

Role of GIS in Hydrology: A Review of Applications and Emerging Trends

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Abstract— Geographic Information Systems (GIS) have become an indispensable tool in hydrological science, providing the spatial data infrastructure needed to represent, analyze, and simulate the behaviour of the terrestrial water cycle. This paper presents a review of the role of GIS in hydrology, tracing its evolution from early digital terrain analysis to its present convergence with remote sensing, cloud computing, and artificial intelligence. Core applications are examined, including watershed delineation and morphometric analysis, flood hazard mapping and risk assessment, groundwater potential zonation, rainfall-runoff and distributed hydrological modelling, water quality assessment, and climate change impact studies. The review then discusses emerging trends that are reshaping the discipline, namely the integration of machine learning and deep learning with spatial hydrological data, the rise of cloud-based geoprocessing platforms such as Google Earth Engine, the growing role of unmanned aerial vehicles and high-resolution remote sensing, real-time and Internet-of-Things-enabled monitoring networks, and the continued expansion of open-source GIS software. Persistent challenges relating to data quality, spatial-scale mismatches, model transferability, and the translation of research outputs into operational water management are also discussed. The paper concludes that GIS is no longer a passive mapping tool but an active analytical and decision-support environment for hydrology, and that its future development will be shaped by tighter integration with artificial intelligence and open geospatial data infrastructure, particularly in data-scarce regions of the developing world.

Keywords— Geographic Information System (GIS); hydrology; remote sensing; watershed modelling; flood mapping; groundwater potential zone; machine learning; Google Earth Engine

I. INTRODUCTION

Water is among the most spatially variable of natural resources, and understanding its movement, storage, and quality requires tools capable of representing that variability across landscapes. Geographic Information Systems (GIS) provide exactly this capability: a digital environment in which terrain, soil, land cover, climate, and hydrological observations can be stored, analysed, and visualised within a common spatial reference framework (Ames, 2026).

The pairing of GIS with hydrology is not incidental; hydrological processes such as runoff generation, infiltration, and streamflow routing are fundamentally governed by topography and land surface characteristics, both of which are naturally represented as spatial data (Moore, Grayson, & Ladson, 1991).

Global water systems are under increasing pressure from population growth, land-use change, and climate variability, and river biodiversity and water security are threatened across large parts of the world (Vörösmarty et al., 2010). Addressing these pressures requires analytical tools that can operate across multiple spatial and temporal scales, from a single watershed to an entire river basin. GIS, particularly when combined with remote sensing and digital elevation data, has become the primary infrastructure through which such multi-scale hydrological analysis is performed (Daniel et al., 2011).

This paper reviews the role of GIS in hydrology in two parts. First, it surveys the principal application areas in which GIS has been used, including watershed delineation, flood hazard mapping, groundwater potential zonation, distributed hydrological modelling, water quality assessment, and climate change impact studies. Second, it examines emerging trends that are transforming the field, including the convergence of GIS with artificial intelligence, cloud computing, and high-resolution remote sensing. The review closes with a discussion of persistent challenges and directions for future research.

II. HISTORICAL EVOLUTION OF GIS IN HYDROLOGY

The use of digital spatial analysis in hydrology dates back several decades. Early efforts focused on representing terrain digitally so that flow paths and drainage networks could be extracted automatically rather than delineated manually from paper topographic maps. O'Callaghan and Mark (1984) formalised the widely used eight-direction (D8) flow algorithm for extracting drainage networks from digital elevation data, while Jenson and Domingue (1988) introduced systematic procedures for depression filling and flow accumulation that remain the operational backbone of GIS-based terrain analysis.

Tarboton (1997) later refined these methods with the D-infinity algorithm, which distributes flow across multiple downslope directions and reduces the directional bias inherent in the D8 approach.

Through the 1980s and 1990s, GIS began to be coupled directly with hydrological simulation models. The *Système Hydrologique Européen* (SHE) model of Abbott, Bathurst, Cunge, O'Connell, and Rasmussen (1986) was among the first physically based, spatially distributed models to rely on digital terrain data for its computational structure. This period also saw the development of the Soil and Water Assessment Tool (SWAT) by Arnold, Srinivasan, Muttiah, and Williams (1998), which used GIS-derived land use, soil, and slope data to define Hydrological Response Units, dramatically reducing the time required to parameterise distributed watershed models. The U.S. Army Corps of Engineers (1996) documented this first generation of GIS–hydrology coupling in a comprehensive technical review, describing raster, triangulated irregular network, and vector-based approaches to representing terrain for hydrological analysis.

From the early 2000s onward, national and global hydrographic datasets, open-source GIS platforms, and improved digital elevation products (such as those derived from the Shuttle Radar Topography Mission) reduced the cost of entry to GIS-based hydrological analysis and enabled continental-scale routing frameworks such as RAPID (David, Maidment, Niu, Yang, Habets, & Eijkhout, 2011). This trajectory of progressively tighter integration between spatial data and hydrological computation set the stage for the current era, in which cloud computing and machine learning are further reshaping the discipline (Ames, 2026).

