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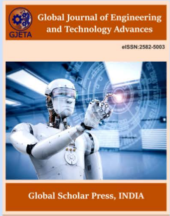

(REVIEW ARTICLE)

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A comprehensive review of flood inundation mapping using HEC-RAS: Advances, challenges, and future perspectives

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Abstract

Floods are among the most destructive natural hazards, causing severe damage to human life, infrastructure, agriculture, and the environment. Accurate flood inundation mapping is essential for effective flood risk management, emergency response, and sustainable land-use planning. The Hydrologic Engineering Center's River Analysis System (HEC-RAS) has become one of the most widely used hydraulic modeling tools for flood inundation studies due to its accessibility, reliability, and continuous technical improvements. This review presents a comprehensive assessment of flood inundation mapping using HEC-RAS, highlighting recent advances, key challenges, and future research opportunities. The study examines the evolution of HEC-RAS from conventional one-dimensional (1D) steady-flow models to advanced two-dimensional (2D) unsteady-flow simulations capable of representing complex floodplain dynamics. Integration with Geographic Information Systems (GIS), remote sensing, LiDAR-derived Digital Elevation Models (DEMs), and climate datasets has significantly enhanced the accuracy and applicability of flood mapping. Recent developments such as real-time forecasting, coupled hydrologic-hydraulic modeling, and machine learning-assisted calibration are also reviewed. Despite these advancements, several challenges remain, including uncertainty in terrain data, boundary conditions, Manning's roughness coefficients, computational limitations, and lack of reliable hydrological data in ungauged regions. Urban flood modeling also remains complex because of drainage systems, impervious surfaces, and rapid land-use changes. Future research should focus on high-resolution data integration, artificial intelligence for rapid prediction, IoT-based monitoring systems, and climate-resilient flood management strategies. Overall, this review highlights the growing importance of HEC-RAS as a robust decision-support tool for flood hazard assessment and provides guidance for researchers, engineers, and policymakers to improve flood resilience through advanced inundation mapping practices.

Keywords: Flood Inundation Mapping; HEC-RAS; Hydraulic Modeling; Flood Risk Assessment; GIS; Remote Sensing; 2D Flood Simulation; Hydrodynamic Modeling; LiDAR; Climate Change Adaptation.

1. Introduction

Floods are among the most frequent and destructive natural disasters worldwide, causing significant loss of life, economic damage, environmental degradation, and disruption to social systems. In recent decades, rapid urbanization, deforestation, encroachment into floodplains, and climate change have increased both the frequency and severity of flood events. Extreme rainfall, river overflow, inadequate drainage systems, and changing land-use patterns further intensify flood hazards, particularly in developing nations. Therefore, accurate flood hazard assessment and inundation mapping have become essential tools for disaster preparedness, emergency planning, infrastructure protection, and sustainable water resources management [10,15].

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Flood inundation mapping refers to the identification and spatial representation of areas likely to be submerged during flood events under various hydrological scenarios. These maps provide critical information such as flood depth, velocity, duration, and extent, which are valuable for evacuation planning, insurance assessment, floodplain zoning, and risk mitigation strategies. Traditionally, flood mapping was carried out using historical flood records and empirical approaches. However, advancements in computational hydraulics, geospatial technologies, and remote sensing have enabled the use of sophisticated numerical models for more reliable flood prediction [3,10].

Among the various hydraulic modeling tools available today, the Hydrologic Engineering Center's River Analysis System (HEC-RAS), developed by the U.S. Army Corps of Engineers, is one of the most widely used software platforms for river hydraulics and floodplain analysis. HEC-RAS was originally designed for one-dimensional (1D) steady-flow water surface profile analysis in natural rivers and artificial channels. Over the years, the software has evolved substantially to include unsteady flow simulations, sediment transport modeling, bridge and culvert hydraulics, dam-break analysis, water quality modules, and more recently, two-dimensional (2D) hydrodynamic flood modeling capabilities [1,2].

The introduction of 2D modeling has significantly improved the ability of HEC-RAS to simulate complex floodplain processes such as lateral flow spreading, storage effects, multiple flow paths, and urban surface runoff interactions. Unlike conventional 1D models, which assume flow movement only along the channel centerline, 2D models solve shallow water equations over a computational mesh and can represent flood dynamics more realistically. This has made HEC-RAS highly effective for urban flood studies, braided rivers, floodplain wetlands, and dam-break scenarios [5,8].

