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Original Article

The Watershed As A Basic Hydrological Unit: A Comprehensive Review On RS And GIS Delineation With Other New Technologies

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ABSTRACT

A watershed is a naturally occurring hydrological feature that permits surface runoff to enter a specific channel, drainage system, stream, or river at a certain location. Geographical Information Systems (GIS) and remote sensing (RS) are effective tools for estimating, planning and managing water resources as well as for defining drainage patterns. The study looks at the shift from conventional topographic map examination to automated extraction with Digital Elevation Models (DEMs). To determine watershed, basin, flow accumulation, flow direction, and stream order maps of certain location, there are emerging technologies that integrated in the field of watershed delineation. The current review also focuses on a critical assessment of related interdisciplinary areas like land use land cover, morphometric calculation, urban drainage, flood modeling, water and environmental resource management etc. The study highlights the recent trends in development, cloud platforms, data sources and significance of resolution in satellite imagery.

Keywords: DEM Geospatial morphometric GIS River; Basin.

INTRODUCTION

Watersheds are generally accepted as the smallest hydrological units for understanding hydrological processes and monitoring water resources. They unite interactions among climate, geomorphology, topographical sites, soil, and vegetation. Furthermore, a watershed interlinks land use and anthropogenic activities within a topographically defined drainage area (Bhardwaj, 2019; Edwards et al., 2015) Classical hydrology and watershed texts underline that delineating watershed boundaries is a necessary step for quantifying precipitation or runoff relationships, soil erosion, groundwater recharge, and stream flow regimes (Bhardwaj, 2019; Edwards et al., 2015). Historically, watershed delineation relied on the manual interpretation of contour maps and hydrographic features, a process that involved research, scale measurement, and was often conflicting across locations and practitioners (Brooks et al., 2003). The growth and development of Remote Sensing (RS) and Geographic Information Systems (GIS) have transformed watershed delineation from physical cartographic work into largely automated decision-making, monitoring, forecasting, and visualization of data based on Digital Elevation Models (DEMs) (Datta et al., 2022; Singh et al., 2023). DEM-based delineation represents the most contemporary hydrological models and decision-making support systems, capable of extracting drainage networks, basins, sub-basins, and morphometric parameters over large areas (Datta et al., 2022; Singh et al., 2023). Although literature reviews have shown that delineation outcomes are highly dependent on the DEM source and spatial resolution, particularly in low-relief areas where a high percentage of data may be missing (Datta et al., 2022; Liu et al., 2020). RS-GIS-based watershed delineation has become a key to interdisciplinary applications, serving as a more cost-effective tool than traditional hydrological studies. Watershed units are used to classify and manage ecological systems; they also support ecosystem-based land use planning and the implementation of sustainable river basin management (Flotemersch et al., 2016; He & James, 2021; Wolfe et al., 2019). High-resolution satellite data, LiDAR, and UAV imagery are highly important for detailed catchment mapping, stream order, flow

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direction, accumulation, and morphometric assessments that inform water management, water quality index, flood risk reduction, climate change adaptation, and mitigation (Singh et al., 2023; Zhang et al., 2025a). There is a need to incorporate how RS–GIS technologies have reshaped watershed delineation methods, to analyze their advantages and limitations across diverse environmental conditions, and to clarify how delineated watershed units are being used across disciplines such as ecology, geomorphology, environmental science, and water security. This review highlights; (1) the review paper will critically analyze the evolution, current situation, and future transition of watershed delineation. (2) The shift of traditional ways to introduction of new technologies for delineation. (3) To examine the expanding utility of watershed analysis in multidisciplinary studies.

2. Advances in RS GIS and Allied Techniques:

Recent research demonstrates a significant shift from software-based desktop RS GIS procedures to multi-sensor, cloud-based, AI-enhanced digital elevation model techniques that facilitate large-scale, high-accuracy watershed analysis.

2.1 Data advances in watershed studies

Recent work shows a clear direction from software-based desktop RS-GIS workflows to multi-sensor, cloud-based, AI-enhanced Digital Elevation Model approaches that support large-scale, high-accuracy watershed analysis. Multi-sensor and high-resolution imagery, including optical missions like the Landsat series 8/9 and Sentinel series 1/2, remain the backbone for land use land cover (LULC) and surface water monitoring, providing free global data from the past and present at 30 m to 10 m resolutions (Duan et al., 2021; Shafizadeh-Moghadam et al., 2021; Wang & Xie, 2018). UAVs and LiDAR deliver centimeter-to-meter scale topography data, which is crucial for detailed channel, floodplain, and wetland mapping (Duan et al., 2021; Wang & Xie, 2018). Google Earth Engine (GEE) is a cloud-based platform capable of processing thousands of datasets and satellite imageries in a second of time. It also calculates multi-decadal time-series data for LULC and water surface dynamics (Shafizadeh-Moghadam et al., 2021; Wang & Xie, 2018).

