Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454

Vol. 24 | No. 4 | Article ID B4316 | 2025

Original Research Paper

https://doi.org/10.46488/NEPT.2025.v24i04.B4316

Open Access Journal

High-Resolution Waterlogging Mapping Along Ghazipur Drain in Delhi: A UAV-Based Bathymetric Analysis Approach

Monika Tiwari[1], Smriti Shukla[2], Kishan Singh Rawat[3]†, Varun Narayan Mishra[4] and Sudhir Kumar Singh[5]
[1]Amity Institute of Environmental Sciences, Amity University, Noida, Uttar Pradesh, India
[2]Amity Institute of Environmental Toxicology Safety and Management, Amity University, Noida, Uttar Pradesh, India
[3]Civil Engineering Department, Graphic Era (Deemed to be University), Dehradun, Uttarakhand, India
[4]Amity Institute of Geoinformatics and Remote Sensing, Amity University, Noida, Uttar Pradesh, India
[5]K. Banerjee Centre of Atmospheric & Ocean Studies (KBCAOS), IIDS, Nehru Science Centre, University of Allahabad, Prayagraj, Uttar Pradesh, India
†Corresponding author: Kishan Singh Rawat; ksr.kishan@gmail.com

Abbreviation: Nat. Env. & Poll. Technol.
Website: www.neptjournal.com

Received: 18-02-2025
Revised: 08-04-2025
Accepted: 19-04-2025

Key Words:

Waterlogging
Ghazipur drain
Bathymetric data
Sedimentation
Drainage

Citation for the Paper:

Tiwari, M, Shukla, S., Rawat, K. S., Mishra, V. N. and Singh, S. K., 2025. High-resolution waterlogging mapping along Ghazipur Drain in Delhi: A UAV-based bathymetric analysis approach. *Nature Environment and Pollution Technology*, 24(4), p. B4316. https://doi.org/10.46488/NEPT.2025.v24i04.B4316

Note: From 2025, the journal has adopted the use of Article IDs in citations instead of traditional consecutive page numbers. Each article is now given individual page ranges starting from page 1.

ABSTRACT

Urban waterlogging, especially post-monsoon, exacerbates environmental, economic and public health problems in rapidly urbanizing areas. This study employed UAV-based orthophotography and bathymetric data to examine waterlogging risks along the Ghazipur Drain in Delhi, India. High-resolution Digital Elevation Models (DEMs) with a 5 cm ground sampling distance and bathymetric profiles revealed considerable drainage losses and sedimentation that reduced channel capacity by 25%. This key finding quantifies the extent of hydraulic degradation and is vital for informing infrastructural needs. A map from the study highlights approximately 1,120 settlements in the low-lying areas, including Kalyan Puri, Jafrabad, Seelampur, and Karawal Nagar, at the highest flood risk during the monsoon months due to poor drainage and a high degree of urbanization. This highlights the scale of precarious urban living and the demand for action. When combined with bathymetry, UAV data are highly beneficial for acquiring the path, elevation, and bottom features of these outflows, revealing issues such as sedimentation and obstacles. Orthophotos (pixel resolution = 0.05 m) provide detailed urban infrastructure visualizations, including drainage systems, to enable site-specific interventions, such as dredging and channel widening. These high-resolution datasets provide a strong evidence base for operational planning and resource allocation. This method emphasizes the social and economic implications of waterlogging, such as property damage, transport disruption, and growing health hazards from waterborne diseases, which profoundly impact low- to middle-income communities. As described in this study, the influence of UAV-bathymetry in urban drainage research can be considerable. This has accurately integrated data from UAVs in flood risk management activities and led to urban systems planning with a higher resilience level. This will translate into actionable insights to improve drainage infrastructure, reduce flood hazards, and increase urban resilience, which is useful information for planners and policymakers. This result confirms that UAV-bathymetry is a scalable, precise, and low-cost solution for urban waterlogging in fast-developing cities worldwide.

INTRODUCTION

Urban waterlogging has caused serious environmental, economic, and public health problems in cities worldwide (Apel et al. 2004, Fleischmann et al. 2019). Rapid development, unsatisfactory drainage systems, and increasingly frequent extreme weather cycles aggravate the problem, and rising global temperatures (such as from heavy rain) also contribute (Berghuijs et al. 2014). Over 100 million urban residents worldwide are affected by waterlogging annually (Diwate et al. 2025). This causes economic losses of $40 billion (Zhi et al. 2020). The economies of developing countries are affected even more severely by the pandemic. In developing countries, with their rapid urbanization far outstripping infrastructural provision, there is a great dependence on urban expansion to bring harmonious living to the countryside if only they can restrain population growth and curb the wastelands of marginal farming areas into rich fields (Annis et al. 2020). In India, cities such as Delhi, Mumbai, and Kolkata frequently experience waterlogging during the monsoon season, resulting in disrupted transportation networks, considerable economic losses, and increased risks of waterborne infection (Tomar et al. 2021). During the 2021 monsoon season, waterlogging in Delhi resulted in direct losses of ₹300 crores owing to property damage and interruptions to everyday trade (Darji et al. 2024).

The Ghazipur Drain in Delhi exemplifies the pressures faced by urban drainage systems. The drain, functioning as a primary channel for rainwater, is sometimes inundated by sediment build-up, solid waste accumulation, and intense rainfall (Bates et al. 2010). This underscores the pressing need for novel, scalable, and precise methods to evaluate, monitor, and alleviate waterlogging. Conventional techniques for evaluating waterlogging predominantly depend on satellite remote sensing, terrestrial surveys, and GIS-based studies (Meshram et al. 2024, Shau et al. 2024, Brakenridge et al. 2007). Satellite imagery from platforms such as Sentinel-1 and Landsat is essential for mapping extensive inundations and offers significant spatial data. However, these methodologies frequently encounter constraints in metropolitan environments. The course spatial resolution of satellite imagery, often 10 m or more, renders it inadequate for detecting fine-scale urban waterlogging patterns.

Moreover, cloud cover during monsoons substantially diminishes the availability and precision of the satellite data. Ground-based surveys are precise but require a lot of resources and time to deploy, and are challenging to conduct in densely populated areas or areas experiencing flooding. Manual geodetic surveys in urban India often encounter delays because of logistical factors, which limit their utility for real-time flood management. The digital elevation model (DEM) is another tool for waterlogging studies, and its accuracy is approximately 1 m or more. Although these models improve the prediction of waterlogging hotspots based on building density, road networks, and drainage systems, they do not provide the dynamic accuracy that is essential for on-demand urban waterlogging management (Wienhold et al. 2023, Parizi et al. 2022). This leads to a lack of ability to respond to rapidly evolving urban waterlogging scenarios. Despite their widespread usage and normalization, such standard methods are limited by their low spatial resolution, temporal rigidity, and cost-effective deployment for real-time urban flood assessment. In particular, because new projects based entirely on existing knowledge would have little chance of change, we introduced UAV-bathymetry as a new solution to these limitations and a significant methodological improvement over satellite and ground-based surveys. The application of Unmanned Aerial Vehicles (UAVs) equipped with advanced sensors, such as LiDAR, multispectral cameras, and bathymetric instruments, has made a significant impact on waterlogging research (Li et al. 2021, Yalcin, 2018). UAVs can acquire sub-meter spatial resolution and generate high-definition topographic and bathymetric maps, thus providing unique insights into the urban drainage of water systems and inundated areas (Darji et al. 2024). Striking and precinct-based methods are unable to provide a feasible answer; however, UAVs can outperform other methods in terms of traveling through complex and dangerous urban environments, which enables rapid and precise data acquisition (Karamuz et al. 2020). Bathymetric mapping using a UAV capable of collecting underwater topography for the analysis of submerged structures, such as sediment deposition, obstacles, and flow disturbances (Bates et al. 2010). These characteristics are key to understanding the dynamics of urban drainage systems but are often overlooked in traditional assessments. Zhi et al. (2020) demonstrated the relevance of UAV-bathymetry in the assessment of urban waterlogging. Mapping of UAV-bathymetric in urban China showed that in mine-enclosed areas, 40% of the drainage capacity was lost due to sediment deposition, highlighting the urgent need for focused intervention.

UAV-bathymetry has many practical advantages. UAV systems allow rapid and cost-effective data capture over wide and complex areas (Quamar et al. 2023). First, UAVs can operate quickly and economically across large and complex sites, and their application to derive digital elevation models (DEMs) has demonstrated an unprecedented level of detail for mapping waterlogged areas in Nanjing, China, with a 0.3-meter resolution that satellite images cannot provide (Yao et al. 2019). Second, UAVs are particularly beneficial in time-critical applications. UAV-bathymetric data were utilized in the 2020 Jakarta, Indonesia monsoon floods to identify critical drainage bottlenecks within the next 24 h to enable rapid mitigation measures that reduced inundation levels in affected areas by 30% (Sihombing et al. 2023). In densely populated areas, such as Delhi, UAVs enable mapping of drainage systems as well as flooded areas, avoiding the logistical and safety challenges that manual surveys can pose (Uwaechia & Mahyuddin 2020). The Ghazipur Drain has a prolonged record of sediment and solid waste deposition, increasing the risk of flooding. UAVs equipped with LiDAR sensors can identify system drainage inefficiencies with 92% sensitivity, making them particularly reliable for urban applications.

The results of pilot experiments with UAVs conducted in India are promising. In 2022, a project in the Indian city of Chennai employed UAV-bathymetry to assess the city's storm water drainage systems, revealing that 60% of the network was rendered non-permeable by sediment or debris (Glendenning et al. 2012). This information aided in the improvement of maintenance practices, resulting in a 35 percent reduction in waterlogging incidences in the following monsoon season (Diwate et al. 2025).

The innovation of UAV-bathymetry revolves around its ability to build precise, high-quality bathymetric maps with a deep understanding of urban-drainage systems (OECD 2024). Unlike standard satellite or terrestrial methods, UAV-bathymetry can recognize submerged features that are vital for determining the extent of waterlogging. This competence enables researchers and city networks to identify the reasons and locations of active waterlogging and assess and develop effective control measures. Moreover, UAV-bathymetry represents a huge leap forward in the time and spatial resolution of urban waterlogging studies. Old methods mostly rely on static information, but UAVs can collect and update their information in almost real time, making them very useful in dynamic waterlogging control situations. During the monsoon floods of 2021 in Mumbai, UAVs monitored water levels in critical drainage systems to better manage pumps and other solutions during the flooding (Raj et al. 2022, Rawat et al. 2019, Wawrzyniak et al. 2016). Urban drainage systems, such as the Ghazipur Drain, are important for stormwater disposal but are often ineffective because of sediment and other debris clogging them. UAV bathymetry solves these problems more effectively. This technology provides the underwater topography of the drainage at high resolutions, thus helping to locate significant areas that are vulnerable to blockage or loss of capacity. Initial UAV measurements suggest that sediment accumulation in the Ghazipur Drain reduces its effective discharge by 25% during heavy rainfall periods (OECD 2024). The information acquired through UAV bathymetry can direct particular activities, such as silt removal and channel widening, which are very important for improving the efficiency of draining. This technique also increases the accuracy of UAV-bathymetry innovation in its ability to quickly and accurately generate detailed maps of Urban Drainage Systems. Unlike traditional satellite or land-based methods, UAV bathymetry can reveal underwater features that are important for understanding waterlogging patterns. Such capability will enable researchers and planners to identify the areas affected by waterlogging, determine the causes, and devise solutions to address the problem. In addition, UAV-bathymetry indicates great progress for enabling urban waterlogging studies of spatiotemporal resolution monitoring.

Moreover, UAV-bathymetry represents a dramatic improvement in the temporal and spatial scope of urban waterlogging studies. Static data are used most frequently by conventional methods, but UAVs can collect and update data almost in real time, making them indispensable for the active management of waterlogging situations. UAVs played an important role in the 2021 monsoon floods in Mumbai to monitor hydraulic level inside a crucial storm water catchment system that aided in pre-positioning pumps and managing other risk. City drains like the Ghazipur Drain are significant to handle stormwater, but they are frequently inherently inefficient due to sedimentation and garbage buildup. UAV-bathymetry provides an adequate solution to these problems. It provides a means to accurately map the underwater topography of the drain and identify key areas where obstruction or loss of capacity is likely to occur. Preliminary survey measurements taken with UAVs suggest that sedimentation in the Ghazipur Drain reduces its effective capacity by approximately 25% during peak rainfall periods (Gautam et al. 2020, Rawat & Panwar 2024, Raj & Rawat 2024, Mahanta et al. 2023). UAV-bathymetric data tend to inform the procedures that need to be performed, such as silt dredging and channel widening, which are important for optimizing drainage processes. This technique reduces the risk of waterlogging and increases the service life of the city's infrastructure. This development addresses important research gaps in responding to rapidly evolving urban waterlogging scenarios and urban flooding by demonstrating the application of UAV-bathymetry to urban drainage. Modern studies often conduct surface investigations of waterlogging problems using an average geographical approach, which misses the crucial submerged components of the drainage mechanisms. This study applied UAV-bathymetric data to show how structural and morphological components contribute to waterlogging, thus offering a new approach to the management of urban drainage.

In contrast to previous studies, UAV-bathymetry is a new approach for studying and managing urban flooding. This approach uses UAV-bathymetry on the Ghazipur drain in Delhi, while addressing an important local issue and forming a replicable study for urban drainage systems worldwide. It can collect real-time data, allowing it to operate with precision in urban spaces. The specific results of this study are crucial for civil engineers and scientists in the development of better methods for combating waterlogging.