The accuracy of flood inundation mapping largely depends on the quality of terrain and hydrological input data. In this context, integration of HEC-RAS with Geographic Information Systems (GIS) has greatly improved model development and visualization. GIS tools such as HEC-GeoRAS and RAS Mapper enable efficient extraction of river geometry, cross-sections, floodplain boundaries, and land-use characteristics from Digital Elevation Models (DEMs). High-resolution terrain data derived from LiDAR surveys have further enhanced the precision of flood extent and depth predictions by accurately capturing levees, embankments, buildings, and channel features [9,14]. Remote sensing data from satellites such as Landsat, Sentinel, and Synthetic Aperture Radar (SAR) are also increasingly used for calibration and validation of flood inundation maps [4,10].

Despite these advancements, several challenges remain in HEC-RAS-based flood modeling. Model uncertainty is one of the most critical issues and arises from inaccuracies in topographic data, inflow hydrographs, boundary conditions, and Manning's roughness coefficients. The selection of roughness values strongly influences simulated water levels and inundation extent, especially in vegetated floodplains and urban areas. In many developing or ungauged watersheds, the lack of reliable rainfall, discharge, and channel survey data reduces model performance and increases prediction uncertainty [7,13].

Another major challenge is the computational requirement of high-resolution 2D simulations, especially for large watersheds or long-duration storm events. As grid size decreases to improve spatial detail, processing time and memory demand increase substantially. Urban flood modeling is even more complex due to stormwater drainage networks, road embankments, buildings, impervious surfaces, and localized pluvial flooding. Therefore, researchers increasingly recommend coupling HEC-RAS with hydrologic and stormwater models for integrated flood assessment [6,16].

In recent years, emerging technologies such as machine learning, cloud computing, and Internet of Things (IoT) sensors have created new opportunities to improve flood inundation mapping. Machine learning methods can support parameter calibration, surrogate modeling, and rapid flood forecasting. Cloud-based computing platforms enable large-scale simulations with faster processing times, while IoT-based rainfall and water-level sensors provide real-time data for dynamic flood forecasting systems. These developments have the potential to transform HEC-RAS into a powerful real-time decision-support tool for flood management and early warning applications [11,12].

Considering the increasing flood risk under climate change and rapid urban development, a comprehensive review of flood inundation mapping using HEC-RAS is both timely and necessary. This review focuses on recent advances in hydraulic modeling, GIS integration, remote sensing applications, uncertainty analysis, and real-time forecasting. It also identifies major challenges and future research needs to improve model accuracy, computational efficiency, and applicability. The findings are expected to support researchers, engineers, planners, and policymakers in developing more resilient and science-based flood management strategies [10,17].

2. Impact of flood inundation using Software

Flood inundation software tools such as HEC-RAS, MIKE FLOOD, SWMM, ArcGIS, and QGIS are widely used to analyze the impacts of flood inundation on people, infrastructure, environment, and the economy. These software platforms simulate flood depth, velocity, extent, and duration under different rainfall and river flow conditions, helping engineers and planners understand flood consequences and prepare mitigation strategies.

2.1. Social Impact Assessment

Flood inundation software helps identify affected population zones, residential areas, schools, hospitals, and evacuation routes. By mapping vulnerable communities, authorities can improve disaster preparedness, rescue operations, and shelter planning. Population exposure maps are especially useful in densely populated urban regions.

2.2. Economic Impact Analysis

Software-based flood mapping estimates damage to roads, bridges, buildings, industries, agriculture, and utilities. By overlaying flood extent with land-use and property data in GIS, direct and indirect economic losses can be quantified. This supports insurance planning and cost-benefit analysis of flood protection projects.

2.3. Infrastructure Impact

Flood models evaluate the performance of bridges, culverts, embankments, dams, drainage systems, and transport networks during extreme events. Engineers use these results to redesign weak structures, improve drainage capacity, and strengthen resilient infrastructure.

2.4. Environmental Impact

Flood inundation software can assess erosion, sediment transport, wetland flooding, contamination spread, and river morphology changes. It is useful for watershed restoration and ecological conservation planning.

2.5. Climate Change Impact

By applying future rainfall and discharge scenarios, software tools help predict how climate change may increase flood frequency and inundation area. This supports long-term urban planning and adaptive flood management.

