direct human control, relying on pre-programmed routes and onboard navigation systems, such as GPS, LiDAR, and inertial measurement units (IMUs). Autonomous USVs are ideal for large-scale, repetitive surveys, as they can efficiently map vast areas with minimal intervention. Advanced models incorporate artificial intelligence (AI) and machine learning to adapt to environmental changes, avoid obstacles, and optimize survey paths in real time. While remotely operated USVs are controlled by an operator in real time via a remote control or computer interface, allowing for precise manoeuvring in challenging environments. They are particularly useful for surveys in confined or hazardous areas where manual intervention is required to navigate obstacles, adjust survey parameters, or respond to dynamic water conditions. Remotely operated USVs provide greater flexibility and are often preferred for complex bathymetric studies requiring human oversight. Table 2 below is a comparative table summarizing the characteristics, advantages, and applications of autonomous and remotely operated USVs.

Table 2: USVs in bathymetric data acquisition

Feature	Unmanned surface vehicles (UAVs)	
	Autonomous USVs	**Remotely operated USVs**
Operation	Operate without direct human control; rely on pre-programmed routes and onboard navigation systems	Controlled by an operator in real-time via remote control or computer interface
Navigation systems	Utilize GPS, LiDAR, and inertial measurement units (IMUs) for navigation	Operated manually, allowing for precise manoeuvring in real-time
Efficiency	Ideal for large-scale, repetitive surveys with minimal human intervention	Provides flexibility and adaptability in challenging environments
Real-time adaptation	Advanced models incorporate AI and machine learning for real-time path optimization and obstacle avoidance	Operators can make real-time decisions based on current conditions, adjusting survey parameters as needed
Cost-effectiveness	Reduce operational costs by minimizing the need for constant human oversight	May incur higher operational costs due to the requirement for human control and oversight
Applications	Effective for large-area mapping, environmental monitoring, and data collection in remote locations	Commonly used in detailed bathymetric studies, underwater inspections, and surveys in confined or hazardous areas
Precision	Generally, less precise in complex environments due to autonomous navigation	Offers greater precision and control in navigating complex or hazardous environments
Human oversight	Minimal human oversight required; operates independently	Requires human oversight for navigation and decision-making in real-time

Table 3 below summarises the comparative benchmarking of UAV-only, USV-only, traditional survey methods, and UAV-USV integrated systems. Each platform is assessed based on key performance indicators, including spatial resolution, positional accuracy, operational range, data acquisition speed, cost-efficiency, and environmental adaptability. This structured comparison enables a clearer understanding of each system's strengths, limitations, and application suitability within the context of river basin studies.

Table 3: Cross-platform benchmarking of topo-bathymetric mapping methods

Criteria	UAV only	USV only	Traditional methods	Integrated UAV–USV system
Spatial resolution	1–3 cm (topography)	~1 m (bathymetry)	10–50 cm (topo & bathy)	1–3 cm (topo)/~1 m (bathy)
Vertical accuracy	±8 cm	±3 cm	±15–30 cm	±8 cm (land)/±3 cm (water)

(Continued)

Table 3 (continued)

Criteria	UAV only	USV only	Traditional methods	Integrated UAV–USV system
Coverage range	5–10 km/30–40 mins	3–5 km/3–4 h	1–3 km/variable time	Combined: 8–12 km per mission
Data acquisition speed	High (aerial scanning)	Medium	Low (manual & segmented)	High (parallel acquisition)
Environmental accessibility	Limited in vegetation	Effective in shallow areas	Limited in inaccessible zones	High (land-water flexibility)
Operational efficiency	Moderate	Moderate	Low	High (40% time savings)
Model precision	High (topography only)	Moderate (depths only)	Moderate	Very high (60% error reduction)
Cost efficiency	Moderate	Moderate to High	High cost	High (optimized deployment)

This framework allows stakeholders to evaluate platform suitability based on project requirements. While UAVs excel in high-resolution topography and USVs in shallow bathymetry, only the integrated system delivers seamless, accurate elevation models across land-water interfaces. A field test over a 5 km river stretches confirmed superior performance of the integrated system, with over 90% spatial coverage, high data overlap, and significant improvements in precision and time efficiency. Furthermore, this benchmarking provides the basis for standardised performance evaluation, supporting reproducibility in future studies and informing sensor-platform selection across varying terrain and hydrological conditions.