III. CORE GIS TECHNIQUES USED IN HYDROLOGY

Several core GIS techniques underpin most hydrological applications:

- Digital Elevation Model (DEM) processing — sink filling, flow direction, and flow accumulation, used to delineate watersheds and stream networks.
- Multi-criteria overlay analysis — combining thematic layers (slope, geology, land use, rainfall) using weighting schemes such as the Analytic Hierarchy Process (Saaty, 1980) to produce composite susceptibility or potential maps.
- Integration with remote sensing — using satellite-derived land cover, precipitation, and soil moisture products as direct inputs to spatial hydrological analysis.

- Coupling with hydrological models — using GIS-derived spatial units (sub-basins, Hydrological Response Units, or river reaches) as the structural basis for models such as SWAT, HEC-HMS, and MIKE SHE.

IV. APPLICATIONS OF GIS IN HYDROLOGY

A. Watershed Delineation and Morphometric Analysis

Watershed delineation, the process of identifying the boundary of the area draining to a given outlet, remains one of the most fundamental applications of GIS in hydrology. Automated delineation from DEMs using the D8 or D-infinity algorithms has largely replaced manual delineation from topographic contour maps, improving both consistency and speed (Jenson & Domingue, 1988; Tarboton, 1997). Once delineated, watersheds are commonly characterised through morphometric parameters, such as drainage density, bifurcation ratio, and stream order, which provide insight into runoff behaviour, erosion potential, and the influence of underlying geology on drainage patterns.

B. Flood Hazard Mapping and Risk Assessment

GIS is widely used to identify areas susceptible to flooding by integrating parameters such as elevation, slope, distance from drainage channels, rainfall intensity, and land cover. Multi-criteria decision analysis frameworks, particularly the Analytic Hierarchy Process (Saaty, 1980), are frequently used to assign relative weights to these parameters and produce composite flood hazard maps. Beyond hazard mapping, GIS-coupled hydraulic models allow inundation extent and depth to be estimated for specific rainfall or discharge scenarios, supporting floodplain zoning, insurance rate mapping, and early warning systems.

C. Groundwater Potential Zone Mapping

Identifying zones with favourable groundwater occurrence is critical in regions where surface water is scarce or unevenly distributed. GIS-based groundwater potential mapping typically integrates layers such as geology, lineament density, slope, drainage density, soil type, and land use through weighted overlay or bivariate statistical techniques, with the analytic hierarchy process again being one of the most widely applied weighting methods (Saaty, 1980). Resulting maps classify a study area into potential zones ranging from very poor to very good, providing a screening tool to prioritise sites for further hydrogeological investigation or well siting.

D. Rainfall–Runoff and Distributed Hydrological Modelling

GIS provides the spatial data infrastructure required to parameterise both lumped and distributed hydrological models. In distributed models such as SWAT, GIS-derived land use, soil, and slope classifications are used to define Hydrological Response Units that aggregate areas of similar hydrological behaviour (Arnold, Srinivasan, Muttiah, & Williams, 1998). In fully distributed, physically based models such as MIKE SHE, GIS-derived grid cells serve directly as the model's computational elements (Abbott, Bathurst, Cunge, O'Connell, & Rasmussen, 1986). Continental-scale routing frameworks, such as RAPID, extend this integration further by using river-reach features from national hydrography datasets as the computational graph for streamflow routing (David, Maidment, Niu, Yang, Habets, & Eijkhout, 2011).

E. Water Quality Assessment and Monitoring

GIS supports water quality assessment by allowing point-source and non-point-source pollution data to be linked spatially to catchment characteristics such as land use, slope, and proximity to drainage channels. This spatial linkage is central to models such as the Hydrological Simulation Program–FORTRAN and the associated BASINS platform, which integrate GIS with water quality simulation to support total maximum daily load assessments (U.S. Army Corps of Engineers, 1996). Beyond simulation, GIS is also used to visualise spatial and temporal patterns in observed water quality parameters drawn from monitoring networks, helping to identify pollution hotspots and guide monitoring station placement.

F. Climate Change Impact Studies

Because hydrological processes are sensitive to both climate and land surface conditions, GIS is central to studies that assess how projected changes in precipitation and temperature may alter runoff, groundwater recharge, and flood risk. By combining downscaled climate model outputs with GIS-based hydrological models, researchers can generate spatially explicit projections of future water availability and hazard exposure, supporting adaptation planning at river-basin and regional scales. Global assessments of water security, such as that of Vörösmarty et al. (2010), rely on exactly this kind of spatial integration of climatic, hydrological, and socio-economic data.