2.6. Decision-Making and Early Warning

Real-time flood forecasting systems integrated with sensors and hydraulic software provide early warnings, reducing loss of life and property.

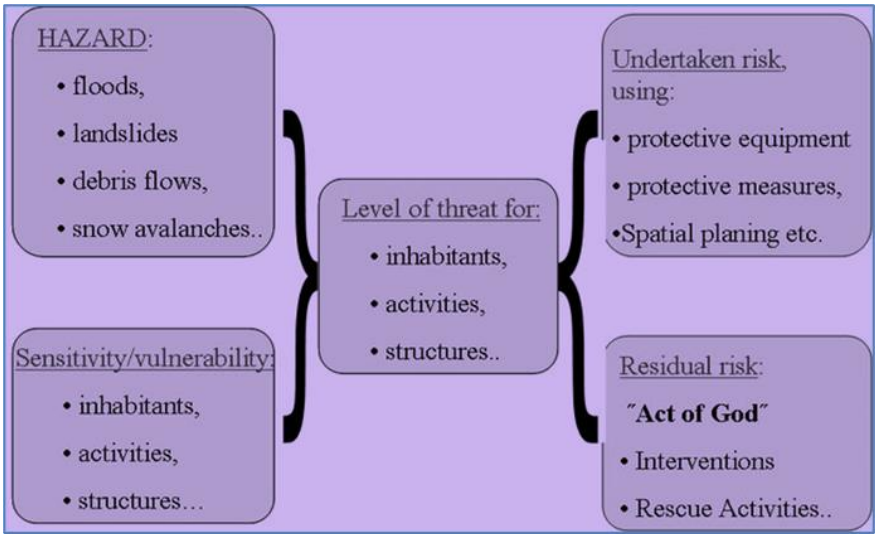

Figure 1 Threat Evaluation Criteria

In Fig 1 indicates the Evaluation Criteria of threat are the parameters used to assess the severity, likelihood, and potential consequences of hazards such as floods, earthquakes, industrial accidents, cyberattacks, or security incidents.

These criteria help decision-makers prioritize risks, allocate resources, and develop effective mitigation strategies. In flood inundation and disaster management studies, threat evaluation is essential for identifying vulnerable zones and minimizing damage. This criterion measures the likelihood that a threat or hazard will occur within a specific time period. Historical records, climate data, rainfall intensity, and return period analysis are commonly used to estimate probability. Events with higher recurrence rates are considered more critical.

Severity refers to the magnitude of damage caused by the threat. It may include loss of life, injuries, economic losses, infrastructure damage, environmental degradation, and service disruption. Higher severity threats require urgent planning and stronger control measures.

Exposure evaluates the number of people, buildings, roads, utilities, and assets located in the hazard-prone area. Densely populated and economically important areas are considered highly exposed and more vulnerable to threats.

Vulnerability indicates how susceptible a system or community is to damage. Poor construction quality, inadequate drainage, weak emergency systems, poverty, and lack of awareness increase vulnerability levels.

This criterion assesses whether the threat can be predicted or detected early enough for response actions. Hazards with short warning times, such as flash floods, are more dangerous than those with longer lead times. Recovery time represents the duration required to restore normal conditions after the event. Threats causing long-term disruption to transport, water supply, power, or livelihoods are considered high priority.

The availability of emergency services, evacuation plans, shelters, communication systems, and technical resources influences threat impact. Better preparedness reduces overall risk.

Based on the above criteria, threats are ranked as low, moderate, high, or very high using scoring methods, matrices, or GIS-based analysis.

3. Challenges, and Future Perspectives

Flood inundation mapping using HEC-RAS has significantly advanced over the past two decades; however, several technical, practical, and data-related challenges still limit its full potential. Addressing these issues is essential for improving model accuracy, reliability, and real-world applicability in flood risk management. At the same time, emerging technologies and interdisciplinary approaches provide promising future directions for next-generation flood modeling systems.

3.1. Challenges in Flood Inundation Mapping Using HEC-RAS

One of the major challenges in HEC-RAS-based flood modeling is the availability and quality of input data. Accurate terrain information is critical because Digital Elevation Models (DEMs) directly influence flood depth, flow paths, and inundation extent. Low-resolution DEMs may fail to capture levees, drainage channels, embankments, and urban obstacles, resulting in significant simulation errors [9,13]. In many developing countries, high-resolution LiDAR data are either unavailable or expensive, limiting model precision.