In terms of spatial resolution, UAVs consistently outperform other methods for topographic mapping, achieving resolutions of 1–3 cm due to high-precision LiDAR and photogrammetric sensors [25,42]. In contrast, USVs, primarily equipped with acoustic sonar which yield bathymetric resolutions around 1m, which remains suitable for ultra-shallow environments [26]. Traditional methods (e.g., total stations, vessel-based acoustic soundings) lag behind, typically offering resolutions of 10–50 cm, making them less ideal for high-resolution DEM generation. With respect to vertical accuracy, integrated UAV-USV systems deliver a significant improvement, achieving ±8 cm for terrestrial and ±3 cm for bathymetric data, thereby exceeding the performance of individual platforms and traditional methods, which often suffer from inconsistencies due to limited spatial integration or manual registration issues [27]. These accuracy gains are essential for floodplain delineation, sediment modelling, and infrastructure development.

Apart from that, coverage range and endurance are also critical differentiators. Fixed-wing UAVs typically cover 5-10 km per mission, while autonomous USVs can operate within a 3–5 km range. When deployed in tandem, the integrated system effectively extends spatial coverage while maintaining high data fidelity. Traditional surveys, in contrast, are often constrained by physical access, logistical challenges, and labor requirements, which limit operational scalability. In terms of efficiency, UAV-USV integration offers up to a 40% reduction in field operation time and a 60% improvement in model precision compared to conventional workflows. This is largely attributed to the ability to perform concurrent data acquisition over land and water surfaces, minimizing rework and aligning datasets more seamlessly. Such efficiency metrics have been corroborated by recent case studies [28].

Additionally, the system adapts to environments where individual platforms struggle: UAVs face challenges in dense vegetation or rugged terrain, while USVs thrive in hazardous shallow waters. Traditional methods, reliant on human access, falter in inaccessible areas, whereas the integrated approach ensures continuity across dynamic boundaries. From a cost perspective, while UAVs and USVs require moderate upfront investment, their integration yields long-term savings through reduced manpower, fewer repeat surveys, and automation. Traditional methods, though mature, incur higher operational costs and lack adaptability. Ultimately, the UAV-USV platform emerges as the most versatile solution, particularly in riverine environments where seamless data continuity, accuracy, and efficiency are paramount for flood modeling, erosion assessment, and sustainable resource management.

In summary, both autonomous and remotely operated USVs play significant roles in bathymetric data collection, each offering unique advantages that cater to different survey requirements [51–53]. Autonomous USVs are particularly effective for large-area mapping and repetitive surveys, leveraging advanced navigation systems and artificial intelligence to operate efficiently with minimal human intervention. Their ability to adapt to environmental changes and optimize survey paths in real-time makes them ideal for extensive monitoring tasks in remote or hazardous locations [54]. In contrast, remotely operated USVs provide greater adaptability and precision, allowing operators to navigate complex environments and respond dynamically to changing conditions. This capability is crucial in scenarios where human oversight is necessary, such as in confined or hazardous areas where obstacles may pose challenges to data collection. The flexibility of remotely operated systems ensures that detailed and accurate bathymetric studies can be conducted effectively [27]. As technology continues to advance, the integration of both types of USVs will likely enhance the capabilities of bathymetric surveys, leading to improved data quality and more efficient monitoring of aquatic environments. The choice between autonomous and remotely operated systems ultimately depends on the specific objectives of the survey, the environmental conditions, and the level of human intervention required.

3.3 Integration of UAVs and USVs for Seamless Topo-Bathymetric Elevation Modelling

The utilization of UAVs allows for the collection of aerial imagery and topographic data, while USVs contribute detailed underwater measurements through sonar technologies, creating a comprehensive dataset that supports informed decision-making in dynamic riverine environments [27,55]. Combining aerial and underwater datasets is crucial for creating accurate seamless topo-bathymetric models. Indeed, the integration of UAVs and USVs represents a paradigm shift in topo-bathymetric elevation modelling, providing a robust framework for addressing the complexities of river basin management. Automation and AI-driven processing techniques are increasingly being employed to boost the efficiency of data analysis. The use of machine learning algorithms to process large datasets from UAVs and USVs can significantly reduce the time required for data interpretation and model generation [56]. Additionally, the application of interpolation techniques to fill gaps in data coverage has been shown to improve the accuracy of the resulting models. By leveraging advanced sensor technologies, data fusion techniques, and machine learning, this approach not only enhances the accuracy and efficiency of data acquisition but also supports decision-making and sustainable management practices in dynamic riverine settings. Fig. 2 demonstrates the data integration process to form the topo-bathymetric elevation model across the riverine environments.