LITERATURE REVIEW

UAV-bathymetry has great advantages in solving and addressing the limitations of current methods of monitoring the degree of waterlogging, as it offers more accurate, faster, and more suited to a global urban environment (Rakha & Gorodetsky 2018). This penetration depth enables high-resolution wide-area mapping to sub-meter accuracy, allowing for the identification of subtle sub-seafloor features that are typically missed by other techniques, such as satellite or ground surveys (Del Savio et al. 2023). Model accuracy is higher using such models, which are beneficial in many regions across the world (Fewtrell et al. 2010). UAV-Bathymetry can detect silt deposition, blockages, and other issues in drainage systems, which are crucial maintenance concerns for minimizing urban waterlogging. Rossi et al. (2020) demonstrated how UAV-Bathymetry effectively identified silt accumulation and obstructions in drainage channels, highlighting its importance for targeted maintenance to reduce urban flooding. These instances demonstrate the immense potential of UAV-bathymetry for solving the multitude of topographic challenges that arise from urban waterlogging (Bilașco et al. 2022).

UAV Bathymetry has the added benefit of acquiring data over extensive regions in a short period of time. This makes UAVs useful for carrying out preventative and mitigative assessments of waterlogging in real time during and after a flood incident. In a study conducted on waterlogging disaster events in Nanjing, China, Rossi et al. (2020) detailed the importance of timely disaster information for environmental planning and mitigation actions and how UAV and bathymetry made it possible to use critical data just hours after the disaster flooding. These capabilities are essential in urban areas with a short time to flood regions, where traditional methodologies take weeks or days to formulate actionable data. Similarly, Bilașco et al. (2022) used UAV bathymetry in the Philippines because of frequent flooding during the monsoon seasons, which required urgent data for disaster relief and enhanced long-term drainage management. In addition to timeliness, UAV bathymetry allows access to remote places that are not safe or easily reachable using traditional surveying techniques. These areas are severely flooded, have thick vegetation, or have complex urban drainage systems. Medvedev et al. (2020) showcased the use of UAV bathymetry in Oregon, USA.

In Oregon, USA, Sott et al. (2020) showcased the use of UAV-Bathymetry to overcome the limitations faced by ground-based crews during urban floods. UAVs allow the collection of critical data while keeping survey personnel safe from hazardous weather conditions. Another important benefit of UAV-bathymetry is that it is cost-effective in terms of labor, time, and equipment compared to conventional topographic surveying. UAVs equipped with state-of-the-art sensors facilitate large-scale aerial data collection without the logistical burden of large field parties or specialized equipment (Del Savio et al. 2023). Del Savio et al. (2023) identified the cost benefits of UAV-Bathymetry for urban drainage infrastructure management, suggesting that if accurate enough, they could more effectively target maintenance and construction activities. In fast-growing metropolitan areas like India, UAV-Bathymetry has been adopted along watercourses to mitigate persistent waterlogging problems at a fraction of the cost of conventional survey techniques.

UAV-bathymetry, both regionally and internationally, has demonstrated its ease of adaptability and functionality in different contexts. In Southeast Asia, parts of the world prone to seasonal flooding have employed UAVs to map submerged geomorphological features with high accuracy in urban areas to aid planners in designing and implementing effective drainage systems. In the Middle Eastern region, UAV-bathymetry is important for evaluating the drainage systems of dry cities, where sudden flash floods lead to severe waterlogging (Fewtrell et al. 2010). UAV bathymetric technology can be adapted to different climatic and geographical conditions, making it universally applicable. Its application in community-based projects has also improved performance. Sufficient examples can be mentioned for the use of UAV bathymetry in Africa that was intended to map flood risk zones in urban centers, enabling local authorities and communities to synergize towards feasible mitigating strategies. With this common action approach, not only is adaptive capacity increased, but there is also a better understanding of the waterlogging phenomenon among different groups of people. Among has many benefits, it also presents certain challenges. The range of adoption has been slower owing to the limitations of sensor technology, data processing requirements, and policies that govern the deployment of UAVs. However, these limits have been slowly changing owing to improvements in sensing and higher access to efficient data processing applications. In addition, more international regulations on the use of UAVs are likely to increase operational barriers in urban settings. This is likely to make UAV bathymetry more possible and useful than it has ever been.

UAV-based bathymetry has proven to be a valuable tool for tackling urban waterlogging problems worldwide. Compared to conventional ground-based methods, it is not only efficient and fast but also cost-effective. This makes it an invaluable tool for urban planners and disaster response teams. Owing to emerging technical innovations, UAV-bathymetry will be at the forefront of the global battle against urban flooding and resilience. This innovative solution will help mitigate what many believe to be the greatest threat to cities in the current times (Fewtrell et al. 2010).

MATERIALS AND METHODS

Study Area

Ghazipur Drain is an important but polluted drainage line in East Delhi, also called the pentamerous drain because it runs along National Highway 24 (NH-9). However, urban encroachment, leachate from landfills, and untreated sewage have made it one of the most contaminated water bodies in the region. The drain excretes rain and wastewater, which is ultimately drained into the polluted Yamuna River. Ghazipur Drain lies between 28.620° N to 28.640° N latitude and 77.290° E to 77.320° E longitude (Fig. 1). It represents a considerable drainage network in East Delhi. The beginning point lies near the Patparganj Industrial Area, which is known for its dense manufacturing units and the industrial waste they add to the drainage system. The drain runs southeast and passes through diverse residential, commercial, and landfill areas before meeting the Yamuna River. Its total length is estimated to be between 12 and 15 km. The drain traverses several densely populated areas, including Ghazipur, Mayur Vihar, and nearby settlements, which further increase pollution levels due to uncontrolled solid waste disposal.

Regarding altitude, the highest level of the drain is situated close to Ghazipur, where the adjacent area attains an altitude of approximately 215-220 meters above sea level. The gradient towards the Yamuna River floodplain is also relatively shallow, with its lowest point being approximately 198–200 masl, which, in principle, should facilitate continuous drainage of the area. However, during the monsoon season. Severe waterlogging and urban flooding occur because of water stagnation caused by sediment accumulation, excessive siltation, and solid waste blockage. The Ghazipur Drain is well-known for being one of the major environmental issues, namely, the direct escape of toxic landfill leachate from the neighboring Ghazipur landfill. Research has indicated that elevated levels of heavy metals, organic pollutants, and microplastics have been found in water samples from the drain, making it one of the most ecologically dangerous drainage systems in India. In addition, its slow flow speed and lack of proper dredging reduce its conveyance, exacerbating local floods and health threats for communities downstream. The use of unmanned aerial vehicles (UAVs) for high-resolution bathymetric mapping has provided essential information regarding the depth profile, sedimentation, and obstruction points in

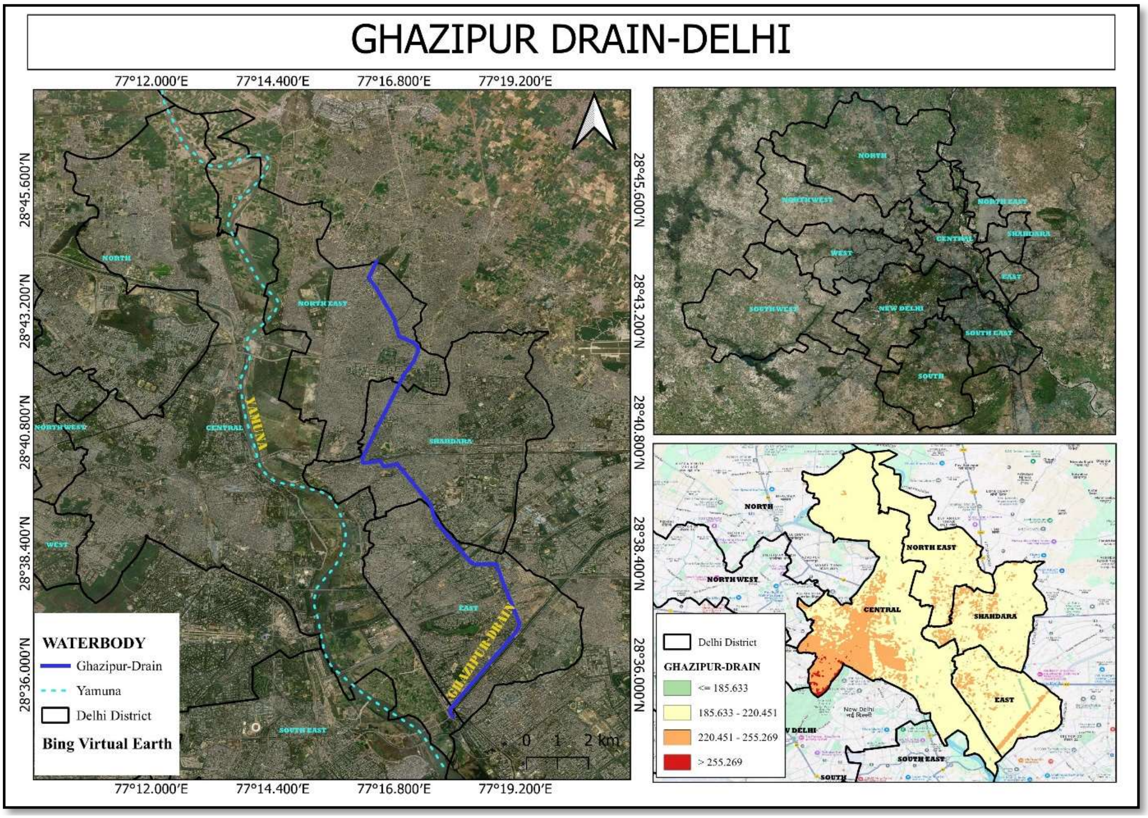


Fig. 1: The Ghazipur Drain and surrounding areas in Delhi, India.

the drain. By utilizing LiDAR technology, multispectral imaging, and drone-assisted remote sensing, researchers can create hydrological models to evaluate water flow dynamics and pinpoint areas that are susceptible to excessive sediment accumulation and blockages. This approach supports improved drainage planning, flood risk reduction, and water quality enhancement efforts in East Delhi.

Data Used and Methods

A robust methodology was employed that combined UAV-based aerial imagery, DGPS ground survey, and bathymetric data for high-resolution mapping and analysis of waterlogging in the Ghazipur Drain. These methods resulted in a high-value, high-density dataset necessary for successful hydrodynamic and topographic models in the study area. The flowchart in Fig. 2 shows each component of the process.

This process involves collecting geographical data using UAVs and advanced surveying methods to provide a comprehensive analysis (Suzuki 2020). The internal parameters of the drone camera were calibrated before the flights and in the preprocessing phase in the Agisoft Metashape software. With overlapping RTK correction windows (static base station logs) providing temporal alignment, photogrammetry was made consistent using a differential global navigation system approach. DGPS involves a stationary base station that compares its known coordinates to satellite signals, measures the difference between them to transmit corrections to a mobile unit known as a rover, and then applies the corrections to the GPS signals received by the rover, achieving a positional accuracy of less than one meter. Both RTK and Static methods employ carrier-phase corrections, with RTK achieving real-time centimeter accuracy and static surveying providing even greater precision through longer observation times and post-processing.

A certified A-200 drone equipped with an RTK-enabled GPS was used to capture high-resolution JPEG images (Fig. 2), ensuring precise geotagging and a ground sampling distance (GSD) of 2–5 cm for detailed surface examination (Nielsen et al. 2022). Aerial surveys were conducted with side and forward overlaps to ensure data redundancy and seamless image stitching. GCPs use DGPS technology to provide geospatial precision. The use of static reference GCPs and Real-Time Kinematic (RTK) points makes it possible for UAV images to be georeferenced with other geographical datasets (Fig. 3) (Suzuki 2020). An echo sounder recorded bathymetric depth profiles with a vertical precision of ±2 cm. Combining these depth measurements with Differential Global Positioning System (DGPS) coordinates produces

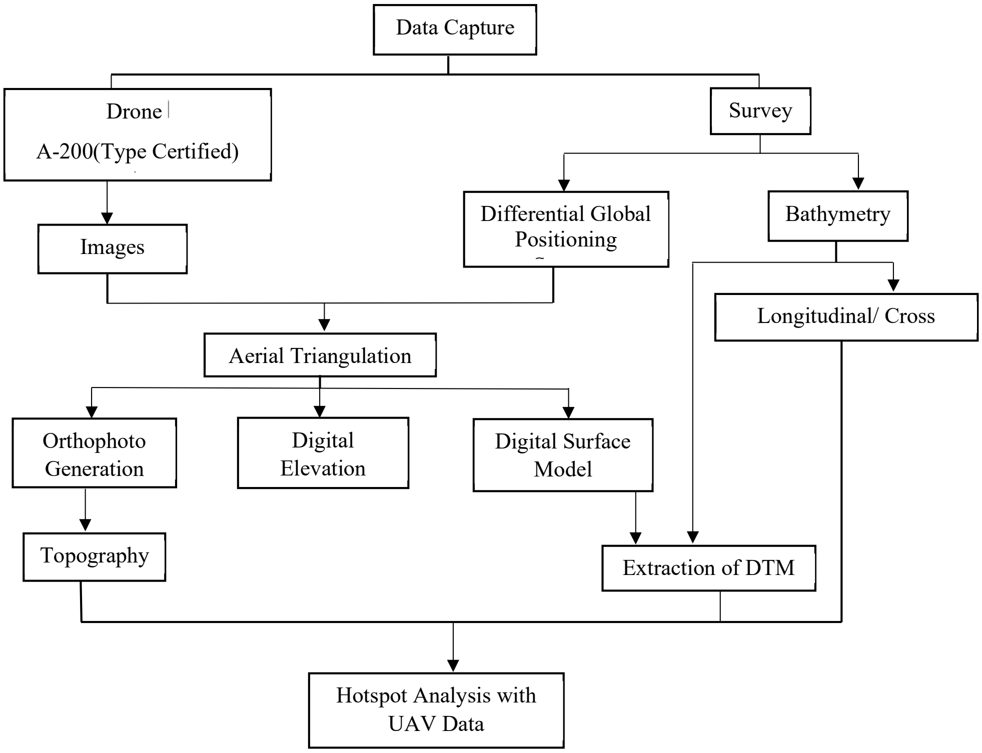


Fig. 2: Methodology.