Another important challenge is uncertainty in hydrological boundary conditions such as rainfall intensity, inflow hydrographs, downstream water levels, and sediment load. Flood models are highly sensitive to these inputs, and small errors can produce large variations in flood extent and water surface elevations. Similarly, selection of Manning's roughness coefficient remains a difficult task because roughness varies spatially with vegetation, channel material, land use, and seasonal conditions [7,10].

Urban flood simulation presents additional complexity. Conventional river-based HEC-RAS models may not fully represent stormwater drainage systems, sewer overflows, road networks, and building interactions. Rapid urbanization and land-use change continuously alter runoff behavior, making calibration more difficult [16]. Furthermore, high-resolution 2D unsteady flow simulations require substantial computational resources, especially for large watersheds or long-duration storm events.

Validation is another challenge because observed flood extent, water depth, and velocity data during extreme flood events are often limited or unavailable. Without proper validation, model confidence and practical adoption may be reduced [4,15].

3.2. Future Perspectives

Future flood inundation mapping using HEC-RAS is expected to benefit greatly from advancements in geospatial technologies, artificial intelligence, and real-time monitoring systems. High-resolution LiDAR, drone-based photogrammetry, and satellite remote sensing can improve terrain representation and post-flood validation [9,14].

Artificial intelligence and machine learning techniques can be integrated with HEC-RAS for automatic calibration of Manning's coefficients, rapid flood prediction, and uncertainty analysis. These hybrid approaches can reduce computation time while maintaining acceptable accuracy [11,12].

Cloud computing and high-performance computing platforms will allow faster processing of large 2D models and ensemble flood scenarios. This is particularly valuable for real-time flood forecasting and emergency response systems. Integration with Internet of Things (IoT) sensors for rainfall, river stage, and flow monitoring can enable dynamic model updating and early warning systems.

Another promising direction is the development of digital twin river basins, where real-time field data continuously interact with hydraulic models for predictive flood management. Climate change scenario modeling will also become increasingly important for designing resilient infrastructure and adaptive land-use policies [10,17].

Overall, overcoming current challenges through advanced data integration, intelligent algorithms, and real-time decision-support frameworks will strengthen the role of HEC-RAS as a powerful tool for sustainable flood risk management.

4. Methodology

The methodology of flood risk mapping involves a systematic integration of hydrological, hydraulic, and geospatial techniques to identify areas vulnerable to flooding and estimate potential impacts. Initially, relevant datasets such as Digital Elevation Model (DEM), rainfall records, river discharge data, land use/land cover maps, soil characteristics, population distribution, and historical flood records are collected from reliable sources. These data are processed in GIS and remote sensing platforms for spatial analysis. Hydrological and hydraulic models such as HEC-RAS are then used to simulate flood behavior, including water depth, flow velocity, inundation extent, and flood duration under different return periods. The hazard outputs are overlaid with exposure layers representing settlements, agricultural lands, transport networks, and public infrastructure to identify assets located in flood-prone regions. Vulnerability assessment is further carried out by considering socio-economic conditions, building characteristics, population density, and emergency response capacity. The overall flood risk is estimated by combining hazard, exposure, and vulnerability indices through weighted overlay or multi-criteria decision-making methods in GIS. Finally, the generated flood risk maps are validated using past flood events, satellite imagery, and field observations to improve accuracy and reliability. These maps serve as valuable tools for disaster management authorities, urban planners, and policymakers in implementing mitigation strategies, land use planning, and emergency preparedness measures.