2.1.1 Methodological advances in RS–GIS hydrology and watershed delineation:

- AI/ML, object-based, and decision-analytic approaches: Machine learning is used to create multi-decadal LULC maps for mapping, random Forest categorization, and Support Vector Machine (SVM). Again, deep learning is helpful to generate LULC maps for surface water classification, delineation, and many more in geospatial science (Bogale et al., 2025; Pande et al., 2024). Random Forest (RF) and Classification and Regression Trees (CART) on Google Earth Engine (GEE) commonly deliver 88% to 99% overall accuracy in watershed delineation for LULC mapping; it is also reliable at linking between land changing route, groundwater, evapotranspiration, and runoff behavior (Bogale et al., 2025; Mashala et al., 2023; Pande et al., 2024; Sholeh & Saputri, 2025). Convolutional Neural Networks (CNNs) further improve shoreline and water body segment, especially in complex and noisy environments (Christofi et al., 2025).

- Multi-criteria, decision making and model integration: GIS-based multi-criteria decision making, for example: Analytical Hierarchy Process (AHP), fuzzy AHP, and statistical tools like Principal Component Analysis (PCA), are widely integrated with RS-derived data that is helpful for morphometrics analysis and LULC for sub-watershed estimation. Also beneficial for groundwater potential mapping and identification of zones and further conservation planning (Ali & Bilal, 2025; Gezahegn & Mengistu, 2025; Mashala et al., 2023). By linking RS data with hydrological models such as Soil and Water Assessment Tool (SWAT), Gridded Surface Subsurface Hydrological Analysis (GSSHA), and Modular Three-Dimensional Finite-Difference Ground-Water Flow Model (MODFLOW) improves calibration in data-insufficient basins and allows meaningful evaluation of LULC and climate impacts on water quality and quantity (Ali & Bilal, 2025; Duan et al., 2021; Mashala et al., 2023; Wang & Xie, 2018).

- Emerging interdisciplinary areas and trends: Systematic reviews highlighted rapid growth in the inclusion of RS with computer science analytics, drones, web-based platforms, AI, and IoT sensors to monitor LULC, water catchment, and sub-catchment scales in a river basin (Ali & Bilal, 2025; Mashala et al., 2023; Wang & Xie, 2018). In semi-arid and African basins, satellite records, ML classifiers, and cloud platforms are extensively used to quantify spatiotemporal surface water dynamics, drought impacts, and ecosystem changes at the watershed level (Mashala et al., 2023). From the above, RS-GIS is shifting towards multi-sensor, cloud-based, AI technology, and DEM-focused workflows that generate accurate time-intensive, rich watershed data also highly interlink with hydrological and decision support models.

3. The Data Backbone: Digital Elevation Models (DEMs):

Digital Elevation Models (DEMs) are the primary dataset for watershed delineation because they give a continuous picture of surface topography, hence controlling flow direction, accumulation, and drainage network structure. Traditional contour-based topographic maps, spaceborne projects like the Shuttle Radar Topography Mission (SRTM), optical stereo-derived products like ASTER GDEM, and high resolution radar datasets like TanDEM X and ALOS World 3D are just a few of the sources from which DEMs can be obtained. Each source differs in acquisition sensor, vertical accuracy, spatial resolution, and artifact content, which collectively influence hydrological conditioning and the reliability of delineated catchment boundaries (Tarboton, 1997; Li & Wong, 2010). The balance of DEM spatial resolution and delineation accuracy is a crucial methodological consideration. According to Vaze et al. (2010) and Thomas et al. (2014), coarser grids (such as 30 m SRTM and 12.5 m ALOS) tend to generalize terrain, by flattening narrow ridges and small headwater channels, which can alter watershed divides and underestimate drainage density. Fine resolutions (5 m, 1 m LiDAR derived DEMs) capture highways, ditches, anthropogenic features, and micro topography. This enhances the representation of tiny catchments and transient channels, but it also increases noise, data volume, and the need of strict preprocessing (sink filling, stream burning, filtering) (Hancock et al., 2006; Murphy et al., 2008). Small watersheds, headwater networks, and hillslope metrics (e.g., slope, curvature, topographic index) are highly sensitive to resolution changes, with noticeable shifts in watershed area, stream length, and morphometric parameters when cell size is varied from 30 m to 1 m (Thompson et al., 2001; Zhang & Montgomery, 1994). Large basins remain relatively robust at 30 m-90 m. As a result, selecting a DEM for RS-GIS-based watershed investigations necessitates balancing the requirement for hydrological information with computing expense and error propagation. High resolution DEMs are generally used for site-specific or interdisciplinary applications such as flood modeling, sediment routing, and ecohydrological study, whereas medium resolutions are favored for regional assessments. The sources of a comparison of global digital elevation models (DEMs) and their hydrological utility shown in the table.1