Table 1: An Assessment of Techniques for Capturing Waterlogging Extents along the Ghazipur Drain.

Data Type	Description	Methodology	Purpose
Drone Imagery	Asteria A200 drone-captured high-resolution JPEG photos with RTK-enabled GPS geotagging	Aerial survey is scheduled with a 70% side lap and 80% overlap to guarantee comprehensive coverage and facilitate seamless image stitching.	To obtain intricate surface pictures of the subject region for topographical examination
Ground Control Points (GCPs)	Control points based on DGPS are established at intervals of 1 km using static observations, while RTK points are positioned every 250 meters.	Accurate GNSS location to guarantee high absolute precision and facilitate the synchronization of bathymetric and UAV data.	To accurately align UAV imagery with bathymetric data and ensure consistency in mapping.
Bathymetric Data	Depth profiles collected using an echo sounder along the waterlogged areas	Integration of bathymetric data with DGPS coordinates for comprehensive underwater topography mapping	To ascertain underwater topography, silt deposition, and depth fluctuations in drainage systems
Digital Elevation Model (DEM)	Depth profiles obtained through the use of an echo sounder in the waterlogged regions	Generation of a Digital Elevation Model (DEM) utilizing UAV data and Ground Control Points (GCPs) to construct a surface elevation model for topographical study.	To identify low-lying regions and probable waterlogging sites based on elevation variances.
Digital Terrain Model (DTM)	Enhanced Digital Elevation Model integrating bathymetric data for seamless terrain mapping	Integration of bathymetric data with Digital Elevation Models to produce an accurate depiction of both terrestrial and subaqueous terrain.	To examine the dynamics of waterlogging in regions with intricate drainage systems
Orthophoto	An aerial image that has undergone geometric correction, depicting the specified area of interest.	Generation of orthophotos through the application of geometric adjustments to UAV imagery	To illustrate surface characteristics and offer context for recognizing potential waterlogging areas.
Topographical Mapping	Evaluation of elevation, depressions, and slopes through the application of Digital Elevation Models (DEM) and Digital Terrain Models (DTM).	Utilize GIS technologies to detect depressions, inclines, and additional topographical characteristics linked to waterlogging.	To produce maps and visualizations for the identification of locations susceptible to waterlogging

a high-resolution bathymetric map. UAV imagery and GCP data was used to produce Digital Elevation Models (DEMs) with a vertical resolution of 5–10 cm (Saponaro et al. 2020). This reveals low-lying areas and small elevation changes.

Additionally, using bathymetric data, DEMs were processed into Digital Terrain Models (DTMs). The DTMs provide a high spatial resolution of both terrestrial and submerged landscapes (Table 1) (Zhu et al. 2019). A standardized bar check was performed to field-calibrate the echo sounder at the beginning of each survey to adjust for signal lag and environmental variability. A bar check was used to calibrate the echo sounder, where a reference plate was raised and lowered to known depths, allowing for correction adjustments associated with signal lag, transducer draft, and environmental variability. The speed of sound in water was also configured from the in-situ temperature and salinity of each section; therefore, the acquired data were corrected considering the depth of the detection section under field conditions. GPS timestamps were used to time-synchronize the recorded depth values with DGPS and UAV logs, which facilitated spatial alignment and minimized error propagation in the resulting DTMs.

Orthophotos were created by geometrically correcting UAV images, achieving pixel-level precision with a ground sample distance (GSD) of 2–5 cm. Such orthophotos are accurate, georeferenced representations of surface features that form the basis of waterlogging vulnerability mapping. Topographical maps are extremely useful for analyzing elevation, depressions, and slopes from DEMs or DTMs by utilizing GIS technology to map high-resolution maps that contain valuable information about the topography of the area (Zhu et al. 2019). These outputs can assist in spatializing waterlogging vulnerability and in informing mitigation strategies (Chai & Draxler 2014). The methodology serves as a leap mechanism for effective waterlogging mapping and management by supplementing UAV high-resolution data, GCP placement, and GIS analysis.

Table 2 shows how the A200 can provide a GSD of up to 3 cm, depending on the altitude, allowing for detailed surface mapping. This drone effectively captured the topographical features that led to water pooling, including slope variations, fissures, and dips, even at a low GSD. When mapping extensive waterlogged areas, the 3-axis gimbal stabilization ensures that the camera remains steady during flight, resulting in clear, motion-free images. This adds stabilization, allowing for consistent image quality for

Table 2: UAV specifications.

Specification	Details
Drone Model	Asteria A200
Type	Multi-rotor UAV
Max Flight Time	Up to 40 minutes (depending on payload)
Max Flight Speed	15 $m.s^{-1}$
Operating Range	Up to 5 km
GPS Mode	Real-Time Kinematic (RTK) and GNSS
Camera Resolution	Up to 20 MP
Camera Type	Frame camera
Image Format	JPEG, RAW
Ground Sample Distance (GSD)	As low as 3 cm (depending on altitude)
Max Wind Resistance	10 $m.s^{-1}$
Stabilization	3-axis gimbal
Payload Capacity	Approximately 2 kg
Battery Type	Li-Po (Lithium Polymer)
Battery Capacity	6,000 mAh
Charging Time	Approximately 60–90 minutes
RTK Accuracy	Horizontal: ±1 cm, Vertical: ±2 cm
Operating Temperature	-10°C to 40°C
Dimensions	Folded: 350 x 200 x 150 mm
Weight	2.2 kg (including battery and camera)

accurate surface models, even in moderate winds. The A200 has a 40-minute flight time, allowing the user to cover larger areas in one flight, making waterlogging studies less cumbersome with no need to change batteries frequently. Based on the above specifications, Asteria A200 is a powerful tool for land analysis, mapping, and monitoring of waterlogged areas for waterlogging risk analysis and water management planning.

The flight plan had a 70% side lap and an 80% overlap between all images taken, resulting in a good and complete collection with almost no gaps (Fig. 3). The area covered was 100 m wide, with a distance of 35.25 m between the flight lines, as shown in Fig. 4. The Ground Control Points (GCPs) used for georeferencing were sized at 1.5 × 1.5 m to improve visibility from the UAV altitude, thereby enhancing overall accuracy by providing clearly identifiable spots in the landscape, as shown in Fig. 4. In addition to spatial control, redundancy was introduced by surveying each GCP three times, with the mean of the points used as the coordinate values to eliminate any outliers. Together, these steps led to an improvement in the overall model georeferencing accuracy of the images.

A Differential Global Positioning System (DGPS) survey was conducted to enhance the positional accuracy of aerial photography and provide vital data for water level rise that leads to waterlogging. This DGPS survey utilized Global Navigation Satellite System (GNSS) constellations to achieve high-precision location tracking (Saponaro et al. 2020). Primary Ground Control Points (GCPs) were established at 1 km intervals to measure the Ghazipur Drain

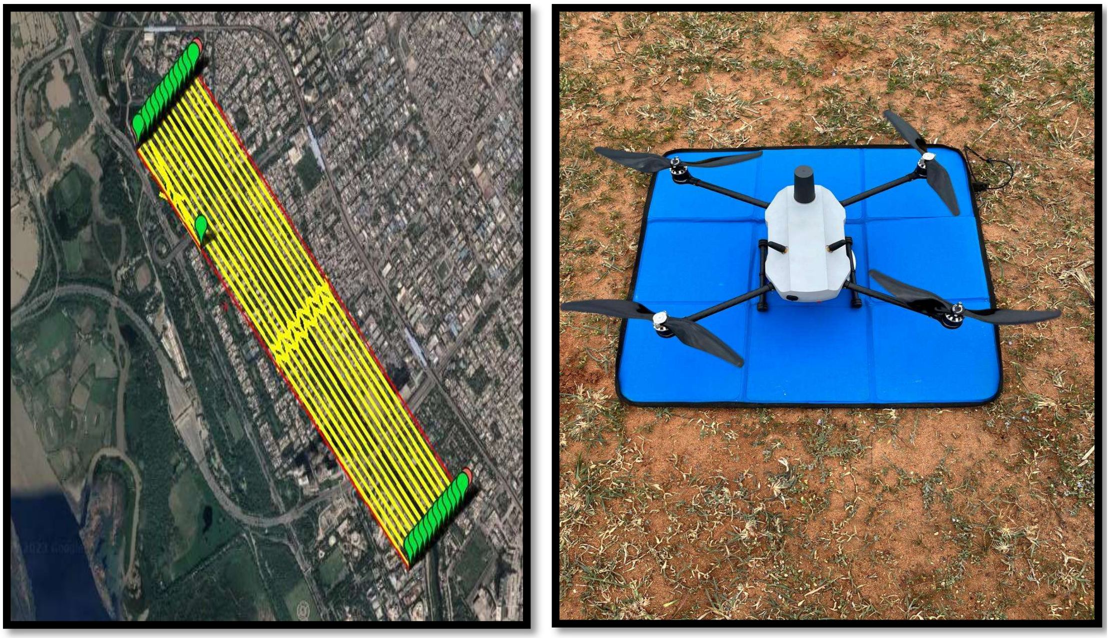
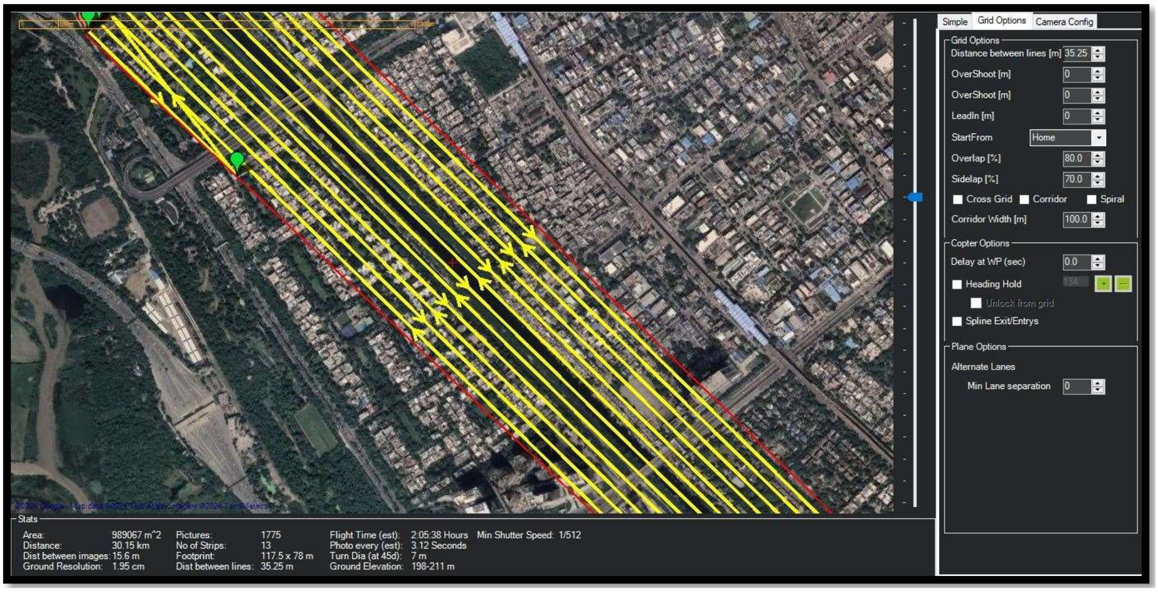


Fig. 3: Flight strategies and unmanned aerial vehicles for surveying the site.



Grid Options
Distance between lines [m] 35.25
OverShoot [m] 0
OverShoot [m] 0
LeadIn [m] 0
StartFrom Home
Overlap [%] 80.0
Sidelap [%] 70.0
☐ Cross Grid ☐ Corridor ☐ Spiral
Corridor Width [m] 100.0

Copter Options
Delay at WP (sec) 0.0
☐ Heading Hold 134
☐ Unlock from grid
☐ Spline Exit/Entrys

Plane Options
Alternate Lanes
Min Lane separation 0

Stats
Area: 989067 m^2
Distance: 30.15 km
Dist between images: 15.6 m
Ground Resolution: 1.95 cm
Pictures: 1775
No of Strips: 13
Footprint: 117.5 x 78 m
Dist between lines: 35.25 m
Flight Time (est): 2:05:38 Hours
Photo every (est): 3.12 Seconds
Turn Dia (at 45d): 7 m
Ground Elevation: 198-211 m
Min Shutter Speed: 1/512

Fig. 4: Details of Flight Plan.

Latitude: 28.559009
Longitude: 77.320559
Elevation: 225.15±18 m
Accuracy: 5.9 m
Time: 10-01-2023 08:21
Note: GCP6

Latitude: 28.735366
Longitude: 77.273422
Elevation: 229.13±3 m
Accuracy: 11.6 m
Time: 09-29-2023 07:59
Note: GPS1
HIGHT:-1.621

Fig. 5: Ground control points taken within the study area.