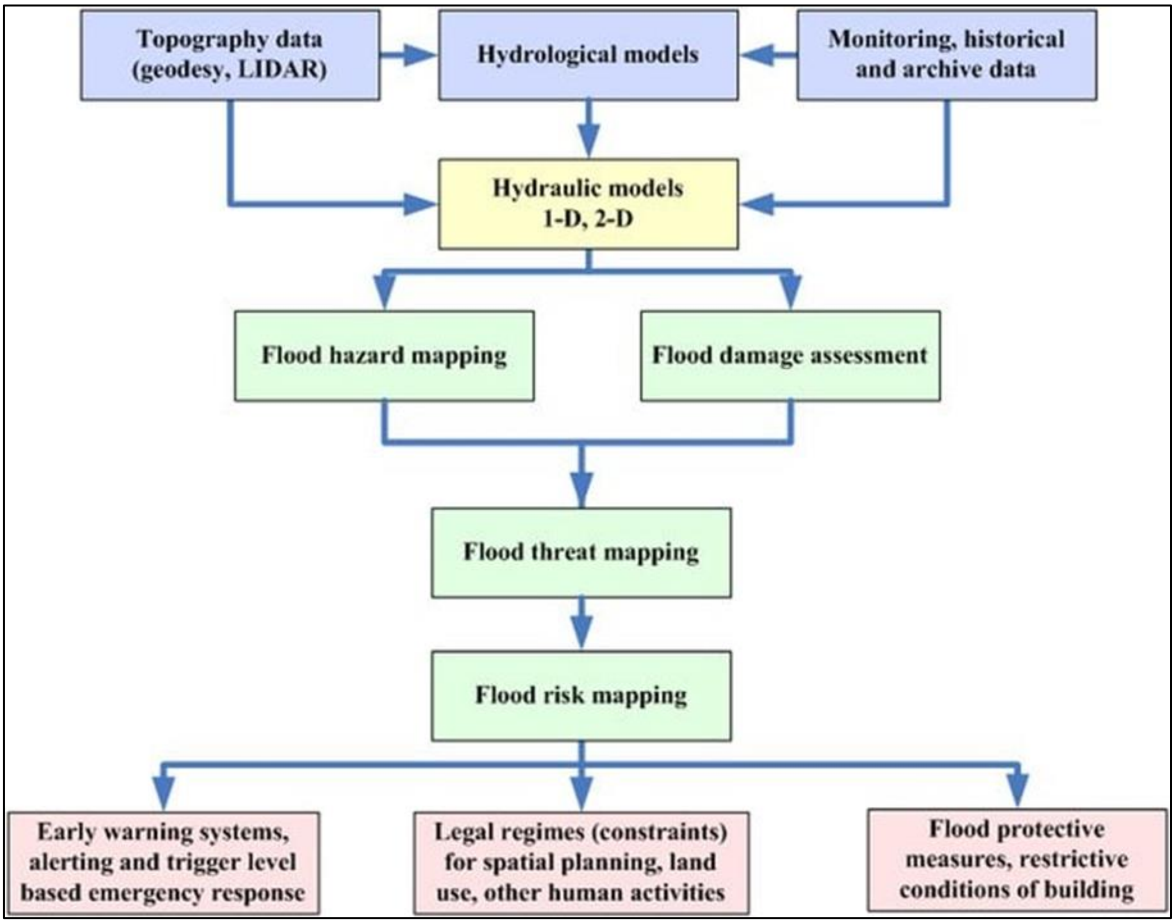

Figure 2 Methodology of flood risk mapping

In Fig 2 presents an integrated framework for flood risk mapping by combining topographical, hydrological, and historical datasets. Initially, topography data obtained from geodesy surveys, Digital Elevation Models (DEM), and LiDAR are used to represent terrain characteristics, river geometry, and drainage patterns. Simultaneously, monitoring records, historical flood events, and archived hydro-meteorological data are collected to understand previous flood behavior and calibrate model performance. These datasets are incorporated into hydrological models to estimate rainfall–runoff processes and river discharge under various storm conditions. The outputs from hydrological models are then coupled with one-dimensional (1-D) and two-dimensional (2-D) hydraulic models to simulate water flow, flood depth, velocity, and inundation extent across the study area. Based on these simulations, flood hazard mapping is carried out to classify areas according to flood intensity and probability, while flood damage assessment evaluates the potential losses to population, infrastructure, agriculture, and property. The combination of hazard and damage information leads to flood threat mapping, which highlights zones requiring urgent attention. Further integration of exposure and vulnerability parameters results in comprehensive flood risk mapping. Finally, the generated flood risk maps support practical decision-making such as establishing early warning systems, emergency response planning, implementing legal regulations for land use and spatial planning, and designing flood protection measures with suitable building restrictions in highly vulnerable areas.

The review also examined the input datasets commonly used in HEC-RAS modelling. These included Digital Elevation Models (DEM), LiDAR-derived terrain data, bathymetric surveys, satellite imagery, rainfall data, streamflow hydrographs, roughness coefficients, land use maps, and cross-sectional survey data. Particular attention was given to how terrain resolution, data quality, and preprocessing methods influence model accuracy. Studies integrating GIS platforms such as ArcGIS and QGIS with HEC-RAS through HEC-GeoRAS or RAS Mapper were critically assessed for terrain preparation, geometry extraction, floodplain delineation, and map visualization.