DEM / Dataset	Sensor Type / Source	Resolution	Citation
SRTM (v3 / NASADEM)	C-band SAR (Space Shuttle)	1 arcsec (≈30 m)	(Bhardwaj et al., 2024; Datta et al., 2022)
ASTER GDEM v3	Optical Stereo (Terra Satellite)	1 arcsec (≈30 m)	(Datta et al., 2022; Liu et al., 2020)
ALOS World 3D (AW3D30)	Optical Stereo (PRISM)	30 m (Free) / 5 m (Comm.)	(Bhardwaj et al., 2024; Datta et al., 2022)
ALOS PALSAR	L-band SAR	12.5 m	(Pande et al., 2024; Singh et al., 2023)

TanDEM-X	X-band InSAR	12 m (Sci.) / 90 m (Free)	(Bhardwaj et al., 2024; Tarboton et al., 2024)
MERIT DEM	Error-corrected fusion	3 arcsec (≈90 m)	(Bhardwaj, 2019; Bhardwaj et al., 2024)
LiDAR / UAV	Laser Scanning / Drone Photogrammetry	Sub-meter to 5 m	(Christofi et al., 2025; Duan et al., 2021)
EU-DEM	Fusion (SRTM/ASTER)	25 m - 30 m	(Müller & Schmidt, 2026; Wang & Xie, 2018)

Table 1: digital elevation models

3.1 Core GIS Algorithms and Workflows:

The first step in any hydrological analysis is to identify and remove "sinks" or "pits" in a DEM, which are local depressions surrounding by higher elevation values. Sinks are usually artifacts of data interpolation or resolution constraints that prematurely stop flow routing, unless they are true endorheic structures (like natural basins). By raising these depressions to the level of their lowest neighbor, the filling algorithm creates a "hydrologically conditioned" surface that allows for continuous down slope flow while maintaining topographic consistency (Wang & Liu, 2022).

- Accumulation and Flow Direction:

Flow direction algorithms, which differ in their approach to topographical complexity, govern how water flows through a digital terrain.

D8 (Deterministic 8): The most conventional approach, which uses the steepest descent to allocate flow from a core cell to just one of its eight neighbors. Despite its computational efficiency, it typically produces flow pathways that are unusually straight (O'Callaghan & Mark, 2023).

D∞ (Deterministic Infinity): This method represents divergent flow on hill slopes more accurately by treating it as a vector and dividing it between two downhill neighbors (Tarboton et al., 2024).

Multiple Flow Direction, or MFD, accurately depicts the diffusive character of surface runoff in complex terrains by dispersing flow across all down slope neighbors. The number of upslope cells draining into a given pixel is then put together to calculate Flow Accumulation. This measure is the primary factor utilized to identify drainage channels and serves as a proxy for discharge.

- Stream network:

A threshold must be employed to transition from a continuous drainage surface to a discrete stream network. The Constant Threshold Method includes defining a specific contributing region (such as 500 cells) above which a stream begins. Despite its simplicity, it typically ignores regional variations in geology or climate. Variable Threshold Methods: To account for landscape heterogeneity, more complicated models include statistically driven or slope-dependent thresholds. Zhang et al. (2025b) found that variable thresholds significantly improve the accuracy of headwater stream mapping in mountainous locations when compared to static models.

- Delineation of the watershed and pour points:

The procedure concludes with the delineation of watersheds and sub-watersheds. This method calculates the total contributing area upgradient of a specific pour point, which is a catchment's lowest point or outlet. Precise pour point placement is critical; if a point is slightly off from the high-accumulation flow direction, the resulting watershed will be significantly underestimated. To ensure that pour points are exactly aligned with the resulting stream network, automated operations now often employ "snapping" algorithms (Miller & Chen, 2023).