(3 × 30 min static observations at each site). Moreover, Real-Time Kinematic (RTK) points were collected at every 250-meter distance to verify that the accuracy of the data remained consistent across the extent of the study area (see Fig. 5). The horizontal accuracy was ±3 cm and the vertical accuracy ±5 cm, which can be achieved through the integration of DGPS and RTK. Over vegetated or canopied areas, there were minor deviations due to the GNSS signal attenuation. Bathymetric data were collected using an echo sounder simultaneously with the DGPS survey to acquire the depth profiles of the Ghazipur Drain. The echo sounder data played a key role in establishing a holistic understanding of the morphology and hydrodynamic processes of the drain spoil.

Once the data was captured, processing with the aerial triangulation of the UAV images began. In this case, the DGPS ground control points can be used to match the geotagged images, thus leading to a highly precise composite image (Acharya et al. 2021). It improves both the absolute accuracy, which refers to alignment with real-world coordinates, and relative accuracy, ensuring consistency among the images. This guarantees that every part of the collected data aligns perfectly with its neighboring sections. This approach was augmented for vertical consistency within the digital terrain models by considering parallax distortions and terrain shifts in dense point-cloud generation using Multiview stereo algorithms. Ground control points (GCPs) that were collected using DGPS technology were imported into Agisoft Metashape. To serve as real-world imaging reference points, all GCP coordinates were entered into the software. The GCPs acted as control sites during alignment, allowing Agisoft Metashape to properly align the drone photos (Li et al. 2021). By placing the GCPs, aerial images are aligned to the ground position, thus providing a model that is spatially accurate and improves the absolute accuracy of the model. After importing the photos and GCPs, Agisoft Metashape detected features in the photos. The software identifies key features in overlapping photos to establish tie points, matching characteristics such as corners and textures (Bates et al. 2010). Matching determines the relative positions between the photos, which is required for triangulation. The photogrammetric bundle block adjustment algorithms in Agisoft Metashape optimize image alignment by correcting discrepancies (Darji et al. 2024). This adjustment modifies the locations and orientations of the images to best fit the GCPs. Each image was treated as a "block," and the software calculated the spatial relationships between these blocks and the GCPs to enhance alignment. The Root Mean Square Error (RMSE) across the three spatial dimensions was 4.2 cm (X), 3.6 cm (Y), and 5.1 cm (Z), indicating a high level of spatial accuracy between UAV images and control points after the bundle block adjustment process.

Photogrammetric Processing

The bundle blocks were adjusted by a camera using camera information, such as the focal length (f), offsets of the principal point (cx, cy), and distortion coefficients (K1, K2, K3, K4, P1, and P2) in Agisoft Metashape (Zhu et al. 2019). These parameters help reduce lens distortion, such as radial and tangential distortions, which can also create errors in the model.

Lens Distortion Correction and Normalization

By minimizing the position control errors between adjacent photos, bundle adjustment enhances the relative accuracy and ensures seamless alignment of the dataset.

$$x = X/Z \qquad \ldots (1)$$

In this context, X represents the horizontal position, and Z indicates the depth, which helps normalize the point's position on the image plane. Photogrammetry and aerial triangulation involve the conversion of 3D points from the camera's local coordinate system into 2D coordinates on what is referred to as a "normalized image plane," as illustrated in Eq. 1. The local coordinate system of the camera assigns coordinates (X, Y, Z) to any point in 3D space, where X and Y denote the horizontal and vertical distances from the optical center, respectively, and Z signifies the depth. To get the normalized image coordinates independent of depth the image coordinate is divided by per pixel depth value. That is, the normalized image coordinates are derived from

$$x = X / Z \text{ and } y = Y / Z \qquad \ldots(2)$$

In this context, Y represents the vertical position and Z indicates the depth, which helps normalize the point's position on the image plane. According to Eq. 2, the normalized coordinates are given by $(x, y) = (X, Y)$ or (x,y) = (Z X, Z Y). This transformation effectively scales all points as if they were projected onto a unit-distance plane from the camera, thereby removing the depth factor. The normalized coordinate system makes it easier to manipulate these points during computation, as the intrinsic properties of the camera (focal length, distortion coefficients, etc.) can be applied seamlessly when projecting a point to an image. Working with normalized coordinates allows for more intuitive, uniform lens distortion correction, which improves the alignment of 3D points to their 2D projections. This technique has been used in photogrammetry because it makes the transformation of 3D points to a 2D image plane as accurate as possible.

$$r = \sqrt{}\,(x^2+y^2 \qquad \ldots (3)$$

In this case, x^2 and y^2 are simply the Euclidean square distances from the origin to a given point. The radial distance from Equation 3 is needed to correct radial lens distortion, which is an optical artifact that occurs when the lens curvature causes points located outside the image to shift. To obtain r, the square root of the x value squared + the y value squared is taken. This gives us the Euclidean distance from the image center (the origin, in normalized coordinates) to the point we selected. The radial distance r is important to find out how near a point is to the center of the image, which is further required to carry out distortion correction. Calculating r allows us to better align positions closer to the edges of the image (that have the highest distortion) with their more accurate representation on the image plane. Such an improvement will enable spatial data to more accurately reflect real-world coordinates and distances, which is useful in applications such as 3D cartography.

$$x' = x\,(1+k_1r^2+k_2r^4+k_3r^6+k_4r^8)+[P_1(r^2+2x^2)+2P_2xy] \qquad \ldots(4)$$

Here, x' = Asymmetry of the image

K1, K2, K3, K4 are radial distortions coefficients

P1, P2 are tangential distortion coefficients

$$y' = y(1+k_1 r^2+k_2 r^4+k_3 r^6+k_4 r^8)+(P_1 (r^2+2x^2)+2P_2 xy) \quad \ldots(5)$$

Here, y' = Asymmetry in the image

K1, K2, K3, K4 are radial distortions coefficients

P1, P2 are tangential distortion coefficients

All equations are shown in Eqs. 4 and 5 take care of radial and tangential distortion, respectively, and the output coordinates (x', y') impose the position of the point correctly on the image plane. Therefore, correcting this is a key part of photogrammetry for high accuracy, as minimizing the effects of displacement and distortion together leads to better alignment of the measurements and, ultimately, better root mean square error (RMSE) in mapping and 3D applications.

Image Projection to Pixel Coordinates

The last transformation from normalized coordinates to image pixel coordinates, considering the camera's intrinsic parameters and sensor geometry, is

$$u = w0.5+Cx+x'.f+x'.B+y:B_2 \quad \ldots(6)$$

Where, F = Focal length

Cx, cy are the principal point offsets

B1 and B2 are the skew coefficients

W and h are the width and height of the image in pixels

Eq. 6 correctly projects a normalized coordinate point (x', y') onto the pixel grid of the image, while considering the camera's characteristics. Focal length and skew coefficients are major parameters that play a pivotal role in placing point u in a plane, which helps in mapping 3D points to a 2D plane. This changes photograph mapping more prominent precision for 3D rebuilding and mapping.

$$v = h0.5+Cy+y'.f \quad \ldots(7)$$

Where, F = Focal length

Cx, cy are the principal point offsets

B1 and B2 are the skew coefficients

W and h are the width and height of the image in pixels

Eq. 7 similarly is a function that converts a point with normalized, corrected coordinates y' into the vertical pixel coordinate v, considering the internal parameters of the camera. The focal length of scales the normalized coordinate y to match the distance of the camera to the scene, and the principal-point offset cy centers the optical axis aligned to the sensor when the center of the optical axis does not coincide with the sensor center. It correctly projects 3D points to the 2D image plane in photogrammetry, which is the image formation model that should yield consistent images that are aligned for more accurate reconstruction and mapping. After triangulation, an orthophoto was generated, where the rectified composite image was geometrically transformed to

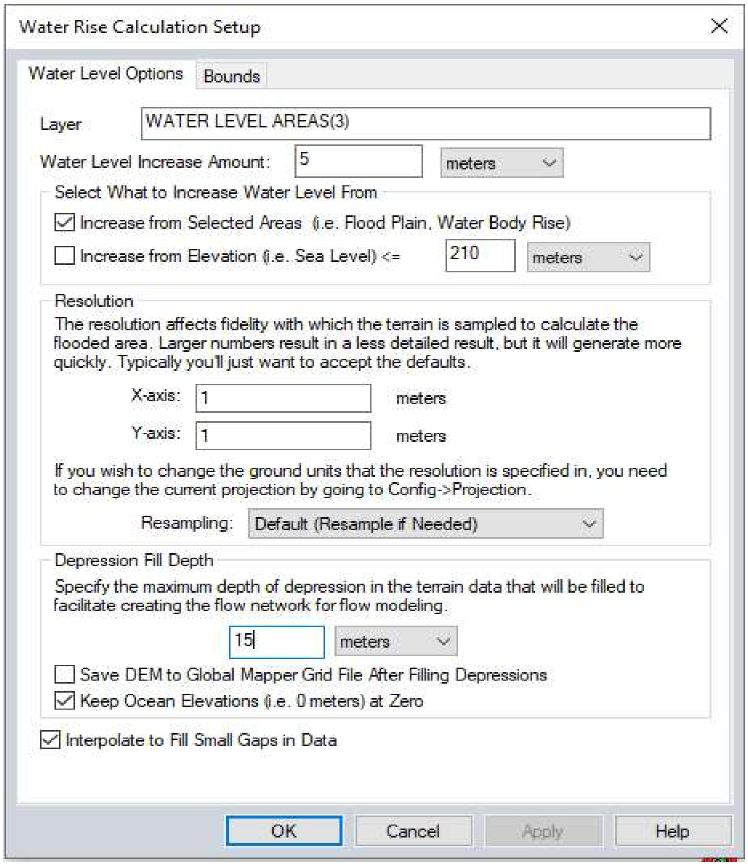
Fig. 6: Survey of the bathymetry of the Ghazipur Drain.

create an orthophoto. This orthophoto acted as a base layer for the topographical mapping of the Ghazipur Drain. Many models were created based on aerial triangulation images to describe the land in digital format like Digital Elevation Model (DEM), Digital Surface Model (DSM), and Digital Terrain Model. A DEM was first developed to illustrate the surface of the Earth in terms of elevation, including natural and artificial structures. This DEM was then filtered to generate a DSM (the upper surface of objects such as buildings and vegetation) which in turn was further manipulated to derive a DTM (ground lying surface without any above ground features). It is a digital representation of the ground surface without any objects such as buildings and vegetation, which is ideal for all-terrain viewing.

Bathymetric Integration and Topographic Modeling

Bathymetric data from the echo sounder were integrated into a Digital Terrain Model (DTM), resulting in a detailed representation of the topography, including the underwater profile of the Ghazipur Drain.

Bathymetry data are important in waterlogging analysis, particularly in urban areas, as they provide the instruments to assess the underwater land surface area of the drains/rivers/reservoirs (depicted in Fig. 6). By adding bathymetric data, UAV surveys provide complementary surface and underwater landscape data (Stark & Oskoui 1989). Such surveys allow for the recognition of the depth and shape diversity of water bodies, sedimentation, and possible areas where water stagnation occurs (Babbar et al. 2017). This is important for assessing the behavior of water in relation to urban areas, particularly in areas at risk of drainage problems or flooding (Del Savio et al. 2023). By accurately mapping underwater topography, bathymetric data can identify problematic areas that may exacerbate waterlogging following heavy rainfall or rising water levels. The images depict a bathymetric survey conducted on the Ghazipur Drain, which is essential for determining underwater depth and mapping the topography of the drain bed. A modest wooden skiff serves as a staging point, highlighting its applicability to shallow inland waterways. Manual depth-gauging devices and echo sounders pinging underwater were employed in tandem by the assessment party to chart the floor elevations via echo return intervals. Concurrently, a Differential Global Positioning System gadget geotagged sounding, ensuring



Layer: WATER LEVEL AREAS(3)

Water Level Increase Amount: 5 meters

Select What to Increase Water Level From

☑ Increase from Selected Areas (i.e. Flood Plain, Water Body Rise)

☐ Increase from Elevation (i.e. Sea Level) <= 210 meters

Resolution

The resolution affects fidelity with which the terrain is sampled to calculate the flooded area. Larger numbers result in a less detailed result, but it will generate more quickly. Typically you'll just want to accept the defaults.

X-axis: 1 meters

Y-axis: 1 meters

If you wish to change the ground units that the resolution is specified in, you need to change the current projection by going to Config->Projection.

Resampling: Default (Resample if Needed)

Depression Fill Depth

Specify the maximum depth of depression in the terrain data that will be filled to facilitate creating the flow network for flow modeling.

15 meters

☐ Save DEM to Global Mapper Grid File After Filling Depressions

☑ Keep Ocean Elevations (i.e. 0 meters) at Zero

☑ Interpolate to Fill Small Gaps in Data

Fig. 7: Configuration settings for Water Rise in Global Mapper.

high spatial precision. Supplementary geospatial metadata, including latitude, longitude, altitude, and measurement dependability, provided important contextual framing for integrating these figures with other pre-existing datasets, such as Digital Elevation Models. Occasionally, deeper pools amid intermittent sandy shallows challenged the draught of the shallow-draught vessel, yet the crew persevered in cataloguing the assorted depths. This survey mapped the underwater topography of the drain and evaluated siltation levels, potential water stagnation areas, and flow blockages. The data were then used to create detailed maps and were combined with information gathered from UAVs.