A comparative synthesis was then performed to identify the major advantages of HEC-RAS, including its free availability, wide acceptance in engineering practice, user-friendly graphical interface, GIS compatibility, robust hydraulic solvers, and ability to model steady, unsteady, sediment, and water quality processes. At the same time, limitations such as computational demand for large 2D models, dependence on high-quality topographic data, instability in complex urban flow conditions, simplified drainage representation, and challenges in real-time forecasting were systematically documented.

In Fig 3 indicates the research methodology of This comprehensive review on flood inundation mapping using HEC-RAS was carried out through a systematic analysis of published literature, technical manuals, and recent case studies focusing on hydraulic modelling applications for floodplain simulation. Relevant journal articles, conference papers, theses, and institutional reports were collected from databases such as Scopus, Web of Science, Google Scholar, and official documentation from the U.S. Army Corps of Engineers. The review primarily considered studies published during the last two decades, with emphasis on recent developments in HEC-RAS versions 5.x and 6.x that introduced advanced two-dimensional (2D) modelling and integrated mapping capabilities.

The collected literature was screened and categorized based on modelling objectives, including one-dimensional (1D) river analysis, 2D floodplain simulation, dam-break studies, urban flood modelling, sediment transport, bridge and culvert hydraulics, and climate-change-driven flood scenarios. Studies were further classified according to input datasets such as Digital Elevation Models (DEM), LiDAR terrain data, rainfall-runoff hydrographs, land use maps, roughness coefficients, and observed discharge records. Particular attention was given to how HEC-RAS integrates with GIS platforms for terrain preprocessing, geometry creation, and inundation map generation.

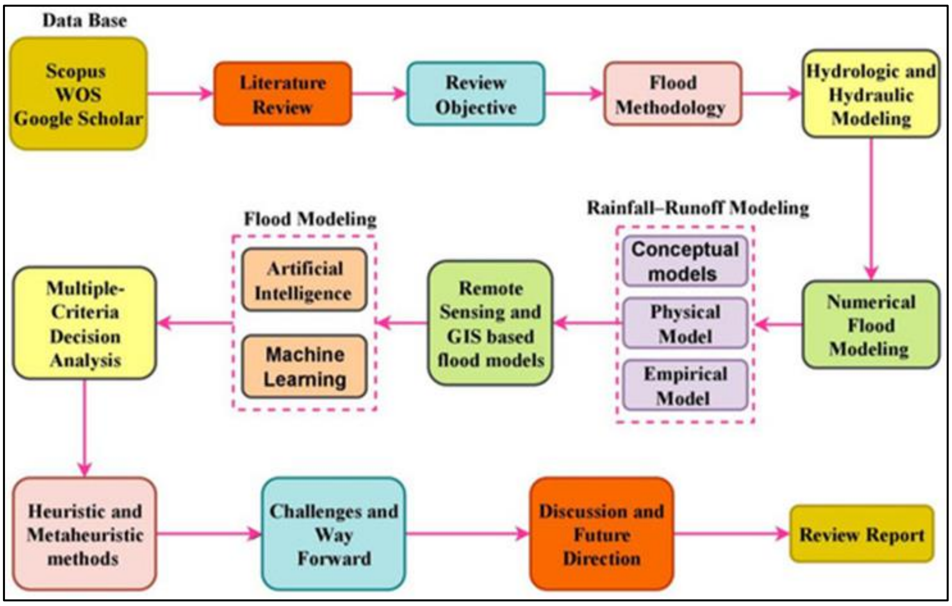

Figure 3 Graphical representation of the research methodology

For comparative assessment, the reviewed studies were analyzed based on model setup procedures, calibration and validation approaches, simulation accuracy, computational efficiency, and applicability in data-scarce or complex terrains. Performance indicators such as water level error, inundation extent overlap, root mean square error (RMSE), and sensitivity to Manning's roughness coefficient were examined where reported. The advantages of HEC-RAS, including free availability, user-friendly interface, GIS compatibility, and robust hydraulic solvers, were synthesized against challenges such as DEM uncertainty, mesh resolution sensitivity, computational time, instability in complex flow regions, and limitations in representing urban drainage interactions. Finally, emerging future perspectives were identified by reviewing recent research on remote sensing integration, real-time forecasting, cloud computing, machine learning surrogates, and hybrid modelling frameworks that enhance the speed and accuracy of HEC-RAS-based flood inundation mapping.