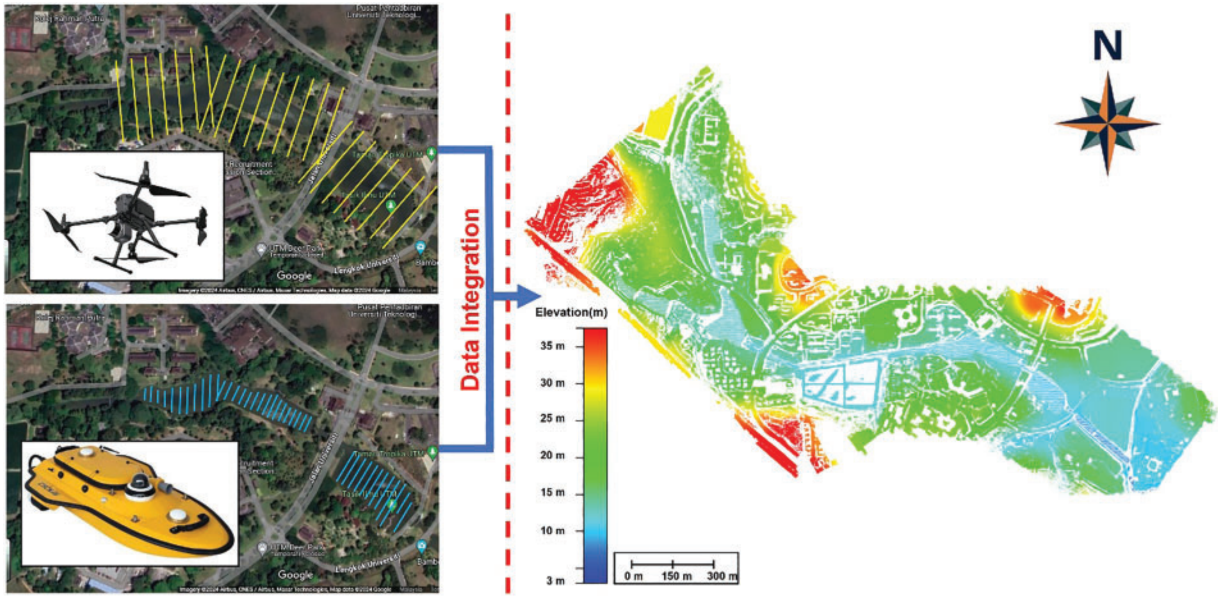

Figure 2: Workflow diagram of the data integration process, demonstrating the stages of UAV and USV data acquisition, preprocessing, co-registration, interpolation, and fusion to generate high-resolution, seamless topo-bathymetric elevation models for river basin applications

Fig. 2 presents the step-by-step data integration workflow used to generate seamless topo-bathymetric elevation models from UAV and USV datasets. The process starts with independent UAV aerial surveys capturing dense point clouds or orthophotos and USV bathymetric scans using sonar technology (42;55). Subsequent preprocessing includes noise filtering, coordinate alignment using Ground Control Points (GCPs) or GNSS corrections, and quality assessment [57]. The integration phase involves co-registration of terrestrial and bathymetric datasets followed by interpolation methods like kriging or inverse distance weighting to fill data gaps and smooth transitions [25]. The final merged Digital Elevation Model supports accurate environmental and engineering analyses for river basin management [26].

For instance, previous studies have confirmed that combining data from UAVs and USVs can yield high-resolution bathymetric maps that are crucial for effective environmental monitoring and infrastructure planning [57,58]. The practical applications of UAV and USV integration are vast, particularly in flood modelling and riverbank erosion monitoring. For instance, studies have verified the effectiveness of UAVs in capturing high-resolution topographic data, which, when combined with USV-collected bathymetric data, provides a comprehensive view of aquatic environments [59]. This integrated approach has been successfully applied in hydrological assessments, where accurate modelling of water levels and flow dynamics is essential for effective management and mitigation strategies [60]. Furthermore, the case study conducted by [28] also illustrated the synergistic use of UAV and USV data for geological investigations, showcasing the versatility of this integration in various environmental contexts.