UAV configuration and bathymetric data for waterlogging analysis. The Resolution field indicates 1 m for both the X and Y-axis samples with a high-resolution terrain model. This resolution improves precision by enabling accurate delineation of terrain elements, making it critical for UAV data integration. Under the Resampling option, it defaults to default (Resample if Needed), making the data adjust automatically to the resolution needs to hold consistency between datasets. This layer was used to fill depressions so that their areas and arrangement in relation to water accumulation and movement across the terrain were understood, and the DEPTH that would take preference was set to 15 m. This also prevents isolated water masses and ensures the continuity of the surface-water-flow model. The floored DEM was saved as a Global Mapper Grid File after depression filling. We maintained Ocean Elevations at zero meters to prevent any unintentional alterations to coastal or oceanic environments while concentrating the analysis on inland waterlogging. To fill small holes in the point cloud, we turned on the interpolation option (Fig. 7), which helped to fill in the gaps and integrate UAV and bathymetric data, as our UAV data can have many gaps due to coverage limitations or obstacles during data collection. This improves the dataset and makes it more suitable for conducting research on waterlogging. High-resolution digital elevation models and bathymetric data derived from UAVs provide a near-complete picture of the land and water topography. To complement the UAV data, bathymetric measurements and depth profiles (from echo sounding) represent a first-of-its-kind data layer that identifies topographical features under the water surface that impact the dynamics of waterlogging.

This method plays a key role in urban waterlogging research because detailed topographical data is essential for analyzing drainage patterns and identifying areas that are at risk (Kumar et al. 2021). This enables the identification of low-lying regions and possible obstructions in urban drains, such as the Ghazipur Drain, through careful mapping of the terrain, including the underwater features. The Integration of UAV and bathymetric data is used as a baseline to identify land susceptible to wetness, which can be used and integrated into urban planning and maintenance plans to enhance drainage systems and reduce flooding risks in urban areas (Zhu et al. 2019).

RESULTS AND DISCUSSION

The current study provides detailed insights into the flooding hazards associated with the Ghazipur Drain in Delhi. A high-resolution Digital Elevation Model (DEM) with a 5 cm ground sample distance (GSD) was generated using UAV-based orthophotography and bathymetric data. The orthophoto (in UTM Zone 43/WGS84) provided a detailed visual aerial image of the Ghazipur Drain and the existing urban surface. Owing to the RGB spectral channels, the visualization of surface objects such as roads, buildings, and vegetation is evident; hence, the exact margins of the drain are precisely identifiable. Such visuals are necessary to ascertain areas vulnerable to waterlogging and to examine the proximity of urban sprawl to the drainage network, along with essential infrastructure such as roads and metro stations. Bathymetric data from the drain were also incorporated to refine the DEM. Such an improvement provided us with a more complete view of the subsurface terrain and surface, reducing ambiguities and enabling better quality control of elevation assessments. Based on the refined DEM, hydrological simulations were conducted to simulate different scenarios of rising water levels and detect the highly waterlogging areas under rainfall events. These hydrology simulations were performed using the "Simulate Water Level Rise" module in Global Mapper (v24), which enabled the discretization of the enhanced DEM into controlled inundation based on incremental elevation thresholds. This was done by implementing a surface of water across the grid defined on the terrain and then checking for those cells in the raster that were below the defined water elevation, effectively emulating ponding or flood propagation over the landscape. Simulated rise scenarios were created at 0.5-meter intervals from 0.5 m to 5 m, resulting in inundation extents under various severity levels. Flood-fill algorithms and raster reclassification helped to identify connected flood zones, allowing the calculation of their spatial extents.

UAV-derived topographic data were assessed and provided new insights into the spatial distribution and intensity of waterlogging in urbanized regions worldwide. This made it possible to identify areas close to the drain that can be flooded because of the poor slope and insufficient drainage ability. Furthermore, the enhanced DEM used in this study allows for accurate volume estimation of potential water accumulation in these areas, providing insights into targeted post-flooding interventions. A quantitative sensitivity analysis was performed to assess model robustness by perturbing the input DEM with synthetic elevation noise of ±0.1 m (for low-lying areas) and ±0.2 m (for mountainous areas). These perturbations simulate real-world vertical uncertainty in UAV photogrammetric products and sensor-derived bathymetry. Sensitivity test results showed that an elevation difference of ±10 cm could produce a 12–18% change in the estimated inundation area and water volumetric accumulation estimates differences of up to 15%.

Furthermore, spatial analyses revealed that the most significant discrepancies in flood extent manifested along transition zones between built-up edges and depressions with topographically ambiguous flow accumulation paths. This explains how localized errors in terrain elevation, particularly in the vicinity of bathymetric discontinuities, play an essential role in the accuracy of hydrological predictions and flood-risk areas. A UAV orthophoto was used as a digital reference to delineate the drain boundary and the surrounding infrastructure, showing where the drainage system interacts with the urban fabric. The combination of high-resolution topography and bathymetry further improved the realization of waterlogging threats and mitigation needs. These results highlight the importance of using UAV-based imagery for effective urban waterlogging management. This study provides insight into the risks associated with waterlogging, which serves as an important baseline for urban planners and policymakers to identify appropriate drainage improvements and risk management strategies to reduce flooding in certain areas or communities.

Drone-based images were referenced using ground control points in georeferencing, ensuring a high-definition aerial image of the Ghazipur Drain in Delhi, showing land cover classification outcomes (Fig. 8). With a pixel resolution of only 0.05 m, the resulting aerial image is so detailed that it shows even roads, neighborhoods, vegetation, and bodies of water in the surrounding area. The use of the WGS84 datum in UTM Zone 43 allows integration with geospatial analysis tools and corresponds with real-world coordinates. The vector overlay designates the study area, where the analysis more directly highlights drainage details, indicating where urban infrastructure interfaces with the Ghazipur Drain. The detailed visual analysis obtained from the true-color RGB bands also aids in identifying potential waterlogged areas and determining the proximity of urban infrastructure to drainage systems. Other characteristics, such as the scale bar and north arrow, help interpret the aerial photograph by providing a clear spatial context.

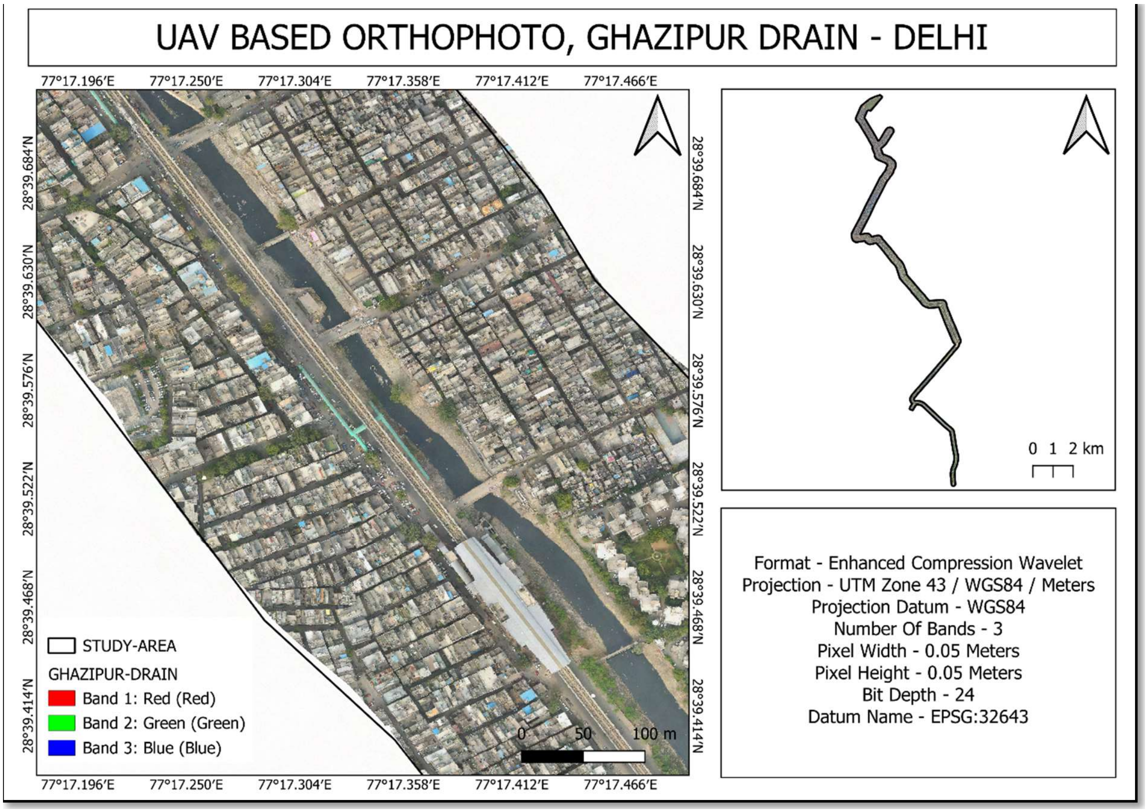


Fig. 8: Drone-based high-resolution georeferenced aerial photograph of the Ghazipur Drain in Delhi.

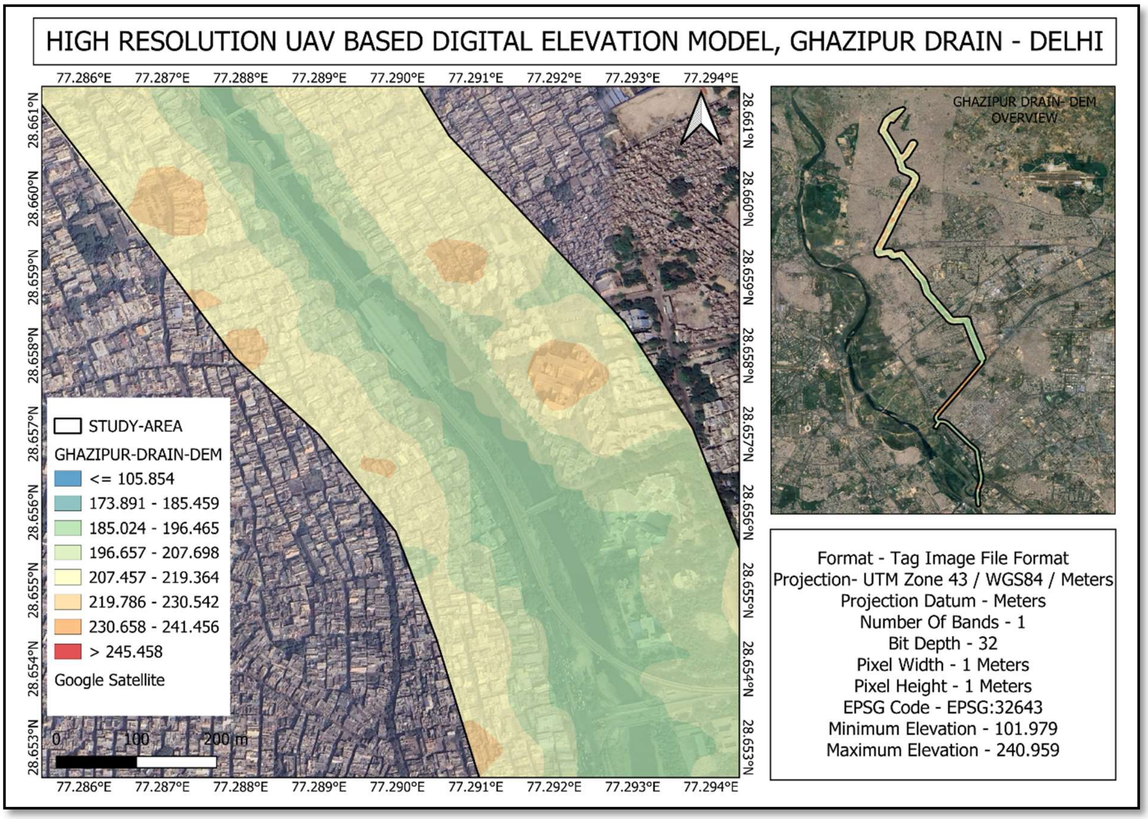


Fig. 9: High-resolution Digital Elevation Model of Ghazipur Drain, Delhi, using UAV.

A high-resolution Digital Elevation Model created from drone images and depth data from an eco-sounder provides detailed surface and subsurface information. Fig. 9 shows that the DEM shows changes in elevation of the study area from 101.979 m to 240.959 m. A color gradient was used to represent low-lying areas at risk of flooding (blue, green) and falling elevations (orange, red). With the incorporation of depth data, the DEM accurately represented the underwater topography, enhancing the visualization of drainage and elevation disparities along the Ghazipur Drain.

The well-defined Fig. 9 of the vector overlay facilitates the targeted analysis. Ground Control Points (GCPs) minimize these differences so that the DEM and orthophoto have real-world coordinates and correspond to the same pixel. The DEM, with its 1-meter resolution, provides insight into elevation modifications and their interactions with hydrological processes in the area. To put the drainage system in context with the nearby urban infrastructure, such as roads and settlements, the following overlay on Google Satellite imagery was created. The integration of UAV imagery and bathymetric data aided in pinpointing waterlogging hotspots in low-lying areas adjacent to the Ghazipur Drain. This study investigated elevation and drainage patterns using high-resolution data, offering insights into areas that require intervention to boost drainage efficiency. The orthophoto and DEM are strengths and provide a basic dataset to explore the interfacing urban environment of the Ghazipur Drain, which is necessary for flood mitigation and drainage planning.