5. Applications of Flood Inundation Mapping Using HEC-RAS

Flood inundation mapping using HEC-RAS has become an essential tool in water resources engineering, disaster management, and urban planning due to its capability to simulate flood extent, water depth, and flow velocity under various hydrological conditions. One of the primary applications is river floodplain management, where HEC-RAS is used to delineate flood-prone zones along rivers and streams for different return periods such as 10-year, 50-year, and

100-year floods. These maps help authorities regulate development activities and reduce encroachment in vulnerable floodplain regions.

Another important application is urban flood management, where HEC-RAS assists in identifying low-lying areas, drainage bottlenecks, and zones susceptible to waterlogging during intense rainfall events. Municipal agencies use these outputs for stormwater drainage improvement, smart city planning, and flood mitigation infrastructure design. In rapidly urbanizing regions, HEC-RAS supports sustainable land use planning by evaluating the hydrological impact of roads, buildings, and impervious surfaces.

HEC-RAS is also widely applied in dam-break and reservoir failure analysis. By simulating sudden release of stored water, the model predicts downstream flood wave propagation, inundation depth, arrival time, and affected settlements. Such studies are highly valuable for emergency preparedness planning, evacuation route design, and reservoir safety assessment.

In the field of bridge, culvert, and hydraulic structure design, HEC-RAS is used to evaluate water surface profiles, afflux, scour potential, and flow behavior around structures. Engineers rely on these simulations to ensure safe design of crossings and minimize obstruction-induced flooding. Another growing application is climate change impact assessment, where future rainfall and discharge scenarios are introduced into HEC-RAS to estimate changing flood hazards. This helps policymakers develop adaptation strategies and resilient infrastructure systems.

HEC-RAS is further used for real-time flood forecasting and early warning systems when integrated with rainfall-runoff models, remote sensing data, and telemetry systems. It can provide advance information on likely inundation zones during storms, enabling timely response.

Additionally, HEC-RAS supports environmental and ecological studies, sediment transport analysis, river restoration projects, and wetland management by understanding flow distribution and water levels. Overall, the wide range of applications demonstrates that HEC-RAS is a versatile and reliable platform for flood inundation mapping and integrated water resources management.