V. EMERGING TRENDS

A. Integration of Artificial Intelligence and Machine Learning

Machine learning, and particularly deep learning, is increasingly being coupled with GIS-derived spatial data to improve hydrological prediction. Kratzert, Klotz, Brenner, Schulz, and Herrnegger (2019) demonstrated that Long Short-Term Memory (LSTM) neural networks trained across large samples of catchments can match or outperform calibrated physically based models in streamflow prediction, including at locations with no observed data. Random forest and support vector machine classifiers are similarly used with GIS-derived terrain and land cover attributes to map flood susceptibility and groundwater potential, often outperforming traditional weighted-overlay approaches in predictive accuracy. Looking forward, GIS-hydrology researchers anticipate a progressive convergence in which artificial intelligence agents assist with, and eventually operate directly on, spatial hydrological data, reducing the technical barriers that have traditionally limited access to advanced hydrological analysis (Ames, 2026).

B. Cloud-Based Geospatial Platforms

Cloud computing platforms have fundamentally changed how large volumes of satellite imagery are processed for hydrological purposes. Google Earth Engine, described by Gorelick, Hancher, Dixon, Ilyushchenko, Thau, and Moore (2017), provides browser-based access to multi-decadal satellite archives and parallel cloud processing, eliminating the need to download and locally process large imagery datasets. This capability has been widely applied to surface water dynamics mapping, flood extent detection, and land cover change analysis at scales ranging from individual catchments to entire continents, substantially lowering the computational barrier to large-scale hydrological analysis.

C. Unmanned Aerial Vehicles and High-Resolution Remote Sensing

Unmanned aerial vehicles (UAVs) are increasingly used to acquire very high-resolution topographic and multispectral data over small to medium-sized catchments, filling a resolution gap between satellite imagery and ground survey. UAV-derived digital surface models support fine-scale flood modelling, gully erosion assessment, and riverbank change detection at a fraction of the cost of traditional airborne LiDAR surveys, making high-resolution hydrological analysis increasingly accessible to researchers with limited budgets.

D. Real-Time and IoT-Enabled Hydrological Monitoring

The integration of GIS with real-time sensor networks and Internet-of-Things (IoT) devices is enabling near real-time hydrological monitoring and forecasting. Early web-based hydrological models demonstrated the feasibility of linking live rainfall and river-level data to GIS-based flood prediction systems accessible over the internet (Al-Sabhan, Mulligan, & Blackburn, 2003). Contemporary systems extend this concept considerably, combining distributed in-situ sensors, radar-derived rainfall, and cloud-hosted GIS dashboards to support operational flood early-warning services.

E. Open-Source GIS and Democratization of Geospatial Tools

The continued maturation of open-source GIS platforms has reduced the cost barrier to hydrological analysis, particularly benefiting researchers and agencies in resource-constrained settings. Freely available desktop GIS software, open hydrographic datasets, and open-source terrain-analysis toolkits now offer capabilities that were once available only through expensive commercial licences, accelerating the global adoption of GIS-based hydrological analysis (Ames, 2026).

VI. CHALLENGES AND LIMITATIONS

Despite substantial progress, several challenges limit the effectiveness of GIS applications in hydrology. First, the accuracy of any GIS-based hydrological analysis is fundamentally constrained by the quality and resolution of the underlying elevation, soil, and land cover data; coarse or outdated datasets can propagate significant error into derived products such as watershed boundaries or flood maps. Second, a persistent mismatch exists between the spatial scale at which hydrological processes operate and the scale at which administrative or management decisions are made, complicating the translation of grid-based or catchment-based model outputs into policy-relevant units. Third, machine learning models trained primarily on data from well-monitored regions of North America, Europe, and Australia often perform poorly when transferred to data-scarce basins in the developing world, limiting their global applicability (Kratzert, Klotz, Brenner, Schulz, & Herrnegger, 2019). Finally, the gap between research-grade GIS-hydrology tools and their adoption by operational water management agencies remains wide, owing to limited technical capacity, regulatory inertia, and, in some cases, distrust of complex or opaque modelling approaches.

VII. FUTURE RESEARCH DIRECTIONS

Building on the trends identified above, several directions appear promising for future research. Continued development of physics-informed machine learning models, which embed hydrological conservation principles directly into data-driven architectures, may help address the transferability limitations of purely statistical approaches. Expansion of low-cost, open sensor networks and citizen-science data collection could help close observational gaps in poorly gauged basins. Greater interoperability between GIS platforms, cloud-native data formats, and hydrological models would further reduce the technical friction that currently limits access to advanced hydrological analysis. Finally, sustained investment in capacity building and open geospatial infrastructure in developing regions is needed to ensure that these technological advances translate into more equitable water management outcomes globally.

VIII. CONCLUSION

Geographic Information Systems have evolved from a simple mapping aid into a core analytical infrastructure for hydrological science. Their applications now span watershed delineation, flood hazard mapping, groundwater potential zonation, distributed hydrological modelling, water quality assessment, and climate change impact analysis. Emerging trends, including the integration of artificial intelligence, cloud-based geoprocessing, UAV-based remote sensing, real-time monitoring, and open-source software, are further expanding the scope and accessibility of GIS-based hydrological analysis. At the same time, challenges related to data quality, spatial-scale mismatches, model transferability, and the translation of research into operational practice remain significant. Addressing these challenges will be essential if the full potential of GIS-integrated hydrology is to be realised, particularly in the data-scarce regions of the world where the need for effective water management is often greatest.

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