Longitudinal profile of the Ghazipur Drain based on UAV-based DEM and bathymetric data (Fig. 10). This profile investigated the flow of the drain from north to south into the Yamuna River, while also demonstrating variation in elevation. The drain begins at 230 m in the north and slopes gradually downward to less than 150 m in the south. The ever-same gradient suggests a natural slope that can allow the natural flow of water towards the Yamuna. Combined UAV and bathymetric data facilitate effective and accurate monitoring of surface and subsurface elevation changes, as demonstrated in the longitudinal profile. The flow direction, from north to south, demonstrates the action of the drainage system and indicates stagnant and capacity-deficient areas. Elevation analysis helps to understand runoff and assists in the drainage positively, as well as negative drainage assists in better drainage management and the prevention of waterlogging in the Ghazipur Drain.

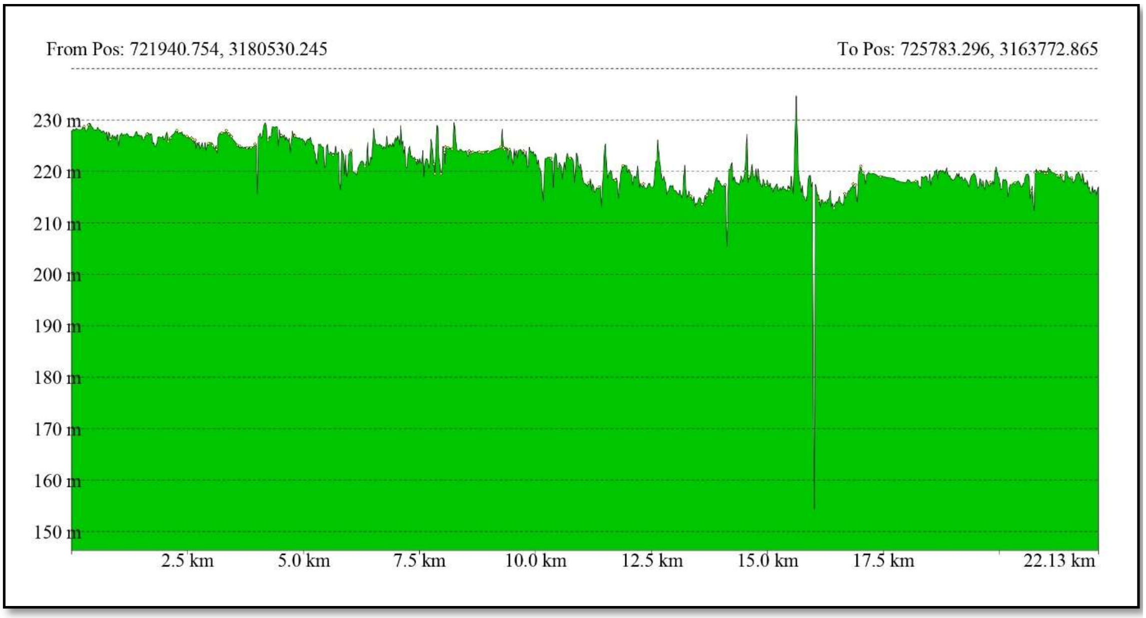


Fig. 10: Longitudinal section to track the water flow direction of Ghazipur Drain using Bathymetry and UAV-based DEM.

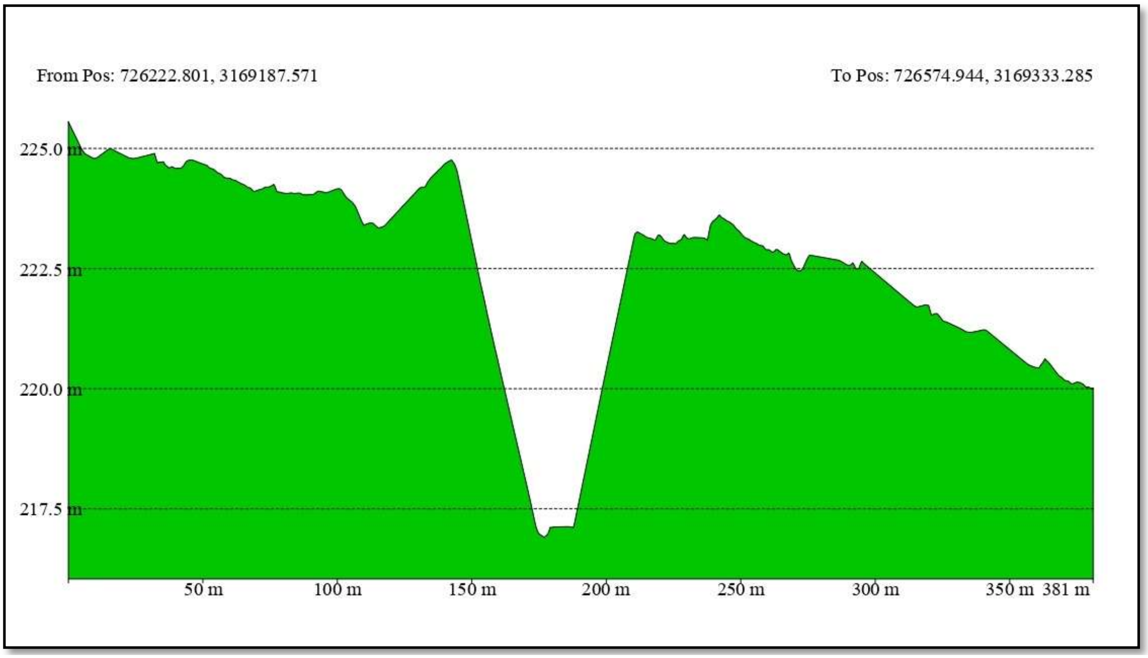
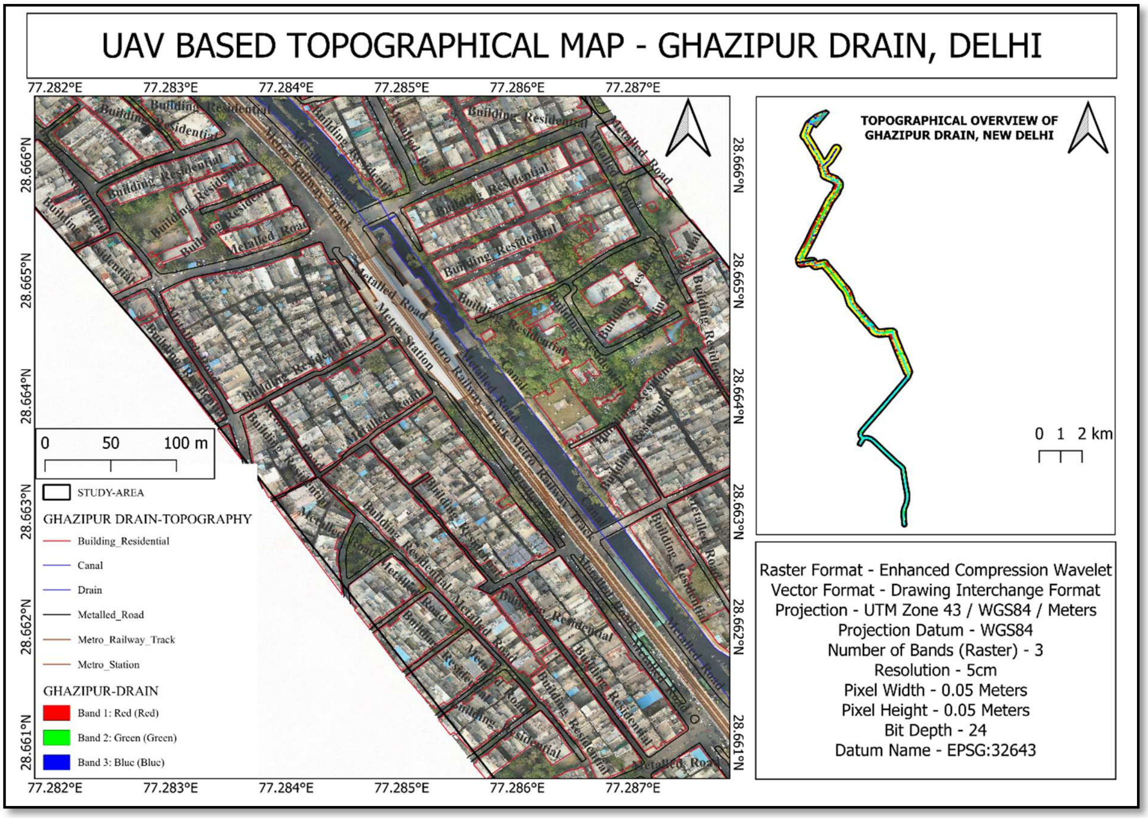


Fig. 11: Cross-section to study the topography of Ghazipur Drain using Bathymetry and UAV-based DEM.

The time-series Ghazipur Drain DEM and bathymetric data are plotted in the cross-sectional profile in Fig. 11. This profile illustrates both the surface and underwater terrain, highlighting elevation changes across the width of the drain, which clarifies the flow dynamics and identifies waterlogging hotspots. The cross-section features a concave shape with steep slopes on either side and a flat or gently sloping channel bed in the center. The edges are approximately 225m wide, and the lowest part of the channel bed is below 217.5m. Underwater changes in topography can influence the water flowing in the drain, helping to identify areas where silt builds up or obstructions can occur to inhibit flow.

Cross-sectional profiles highlight areas where drain depth or narrow sections may inhibit drainage function and identify



Raster Format - Enhanced Compression Wavelet
Vector Format - Drawing Interchange Format
Projection - UTM Zone 43 / WGS84 / Meters
Projection Datum - WGS84
Number of Bands (Raster) - 3
Resolution - 5cm
Pixel Width - 0.05 Meters
Pixel Height - 0.05 Meters
Bit Depth - 24
Datum Name - EPSG:32643

Fig. 12: High-resolution UAV-based Topographical map of Ghazipur Drain in Delhi.

waterlogging hotspots. After a splash of rain, steep slopes or a lumpy channel bed can hold up water, increasing the likelihood of localized flooding. This profile also identifies potential erosion sites and sediment transport processes, which are important for drain longevity. Understanding these topographical features is vital for planning interventions such as dredging silt deposits, repairing eroded banks, and widening constricted sections. This UAV and bathymetric data fusion provides urban planners and engineers with access to targeted improvement measures to increase the capacity of the drainage system, which will mitigate waterlogging in adjacent urban areas. The longitudinal and cross-sectional profiles highlight the need for the integration of UAV and bathymetric data to better evaluate and manage access to the Ghazipur Drain.

Fig. 12 displays a highly detailed topographical map of the Ghazipur Drain in Delhi, constructed using imagery collected by unmanned aerial vehicles and organized within a Keyhole Markup Language file for precise topological analysis. The mapping pinpoints noteworthy elements, such as the metro line running parallel to the drain. It shows eight metro stations—Gokulpuri, Maujpur, Jafrabad, Welcome, and East Azad Nagar Metro Stations, located along a 30 km corridor. The infrastructure, along with the identified 2,954 residential and commercial buildings near the drain, indicates a considerable risk of waterlogging during the monsoon. The map details 237 drainage pathways, subway tracks, metal roadways, culverts, overpasses, retaining walls, and canals, which are critical for comprehending the drainage scheme and its means to manage heavy precipitation. Amassing these layers permits a thorough assessment of the drainage framework and its interaction with urban constituents.

With metro tracks, residential areas, and commercial properties surrounding the metro drainage system, the need for specific strategies against waterlogging is reinforced. UAV aerial mapping in higher resolution makes it easy to pinpoint trouble spots, such as brooks, culverts, or areas where sediment builds up and may restrict water flow. This mapping provides fundamental spatial information to identify susceptible and waterlogging-prone areas for urban planners to develop better drainage improvement plans. This visualization highlights the significance of incorporating UAV mapping along with infrastructure mapping to enable quick action to prevent the repercussions of waterlogging in densely populated, infrastructure-dense regions during the monsoon season.