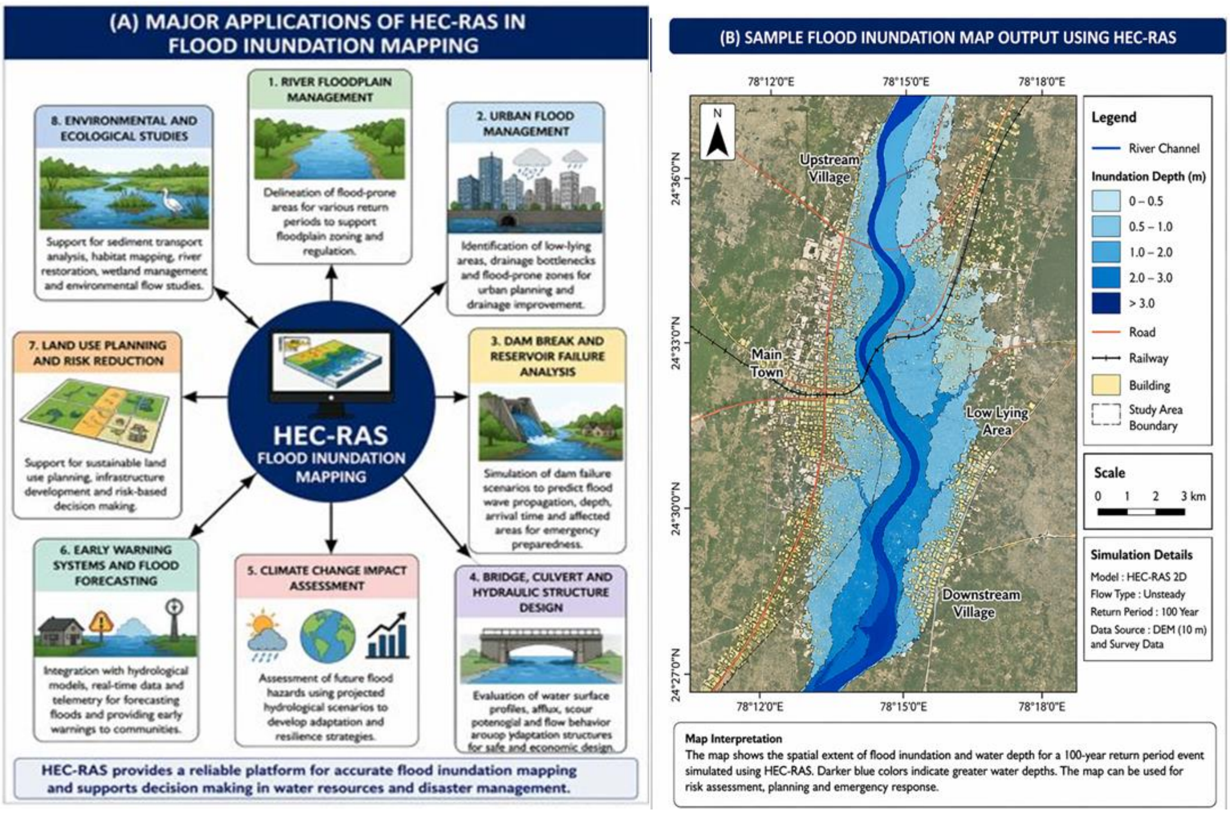

Figure 4 Applications of HEC-RAS in Flood Inundation Mapping and Sample Output

In Fig 4 illustrates the major applications of HEC-RAS in flood inundation mapping along with a representative sample output map generated using the model. The left panel presents the wide range of engineering and management applications of HEC-RAS. These include river floodplain management through delineation of flood-prone zones for different return periods, urban flood management by identifying low-lying areas and drainage bottlenecks, dam-break and reservoir failure analysis for predicting downstream flood propagation, and hydraulic structure design involving bridges and culverts. The model is also extensively used for climate change impact assessment by simulating future flood scenarios under changing rainfall patterns. In addition, HEC-RAS supports early warning systems and flood forecasting when integrated with hydrological models and real-time monitoring data. Other significant applications include land use planning, risk reduction strategies, sediment transport studies, river restoration, wetland management, and ecological flow assessment.

The right panel shows a typical flood inundation map produced using HEC-RAS 2D unsteady flow simulation for a 100-year return period event. The map displays the river channel, surrounding settlements, transport infrastructure, and flood extent with varying inundation depths represented by different color gradients. Darker blue shades indicate deeper water levels, while lighter shades represent shallow inundation zones. Such spatial outputs are highly useful for flood hazard assessment, emergency evacuation planning, infrastructure protection, and sustainable regional development. Overall, the figure demonstrates that HEC-RAS is a reliable and versatile tool for accurate flood inundation mapping and informed decision-making in water resources and disaster management.

6. Conclusion

Flood inundation mapping has become an essential component of modern flood risk management, and HEC-RAS has emerged as one of the most reliable and widely adopted hydraulic modelling tools for this purpose. This review demonstrates that the continuous evolution of HEC-RAS from traditional 1D modelling to advanced 2D unsteady flow simulations has significantly improved the capability to represent complex flood behavior, floodplain interactions, and spatial inundation patterns. The integration of HEC-RAS with GIS, remote sensing, LiDAR-derived DEMs, and climate data has further enhanced mapping accuracy, visualization, and practical applicability in disaster management and planning.

The review also highlights that HEC-RAS has been successfully applied in riverine flood studies, urban flood assessment, dam-break analysis, infrastructure design, flood forecasting, and climate change impact evaluation. However, model performance remains highly dependent on the quality of terrain data, hydrological inputs, calibration parameters, and computational resources. Challenges such as uncertainty in roughness coefficients, data scarcity in ungauged basins, and representation of complex urban drainage systems continue to limit prediction accuracy in some regions.

Future progress in flood inundation mapping using HEC-RAS will depend on the adoption of high-resolution datasets, artificial intelligence techniques, cloud computing, IoT-based monitoring systems, and real-time data assimilation. These emerging technologies can greatly improve simulation speed, accuracy, and operational decision-making. In conclusion, HEC-RAS remains a powerful and cost-effective decision-support platform that will continue to play a vital role in enhancing flood resilience, sustainable land-use planning, and disaster preparedness worldwide.

Reference Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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