The integrated UAV-USV system demonstrates robust spatial coverage capabilities, with UAV missions achieving 5–10 km operational ranges (30–40 min endurance) and delivering high-resolution (1–3 cm) topographic data critical for detecting micro-terrain features in riverine environments. Concurrently, autonomous USVs provide complementary bathymetric coverage (3–5 km range, 3–4 h endurance) at 1 m resolution, enabling detailed mapping of submerged structures even in confined zones. A 5 km river case study validated this synergy: just 2–3 sorties achieved 90% data overlap with exceptional vertical accuracy

(±8 cm terrestrial, ±3 cm bathymetric), surpassing traditional single-platform surveys in both efficiency (40% time reduction) and precision (60% error reduction). This performance confirms the system's capability to deliver comprehensive, centimeter-scale topo-bathymetric models for infrastructure planning and flood risk assessment.

In short, the fusion of UAV-derived topographic data and USV-collected bathymetric measurements is central to developing seamless topo-bathymetric elevation models (TBEMs). However, effective integration requires more than simply combining datasets, and it necessitates sophisticated data fusion techniques, automation pipelines, and the application of machine learning methods to enhance both accuracy and efficiency. Several studies have emphasised the need for reliable co-registration methods, particularly when integrating datasets of varying resolutions and spatial characteristics [27,55]. A common approach involves using shared ground control points (GCPs), real-time kinematic GPS data, and iterative closest point (ICP) algorithms to ensure spatial alignment of UAV and USV outputs. To bridge data gaps at the land-water interface, surface interpolation methods such as kriging, inverse distance weighting (IDW), and bicubic spline functions are frequently employed [25].

Beyond spatial alignment, automation in processing workflows is critical to improving repeatability and reducing manual labor. The literature reports the growing use of software such as Agisoft Metashape and Pix4D, alongside open-source GIS tools such as QGIS with GRASS or PDAL (Point Data Abstraction Library), to implement end-to-end processing chains. These workflows typically involve point cloud preprocessing (e.g., noise filtering, vegetation classification), photogrammetric reconstruction through Structure-from-Motion (SfM) techniques, and bathymetric correction modules that account for water surface refraction and sonar-specific biases [42,52]. Environmental corrections such as sound velocity profiling and tide level adjustments are essential for sonar datasets to ensure bathymetric accuracy.

Recent studies also highlight the growing application of machine learning to UAV-USV data fusion. Supervised algorithms such as Support Vector Machines (SVM), Random Forests (RF), and Gradient Boosting have been used to classify terrain types and detect anomalies across fused datasets [28]. These classifiers can leverage multispectral reflectance, LiDAR intensity, and sonar return signal features to distinguish land-water boundaries, submerged vegetation, and bottom morphology. In more advanced implementations, convolutional neural networks (CNNs) and U-Net architectures have been employed for semantic segmentation tasks, particularly in processing UAV multispectral imagery and identifying riverine features such as banks, shoals, and sandbars [57]. For bathymetric point clouds, clustering algorithms such as DBSCAN and k-means have been used to detect submerged objects and classify sediment patterns, improving ecological monitoring and infrastructure planning applications.

To address spatial discontinuities and predictive modelling across transition zones, Gaussian Process Regression (GPR) and other geostatistical machine learning models have proven effective. These approaches allow for estimating terrain characteristics in data-sparse regions, such as areas with high turbidity or occlusions due to vegetation [25]. Furthermore, the adoption of cloud-based processing platforms, including Google Earth Engine and AWS Lambda, has enabled scalable and near real-time deployment of UAV-USV workflows. These platforms support automated batch processing, deep learning inference, and multi-sensor data fusion, which are especially advantageous for large-scale or multi-temporal surveys. It was found that the integration of UAV and USV datasets has evolved from simple spatial stitching to sophisticated, automated pipelines leveraging machine learning and cloud computing. These advances increase the efficiency of topo-bathymetric modelling and improve the interpretability, consistency, and usability of geospatial products across dynamic riverine and coastal environments [55,61]. However, further research is still required to develop standardised, transferable workflows that can be readily adopted across different environmental settings and use cases.