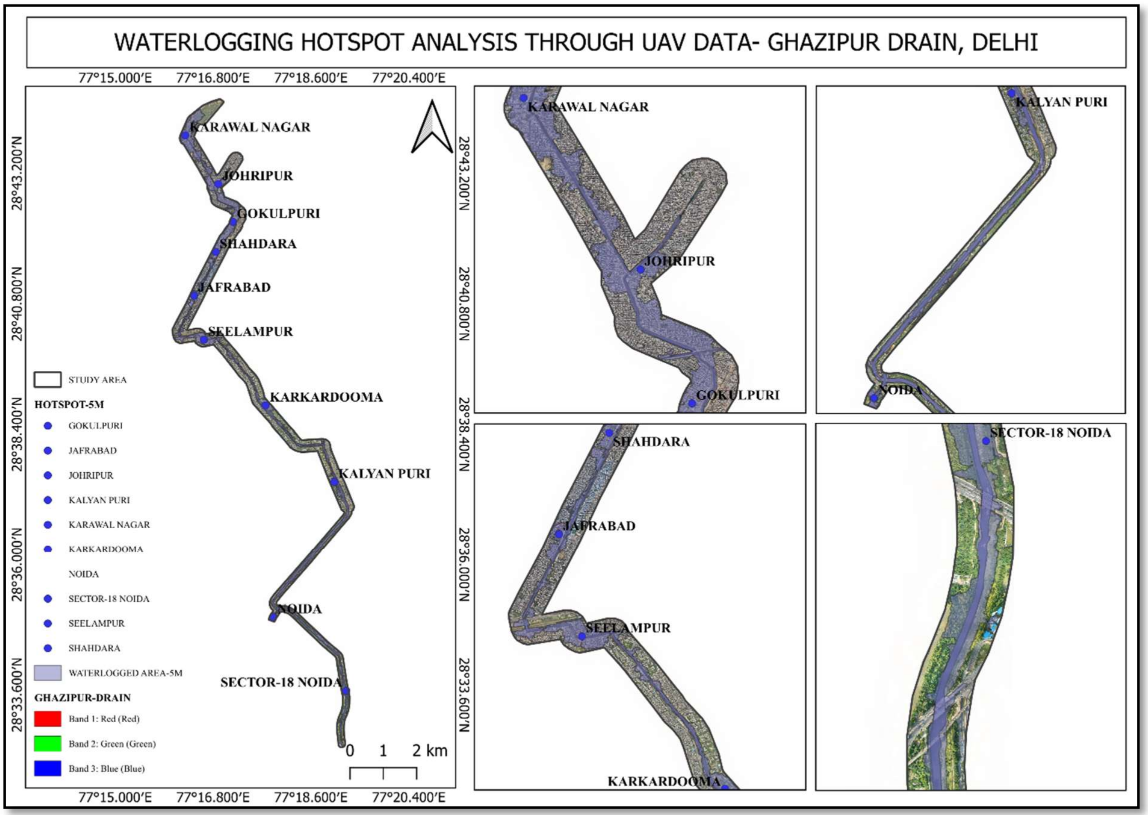


Fig. 13: Identifying Hotspot through high-resolution UAV-based dataset.

The analysis of waterlogging hotspots along the Ghazipur Drain, based on UAV-based DEM, orthophoto, and bathymetric data, indicates areas prone to extreme water level rises (Fig. 13). The analysis also suggests that a 5-meter rise in the water level can result in extensive waterlogging problems in places including Kalyan Puri, Jafrabad, Seelampur, Karawal Nagar, and parts of Noida, with about 1,120 settlements found vulnerable. These settlements, with closely knit residential and commercial structures, are in low-lying pockets without adequate drainage systems, rendering them vulnerable to urban waterlogging. Elevation data with surface mapping and subsurface profile data were leveraged to identify critical intersection hotspots of urban infrastructure with natural drainage pathways that can be a catalyst for overflow drenching during precipitation events or significant rises in water levels. The DEM illustrates these changes in elevation, with lower-lying areas near the Yamuna River, such as Kalindi Kunj at approximately 196 m, and higher elevations in Himarpur and Trilokpuri, which rise to approximately 225 m. These distinctions influence how water accumulates, and particularly low-lying regions, where water lingers for longer. High-resolution, true-color orthophotography provides a complete picture of the area around the study site, highlighting important urban elements such as road infrastructure, metro stations and residential neighborhoods. Moreover, detailed bathymetric data on the underwater profiles of the drain help determine the drainage capacity and identify sediment build-up or a bottleneck that can impede smooth water flow.

The findings also highlight the critical need for specific interventions in informal settlements and densely populated areas, where natural drainage routes are usually blocked. Metro stations such as Gokulpuri, Maujpur, Karkardooma Court, Karawal Nagar, and Seelampur are at high risk, underlining the need for better drainage and urban planning. The findings also stress the importance of regulatory measures to tackle waterlogging, highlighting the need for effective drainage designs and the minimization of construction activities in vulnerable areas. Additionally, while UAV data provide high-resolution mapping, their accuracy may be affected in areas with dense vegetation or poor visibility. The analysis used a generalized rise in water levels over the entire study area, which may not capture localized differences. Moreover, it fails to consider the effects of future urban development or climate change, such as increased rainfall intensity and frequency, which may increase the risk of waterlogging. The lack of complete ground validation also introduces uncertainty into the findings.

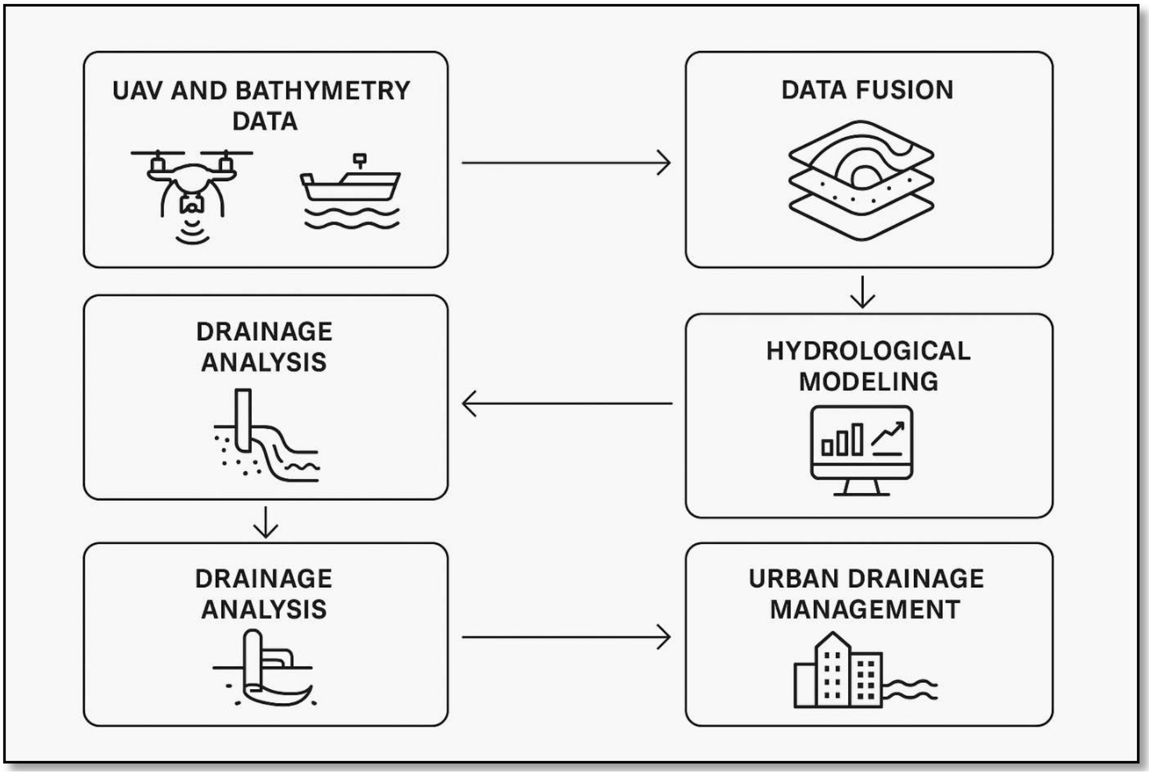


Fig. 14: Connectivity of UAV-based photogrammetry and bathymetric data with urban drainage assessments and decision-making processes.

A combination of UAV and bathymetric data can provide the scenic diversity of surface and subsurface information that is extremely valuable for waterlogging studies. UAVs produce high-resolution images for image classification, accuracy assessment, and modelling, enabling the precise detection of low-lying features, urban features, and drainage paths. A bathymetric map of the seabed provides more detailed insight into the drainage capacity and flow based on local conditions. Overall, these technologies represent powerful tools for identifying areas at risk of waterlogging, prioritizing where prevention work is needed, and directing urban planning efforts. When combined, these tools can assist urban planners in designing cities to enhance flood resilience and mitigate waterlogging issues in rapidly urbanizing regions.

To contextualize the findings, Fig. 14 illustrates the end-to-end workflow that was utilized, from UAV and bathymetric data acquisition to addressing critical drainage planning outcomes through policy recommendations. Here, both orthophotography captured via UAVs and bathymetric data helped uncover waterlogging near the intersections of the Ghazipur Drain, an important urban drainage system situated in Delhi. High-resolution digital elevation models, orthophotos, and underwater topological information collectively facilitated the examination of local topography, subsurface drainage pathways, and vulnerability to waterlogging. Longer sentences were examined alongside shorter ones to reveal a nuanced understanding of the challenges of the environment and how technical insights can inform practical solutions. According to these findings, 1,120 settlements would face the risk of a 5-metre rise in water levels in Kalyan Puri, Jafrabad, Seelampur, Karawal Nagar, and parts of Noida. Monsoons in these areas are characterized by intense rain and long periods without rain. Low elevations, dense infrastructure, and poor drainage make these areas highly prone to flooding. When this DEM is integrated with bathymetric data, a precise representation of topographic alterations along with the underwater profile is obtained, which enables the recognition of waterlogging hotspots and the development of specific mitigation measures, such as dredging and channel widening. The orthophoto shows the relationship between man-made infrastructure and natural drainage systems, with surface features such as streets, metro stations, and houses. Future analyses should complement these findings with socio-economic datasets, including population density, household income levels, housing typology, and access to infrastructure services, to enhance the policy relevance of these findings. This will allow for the identification of critically exposed communities, especially informal settlements and economically disadvantaged neighborhoods, where hydro-meteorological risks are exacerbated by socioeconomic vulnerability. This data fusion can help policymakers identify areas for potential intervention and prioritize where social risk and hydrological exposure converge, allowing for an equitable distribution of drainage upgrades and emergency services.

Waterlogging causes socio-economic drawbacks, especially for economically disadvantaged families in highly populated localities, where the immediate impacts include damage to their properties, disruption of daily lives, and increased vulnerability to water-borne diseases. Disruptions to metro stations and road networks aggravate economic impact. These results highlight the need for targeted mitigation measures, such as upgrading drainage infrastructure, tighter urban planning standards, and community-led water management programs. UAV and bathymetric data provide a more spatial context to explore runoff that may otherwise be missed using traditional methods, especially as related to silt accumulation and drainage pathways, and appear to improve existing works in most cases. While this study has strengths, it also has some limitations. Particularly, the changing waterlogging situations in regions require dynamic hydrological modeling that can better simulate the real-time effective interactions of water flow and rainfall-runoff, thereby providing more comprehensive information on water information to assist in the construction of collection and treatment systems. Future work should aim to integrate such distributed or semi-distributed hydrological models (e.g., HEC-HMS9,7, SWMM10,14, or LISFLOOD-FP12,13) to simulate the temporal dynamics of surface runoff, infiltration, and urban drainage network performance for varying precipitation intensities. Dynamic models can integrate spatially variable precipitation, drainage connectivity, surface permeability, and land use change to produce flood depth and velocity outputs in time series. Additionally, integrating real-time rainfall forecasts and future climate projections from satellite measurements (e.g., CMIP6 datasets) within these models will lead to better estimates of flood recurrence intervals, long-term risks, and consequences of climate-induced extremes. However, it is assumed that water levels rise evenly across the study area, resulting in several major assumptions, and UAV data accuracy can be affected by vegetation cover or inadequate visibility. Moreover, new urban developments and climate change may lead to worsening waterlogging risks, which were not addressed in this study. Legal and operational obstacles, such as restricted airspace and sensor range, may also limit UAV operations. To overcome these limitations, future UAV missions should adopt multispectral or LiDAR payloads that can penetrate vegetated canopies and enhance terrain accuracy. Moreover, drone surveys can be planned after the monsoon season, when vegetation is minimal, or supplemented with terrestrial laser scanning or GNSS rover ground surveying to enhance the calibration and decrease the vertical uncertainty. Legal and regulatory issues can be addressed by designing pre-approved flight corridors and working with local civil aviation authorities to obtain flight permission at emergency sites.

The findings also affect urban planning and waterlogging mitigation strategies. Immediate dredging and channel expansion should be prioritized in the at-risk areas. Rules must be changed to limit development in flood-prone areas and enable water to flow naturally. Using real-time UAV monitoring at different levels during the monsoon season can better relate to flood response and the remote periphery with decision-making levels. From a forward-looking perspective, the need for Early Warning Systems (EWS) that encompass UAV-derived topography combined with Internet-of-Things (IoT) sensor networks for real-time collection of rainfall, flow, and water level data needs to be considered. When incorporated into decision-support frameworks, these systems can enable early evacuation planning, drainage gate management and crisis coordination. Future research should combine climate change projections to improve the understanding of long-term waterlogging trends. This study showed that UAV-based data and bathymetric analysis can considerably improve flood resilience in urban areas. Information on the quality of surface/subsurface topography helps with effective water management practices. Adopting this scalable and replicable approach is an effective solution for reducing risk and ensuring that urban drainage infrastructure can keep pace with growing urbanization and climate change.

CONCLUSIONS

The findings of this study highlight the success of the high-tech integration of UAV-based orthophotography and bathymetric datasets in identifying urban waterlogging problems, especially in examining the Ghazipur Drain in Delhi. The research produces high-resolution Digital Elevation Models (DEMs) and merges them with sub-surface bathymetric profiles to provide a comprehensive understanding of both surface and underwater drainage dynamics. The findings identify critical waterlogging hotspots, indicating that nearly 1,120 communities in low-lying areas, such as Kalyan Puri, Jafrabad, Seelampur, Karawal Nagar, and parts of Noida, are especially vulnerable to flooding after heavy rainfall or significant water level rises.

These data underline the critical need for targeted interventions in the form of dredging, extracting sediments, widening channels, and also improving urban planning to prevent overflooding. This combination of UAV and bathymetric data affords unprecedented spatial and temporal precision, allowing scientists to identify watershed inefficiencies in drainage and sedimentation that previous methods may have missed. Orthophotos capture fine details of the surface and give planners a unique opportunity to evaluate the current situation to determine whether a risk management strategy is viable for sustainable urban growth regarding drainage. They also highlight the socio-economic impact of waterlogging on vulnerable communities, infrastructure, public health, and the local economy. study has limitations, including the lack of dynamic hydrological modeling, localized water level changes, urban development or climate change considerations. Filling these gaps with future research will improve the projected efficacy and relevance of these strategies. The adoption of this technology will also rely heavily on overcoming operational issues associated with UAV deployment and refining the regulatory frameworks surrounding it.