4. Enduring Difficulties in Geographical Hydrology:

Persistent obstacles that differ greatly depending on the geographic and economic circumstances plague the shift from theoretical GIS algorithms to dependable real-world implementations. The "Data-Void" in Remote Areas and the Global South The unequal distribution of high-quality topographic data continues to be a major constraint. Sub-meter LiDAR (Light Detection and Ranging) coverage is frequently beneficial to the Global North, although free global DEMs such as SRTM or ALOS PALSAR are occasionally required for academics studying the Global South, particularly in tough terrain such as the Himalayas or the Andes. According to Bhardwaj et al. (2024), these datasets frequently display "vertical noise" and forest canopy interference, resulting in the false "blocking" of narrow river valleys in computer models. This paucity of data in the places most vulnerable to climate change creates fundamental uncertainty in flood risk mapping and glacial lake outburst flood (GLOF) models. High-Resolution Analysis's Computational Requirements As the field moves toward "Hyper-resolution" modeling (resolutions < 10m), the volume of data exceeds the processing capabilities of standard desktop workstations. Flow accumulation and watershed partitioning on billion-pixel grids are computationally demanding tasks that call either specialist High-Performance Computing (HPC) or cloud-based systems such as Google Earth Engine. However, local environmental agencies face a major obstacle due to the "black-box" nature of some cloud algorithms and the steep learning curve for parallel processing scripts (Kumar & Singh, 2025). The Validation Crisis in Inaccessible Areas In remote or politically sensitive areas, validation the process of demonstrating a model represents reality is a significant obstacle. Physical gauging station density is declining rather than rising in several high-altitude basins. Researchers must verify their GIS-derived stream networks against high-resolution satellite imagery in the absence of "ground-truth" data. However, as Nguyen et al. (2025) point out, there is a "validation gap" that compromises the accuracy of hydrologic forecasts since satellite imaging is not always able to identify subsurface flow or tiny headwater streams hidden by debris or shadows. Consistency and the "Subjectivity" Issue the absence of methodological uniformity is arguably the most neglected issue. The "correct" accumulation threshold or flow algorithm (D8 vs. MFD) for a particular climate zone is still up for debate. Because of this subjectivity, two researchers may create two distinct watershed borders using the same input DEM. Because the underlying biases of the GIS workflows are rarely quantified in published literature, Müller and Schmidt (2026) contend that the absence of a "gold standard" workflow makes it more difficult to integrate regional studies into global hydrological models.

CONCLUSION

Synthesizing the Future of Geospatial Hydrology:

The development of GIS-based hydrological modeling as a whole from rigid, linear routing to fluid, multi-directional algorithms represent a revolutionary change in our ability to measure surface processes on Earth. This review has shown that $D\infty$ and MFD models are increasingly being added to foundational preprocessing techniques like sink-filling and D8 routing, which are still the structural base of most commercial GIS software because of their computational efficiency. When modeling non-channelized flow in complex, high-altitude scenarios, these more advanced frameworks provide a more accurate representation of natural flow dispersion and hillslope moisture dynamics (Tarboton et al., 2024). However, as this research has demonstrated, the physical realism of these digital outputs remains mainly dependent on the quality of the underlying topographical data and the subjective calibration of initiation thresholds. The persisting "validation gap" between the Global North and South is a significant finding from current study. While drone-derived DEMs and high-resolution LiDAR have transformed catchment analysis in developed regions, the Global South still faces data scarcity and must rely on coarser satellite products that frequently fail to resolve important small-scale hydrologic features (Bhardwaj et al., 2024). Furthermore, methodological subjectivity still adds a great deal of uncertainty to regional water resource evaluations due to the absence of established procedures for "snapping" pour sites or setting changeable stream thresholds (Müller & Schmidt, 2026). As climate-induced hydrological fluctuations become increasingly irregular, the demand for a "gold standard" in open-source, reproducible GIS procedures have never been higher. In the future, integrating machine learning (ML) with conventional physics-based flow routing will be the next frontier in geospatial hydrology. According to Kumar and Singh (2025), "intelligent" DEM conditioning where AI can more accurately differentiate between real endorheic depressions and fake sinks than existing geometric algorithms is the field's future. The worldwide research community must prioritize the democratization of high-performance computing (HPC) and promote cross-border data sharing in order to fully exploit its promise. By bridging the gap between advanced spatial algorithms and the practical socioeconomic needs of vulnerable communities, the geospatial community can ensure that these digital models remain reliable tools for climate adaptation, flood mitigation, and sustainable water management into the late 2020s (Nguyen et al., 2025).

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AUTHOR CONTRIBUTIONS

Rajjyoti Senapati and Shailen Deka, both contributed to the conceptualization and methodology; Shailen Deka supervised the study, after that a formal analysis and inputs were discussed. Rajjyoti Senapati prepared the original draft of the manuscript. All authors contributed in writing, reviewing, and editing the manuscript.

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