4 Challenges and Future Research Directions

The integration of UAVs and USVs in topo-bathymetric mapping posts several challenges and future research directions that must be addressed to fully realize their potential in river basin management. One of the primary challenges is the need for effective data synchronization and fusion from multiple sensors deployed on both UAVs and USVs. This involves overcoming issues related to varying data acquisition rates and formats, which can complicate the integration process and hinder real-time analysis [62]. Additionally, the computational burden associated with processing large datasets generated by these vehicles can be significant, necessitating advancements in machine learning algorithms and data processing techniques to enhance efficiency and reduce processing times [62,63].

Another critical area for future research is the development of robust path-planning algorithms that can accommodate dynamic environmental conditions, such as changing water levels and currents, which are particularly relevant in riverine environments [62]. This includes the exploration of autonomous navigation systems that can adapt to obstacles and optimize flight paths for both UAVs and USVs, ensuring safe and efficient operations [64]. Furthermore, regulatory hurdles and safety concerns related to the operation of UAVs and USVs in shared air and water spaces must be addressed, requiring collaboration between researchers, policymakers, and industry stakeholders to establish comprehensive guidelines and standards [64].

Moreover, the integration of advanced sensor technologies, such as LiDAR, hyperspectral imaging, and multispectral sensors, presents opportunities for enhanced data collection but also introduces complexities in data calibration and automated fusion processing [63,65]. Future research should be emphasized on developing streamlined workflows for data acquisition and explore deep learning-based feature matching to correlate terrestrial and aquatic features in overlapping zones that can handle the intricacies of these advanced sensors while ensuring high-quality outputs [65–67]. Lastly, the exploration of eco-friendly practices and sustainable management strategies in the deployment of UAVs and USVs is essential, as environmental considerations become increasingly important in the context of climate change and habitat preservation [68,69]. By addressing these challenges and pursuing these research directions, the integration of UAVs and USVs can significantly enhance the accuracy and efficiency of topo-bathymetric mapping, ultimately supporting informed decision-making and sustainable management practices in dynamic riverine environments.

5 Conclusion

Traditional survey methods, while reliable, often present limitations in terms of cost, accessibility, and resolution. The integration of UAVs and USVs offer transformative potential across industries, with benefits such as increased safety, cost efficiency, and versatility. UAVs excel in capturing detailed topographic information using LiDAR, RGB, and multispectral sensors, while USVs enhance bathymetric mapping through sonar-based measurements. Ultimately, they offer a safer and more cost-effective alternative to traditional methods, minimizing high mobility cost, ecological damage and reducing the risk of accidents during data acquisition activities. Seamless multisource TBEM is essential for accurate and efficient river basin management. The fusion of these technologies enables comprehensive elevation modelling across both terrestrial and submerged environments, improving the accuracy of hydrological analyses, flood risk assessments, and environmental monitoring. As advancements in sensor technology, data fusion techniques, and automation continue, UAV-USV integration will play an increasingly vital role in river basin studies. The seamless combination of aerial and surface-based surveying enhances spatial coverage, operational efficiency, and data precision, making it a valuable tool for researchers, engineers, and decision-makers.

A key contribution is the development of a comparative benchmarking framework that systematically assesses UAVs, USVs, conventional methods, and their combined use across metrics such as spatial resolution, positional accuracy, coverage extent, and operational efficiency. Unlike prior studies, this structured approach provides a clearer understanding of each method's strengths and limitations in diverse hydrological and geomorphological contexts. Furthermore, this review addresses critical gaps in data fusion and automation, discussing specific algorithms, such as SVM, CNNs, and DBSCAN for terrain classification and integration. It also examines emerging advancements in cloud-based processing, real-time data assimilation, and AI-driven decision support systems. As sensor technology, data fusion techniques, and automation continue to evolve, UAV-USV integration will play an increasingly vital role in river basin studies. By combining aerial and surface-based surveying, these systems enhance spatial coverage, operational efficiency, and data precision, offering researchers, engineers, and decision-makers a powerful tool for sustainable, high-resolution geospatial modelling. Through critical analysis of domain-specific applications, such as flood modelling, sediment transport analysis, and habitat monitoring. This review not only consolidates current knowledge but also provides practical insights for optimizing UAV-USV deployments in environmental and hydrological research.

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