This study shows that UAV-bathymetry can be used to develop a scalable, accurate, low-cost response to urban waterlogging. The findings provide valuable insights for policymakers, urban planners, and engineers to prioritize initiatives to improve drainage systems and increase flood resilience in fast-growing urban areas. By combining high-resolution and real-time data, this formulation builds the basis for preventing the risk of waterlogging, which would be a challenge forage system in the future owing to urbanization and climate change.

REFERENCES

Acharya, B.S., Bhandari, M., Bandini, F., Pizarro, A., Perks, M., Joshi, D.R., Wang, S., Dogwiler, T., Ray, R.L., Kharel, G. and Sharma, S., 2021. Unmanned aerial vehicles in hydrology and water management: applications, challenges, and perspectives. *Water Resources Research*, 57(11), pp.1–18. [DOI]

Annis, A., Nardi, F., Petroselli, A., Apollonio, C., Arcangeletti, E., Tauro, F., Belli, C., Bianconi, R. and Grimaldi, S., 2020. UAV-DEMs for small-scale flood hazard mapping. *Water*, 12(6), p.1717. [DOI]

Apel, H., Thieken, A.H., Merz, B. and Blöschl, G., 2004. Flood risk assessment and associated uncertainty. *Natural Hazards and Earth System Sciences*, 4(2), pp.295–308. [DOI]

Babbar, P., Verma, S. and Mehmood, G., 2017. Groundwater contamination from non-sanitary landfill sites – a case study on the Ghazipur landfill site, Delhi (India). *International Journal of Applied Environmental Sciences*, 12(11), pp.1969–1991. [DOI]

Banolia, C., Prabhakar, K.R. and Deshpande, S., 2023. Monitoring urban flooding using SAR—A Mumbai case study. In: *Lecture Notes in Networks and Systems*. Springer, pp.59–68. [DOI]

Bates, P.D., Horritt, M.S. and Fewtrell, T.J., 2010. A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. *Journal of Hydrology*, 387(1–2), pp.33–45. [DOI]

Berghuijs, W.R., Woods, R.A. and Hrachowitz, M., 2014. A precipitation shift from snow towards rain leads to a decrease in streamflow. *Nature Climate Change*, 4(7), pp.583–586. [DOI]

Bilașco, Ș., Hognogi, G.G., Roșca, S., Pop, A.M., Iuliu, V., Fodorean, I., Marian-Potra, A.C. and Sestraș, P., 2022. Flash flood risk assessment and mitigation in digital-era governance using unmanned aerial vehicle and GIS spatial analyses case study: small river basins. *Remote Sensing*, 14(10), p.2481. [DOI]

Brakenridge, G.R., Nghiem, S.V., Anderson, E. and Mic, R., 2007. Orbital microwave measurement of river discharge and ice status. *Water Resources Research*, 43(4), pp.1–12. [DOI]

Chai, T. and Draxler, R.R., 2014. Root mean square error (RMSE) or mean absolute error (MAE)? – Arguments against avoiding RMSE in the literature. *Geoscientific Model Development*, 7(3), pp.1247–1250. [DOI]

Darji, K., Vyas, U.K., Patel, D., Singh, S.K., Dubey, A.K., Gupta, P. and Singh, R.P., 2024. UAV based comprehensive modelling approach for flood hazard assessment and mitigation planning. *Physics and Chemistry of the Earth Parts A/B/C*, 135, p.103609. [DOI]

Del Savio, A.A., Luna Torres, A., Vergara Olivera, M.A., Llimpe Rojas, S.R., Urday Ibarra, G.T. and Neckel, A., 2023. Using UAVs and photogrammetry in bathymetric surveys in shallow waters. *Applied Sciences*, 13(6), p.3420. [DOI]

Diwate, P., Lavhale, P., Pande, C.B., Sammen, S.S., Refadah, S.S., Khan, Y.A., Elkhrachy, I. and Salem, A., 2025. Evaluating flood dynamics and effects in Nagpur city using remote sensing and Shannon's entropy analysis. *Scientific Reports*, 15(1). [DOI]

Fewtrell, T.J., Duncan, A., Sampson, C.C., Neal, J.C. and Bates, P.D., 2010. Benchmarking urban flood models of varying complexity and scale using high resolution terrestrial LiDAR data. *Physics and Chemistry of the Earth Parts A/B/C*, 36(7–8), pp.281–291. [DOI]

Fleischmann, A., Paiva, R. and Collischonn, W., 2019. Can regional to continental river hydrodynamic models be locally relevant? A cross-scale comparison. *Journal of Hydrology X*, 3, p.100027. [DOI]

Gautam, S., J., B. and R., D., 2020. Spatio-temporal estimates of solid waste disposal in an urban city of India: A remote sensing and GIS approach. *Environmental Technology & Innovation*, 18, p.100650. [DOI]

Glendenning, C.J., van Ogtrop, F.F., Mishra, A.K., Vervoort, R.W., Garg, K.K., George, B., Acharya, S., Jella, K., Narasimhan, B. and Kumar, M.D., 2012. Balancing watershed and local scale impacts of rain water harvesting in India—A review. *Agricultural Water Management*, 107, pp.1–13. [DOI]

Karamuz, E., Romanowicz, R.J. and Doroszkiewicz, J., 2020. The use of unmanned aerial vehicles in flood hazard assessment. *Journal of Flood Risk Management*, 13(4). [DOI]

Kumar, P., Debele, S.E., Sahani, J., Rawat, N., Marti-Cardona, B., Alfieri, S.M., Basu, B., Basu, A.S., Bowyer, P., Charizopoulos, N., Juvonen, J., Loupis, M., Menenti, M., Mickovski, S.B., Pfeiffer, J., Pilla, F., Pröll, J., Pulvirenti, B., Rutzinger, M., Sannigrahi, S., Spyrou, C., Tuomenvirta, H., Vojinovic, Z. and Zieher, T., 2021. An overview of monitoring methods for assessing the performance of nature-based solutions against natural hazards. *Earth-Science Reviews*, 217, p.103603. [DOI]

Li, B., Hou, J., Li, D., Yang, D., Han, H., Bi, X., Wang, X., Hinkelmann, R. and Xia, J., 2021. Application of LiDAR UAV for high-resolution flood modelling. *Water Resources Management*, 35(5), pp.1433–1447. [DOI]

Mahanta, A.R., Rawat, K.S., Kumar, N., Szabo, S., Srivastava, P.K. and Singh, S.K., 2023. Assessment of multi-source satellite products using hydrological modelling approach. *Physics and Chemistry of the Earth*, p.103507. [DOI]

Medvedev, A., Telnova, N., Alekseenko, N., Koshkarev, A., Kuznetchenko, P., Asmaryan, S. and Narykov, A., 2020. UAV-derived data application for environmental monitoring of the coastal area of Lake Sevan, Armenia with a changing water level. *Remote Sensing*, 12(22), p.3821. [DOI]

Meshram, P.K., Rawat, K.S. and Singh, G., 2024. Kharif rice crop acreage and yield estimation using microwave and optical remote sensing time series satellite data: A case study of the eastern region of Maharashtra. *Acta Scientiarum Polonorum*, 23(2), pp.112–128. [DOI]

Nielsen, K.M.E., Duddu, H.S.N., Bett, K.E. and Shirtliffe, S.J., 2022. UAV image-based crop growth analysis of 3D-reconstructed crop canopies. *Plants*, 11(20), p.2691. [DOI]

OECD, 2024. *Compendium of Good Practices on Quality Infrastructure 2024: Building Resilience to Natural Disasters*. OECD Publishing. https://www.oecd.org/content/dam/oecd/en/publications/reports/2024/04/compendium-of-good-practices-on-quality-infrastructure-2024_7c2782d4/54d26e88-en.pdf.

Parizi, E., Khojeh, S. and Hosseini, S.M., 2022. Application of unmanned aerial vehicle DEM in flood modeling and comparison with global DEMs: Case study of Atrak River Basin, Iran. *Journal of Environmental Management*, 317, p.115492. [DOI]

Quamar, M.M., Al-Ramadan, B., Khan, K., Shafiullah, M., and El Ferik, S., 2023. Advancements and applications of drone-integrated geographic information system technology—A review. *Remote Sensing*, 15(20), p.5039. [DOI]

Raj, S. and Rawat, K.S., 2024. A morphometric and multivariate analysis approach to prioritization of sub-watershed: A case study on Muzaffarpur District of Bihar, India. *Acta Scientiarum Polonorum*, 23(1), pp.37–54. [DOI]

Raj, S., Rawat, K.S. and Singh, S.K., 2022. Groundwater potential zones identification and validation in Peninsular India. *Geology, Ecology, and Landscapes*, *8*(1), pp.86-100. [DOI]

Rakha, T. and Gorodetsky, A., 2018. Review of unmanned aerial system (UAS) applications in the built environment: Towards automated building inspection procedures using drones. *Automation in Construction*, 93, pp.252–264. [DOI]

Rawat, K.S., Singh, S.K. and Singh, M.I., 2019. Comparative evaluation of vertical accuracy of elevated points with ground control points from ASTERDEM and SRTMDEM with respect to CARTOSAT-1DEM. *Remote Sensing Applications: Society and Environment*, 13, pp.289–297. [DOI]

Rawat, K.S. and Panwar, G.S., 2024. Mapping flooded areas utilizing Google Earth Engine and open SAR data: A comprehensive approach for disaster response. *Discover Geoscience*. [DOI].

Rossi, L., Mammi, I. and Pelliccia, F., 2020. UAV-derived multispectral bathymetry. *Remote Sensing*, 12(23), p.3897. [DOI]

Saponaro, M., Capolupo, A., Caporusso, G., Borgogno Mondino, E. and Tarantino, E., 2020. Predicting the accuracy of photogrammetric 3D reconstruction from camera calibration parameters through a multivariate statistical approach. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLIII-B2-2020, pp.479–486. [DOI]

Shau, S.R., Rawat, K.S., Singh, S.K. and Gupta, K.K., 2024. Analysis of drainage morphometry and spectral indices using earth observation datasets in Palar river basin. *Discover Geoscience*. [DOI]

Sihombing, Y.I., Rizaldi, A., Farid, M., Januriyadi, N.F. and Moe, I.R., 2023. 2023. Jakarta's 2020 New Year flood assessment with a Rainfall–Runoff–Inundation (RRI) model. *MDPI Proceedings*, 3 April. [DOI]

Sott, M.K., Furstenau, L., Imran, M., Abbasi, Q.H., Kremer, M., Alazab, M., Rodrigues, J.J.P.C., Figueiredo, V.A.C., Campos, M. and Silva, A., 2020. Precision techniques and Agriculture 4.0 technologies to promote sustainability in the coffee sector: State of the art, challenges and future trends. *IEEE Access*, 8, pp.149854–149867. [DOI]

Stark, H. and Oskoui, P., 1989. High-resolution image recovery from image-plane arrays using convex projections. *Journal of the Optical Society of America A*, 6(11), pp.1715-1725. [DOI]

Suzuki, T., 2020. Time-relative RTK-GNSS: GNSS loop closure in pose graph optimization. *IEEE Robotics and Automation Letters*, 5(3), pp.4735-4742. [DOI]

Tomar, P., Singh, R., Verma, A. and Gupta, S., 2021. GIS-based urban flood risk assessment and management—A case study of Delhi National Capital Territory (NCT), India. *Sustainability*, 13(22), pp.12850-12865. [DOI]

Uwaechia, A.N. and Mahyuddin, N.M., 2020. A comprehensive survey on millimeter wave communications for fifth-generation wireless networks: feasibility and challenges. *IEEE Access*, 8, pp.62367-62414. [DOI]

Wawrzyniak, V., Smith, J., Lee, C. and Brown, P., 2016. Effects of geomorphology and groundwater level on the spatio-temporal variability of riverine cold water patches assessed using thermal infrared (TIR) remote sensing. *Remote Sensing of Environment*, 175, pp.337-348. [DOI]

Wienhold, K.J., Miller, D., Zhao, L. and Ahmed, R., 2023. Flood inundation and depth mapping using unmanned aerial vehicles combined with high-resolution multispectral imagery. *Hydrology*, 10(8), pp.158-172. [DOI]

Yalcin, E., 2018. Two-dimensional hydrodynamic modelling for urban flood risk assessment using unmanned aerial vehicle imagery: a case study of Kirsehir, Turkey. *Journal of Flood Risk Management*, 12(S1), pp.25-38. [DOI]

Yao, H., Qin, R. and Chen, X., 2019. Unmanned aerial vehicle for remote sensing applications—A review. *Remote Sensing*, 11(12), pp.1443-1458. [DOI]

Zhi, G., Li, W., Chen, J. and Wang, H., 2020. Urban flood risk assessment and analysis with a 3D visualization method coupling the PP-PSO algorithm and building data. *Journal of Environmental Management*, 268, pp.110521-110536. [DOI]

Zhu, Z., Wang, Y., Liu, H. and Zhang, X., 2019. Distortion correction method of a zoom lens based on the vanishing point geometric constraint. *Measurement Science and Technology*, 30(10), pp.105402-105415. [DOI]