COMPREHENSIVE LECTURE NOTES AND TUTORIAL

on

Hydrological Analysis using the ArcGIS Pro Spatial Analyst Hydrology Toolset

(Theory, Algorithms, and Step-by-Step Watershed Delineation Workflow)

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For PhD Scholars and Researchers
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PART I: THEORETICAL FOUNDATION OF HYDROLOGICAL ANALYSIS

1. Introduction to Hydrological Modelling and Watershed Analysis

Hydrological analysis using Geographic Information Systems (GIS) provides the quantitative basis for water resource management, flood forecasting, soil erosion modelling, and environmental impact assessment. The drainage basin (or catchment) is the principal unit of hydrological investigation: it represents the area of land surface that contributes surface runoff to a single outlet through a connected channel network. Delineation of this contributing area, identification of the stream network, and characterisation of basin morphometry together form the foundation of distributed and semi-distributed hydrological models.

The Spatial Analyst Hydrology toolset in ArcGIS Pro implements a sequence of raster-based operations that transform a Digital Elevation Model (DEM) into hydrologically meaningful surfaces. The toolset performs sink filling, flow-direction encoding, flow-accumulation computation, stream-network extraction, stream ordering, and watershed delineation. Each operation produces a spatial dataset that may be used independently or combined with subsequent operations within an ordered analytical chain.

These tools are widely applied in academic research and operational hydrology. The outputs are used as inputs to physically-based models such as the Soil and Water Assessment Tool (SWAT), the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS), and the MIKE SHE distributed hydrological framework. In Indian conditions, the toolset has been employed for groundwater recharge assessment in lateritic terrains, flood hazard mapping in deltaic and coastal river basins, and morphometric prioritisation of micro-watersheds for soil and water conservation planning.

2. Historical Context and Significance of Digital Terrain Analysis

The origin of automated drainage extraction from digital elevation data is attributed to the work of O'Callaghan and Mark (1984), who proposed the deterministic eight-direction (D8) algorithm for assigning flow direction in a regular grid. This algorithm, despite its simplicity and the discretisation error it introduces, remains the most widely used flow-direction method in operational hydrological GIS. Subsequent refinements introduced multiple-flow-direction methods (Quinn et al., 1991), the D-Infinity method based on triangular facet decomposition (Tarboton, 1997), and stream-burning techniques to enforce known channel locations.

The integration of these algorithms into commercial GIS software began with ArcInfo Workstation in the late 1980s, where the GRID module exposed hydrological functions through Arc Macro Language (AML) scripts. Jenson and Domingue (1988) formalised the modern raster-hydrology workflow: fill sinks, compute flow direction, compute flow accumulation, threshold the accumulation grid to extract streams, and delineate watersheds from pour points. This sequence remains the canonical workflow in ArcGIS Pro and is preserved across QGIS (using GRASS or SAGA), GRASS GIS native r.watershed, and the open-source TauDEM library.

ArcGIS Pro inherits and extends this lineage. The Spatial Analyst Hydrology toolset is licensed as part of the Spatial Analyst extension and is required for advanced raster hydrology. ArcGIS Pro additionally provides newer tools such as Derive Stream As Line and Derive Stream As Raster, which combine multiple steps of the classical workflow into single operations and apply to wide application in rapid, exploratory analysis.

3. The ArcGIS Pro Hydrology Toolset

The Hydrology toolset is contained within the Spatial Analyst toolbox in ArcGIS Pro. It groups together the raster operations required to model surface water flow over a terrain. The toolset assumes that gravity is the only force driving overland flow and that flow follows the steepest descent path from each cell. These assumptions are appropriate for first-order hydrological characterisation but should be revisited when modelling karst, urban drainage, or terrain with strong subsurface flow contributions.

3.1 Evolution from ArcInfo Workstation to ArcGIS Pro

Version	Year	Platform	Key Features
ArcInfo GRID	Late 1980s	ArcInfo Workstation (UNIX)	First implementation of Jenson–Domingue workflow through GRID and AML
ArcView 3.x	Mid 1990s	ArcView with Spatial Analyst extension	Hydrologic Modeling sample extension; menu-driven access to fill, flowdirection, flowaccumulation
ArcGIS 9.x	2004–2010	ArcMap with Spatial Analyst	Hydrology toolset formalised; Watershed and Basin tools standardised
ArcGIS 10.x	2010–2022	ArcMap and ArcCatalog	D-Infinity option added for Flow Direction (10.4+); Geometric Network deprecated in favour of raster–feature workflows
ArcGIS Pro 2.x	2018–2022	ArcGIS Pro 64-bit	MFD option added; Storage Capacity tool introduced; Python 3 (arcpy) replaces Python 2
ArcGIS Pro 3.x	2022–present	ArcGIS Pro 3.0–3.x	Derive Stream As Line and Derive Stream As Raster tools; performance improvements through parallel processing

3.2 Tools in the Spatial Analyst Hydrology Toolset

The toolset exposes the following tools in ArcGIS Pro 3.x. Each tool is documented with its required inputs, output type, and the typical position it occupies within the workflow.

Tool	Output Type	Workflow Position	Primary Use
Fill	Raster (DEM)	Step 1	Removes spurious sinks from the input DEM

Tool	Output Type	Workflow Position	Primary Use
Flow Direction	Raster (integer codes)	Step 2	Encodes the direction of steepest descent for each cell
Flow Accumulation	Raster (counts)	Step 3	Counts upstream cells contributing to each cell
Flow Length	Raster (distance)	Optional	Computes upstream or downstream flow distance
Sink	Raster	Diagnostic	Identifies cells of internal drainage in unfilled DEM
Con (with threshold)	Raster (1/NoData)	Step 4	Defines stream cells from the accumulation raster
Stream Link	Raster (integer IDs)	Step 5	Assigns unique IDs to stream segments between junctions
Stream Order	Raster (order values)	Step 6	Assigns Strahler or Shreve order to stream segments
Stream to Feature	Polyline feature class	Step 7	Vectorises the stream raster
Snap Pour Point	Raster (point cells)	Step 8	Relocates user-supplied outlets onto high-accumulation cells
Watershed	Raster	Step 9	Delineates contributing area for snapped pour points
Basin	Raster	Step 10	Delineates all natural drainage basins from the flow-direction raster
Storage Capacity	Table	Optional	Computes elevation–volume relationship for reservoirs
Derive Stream As Line	Polyline feature class	All-in-one	Combines fill, flow direction, accumulation, and vectorisation
Derive Stream As Raster	Raster	All-in-one	Same as above with raster output

4. Fundamental Concepts and Terminology

4.1 Digital Elevation Model (DEM)

A Digital Elevation Model is a raster representation of the bare-earth elevation surface, in which each cell stores a single elevation value (typically in metres above mean sea level). The horizontal resolution of the DEM determines the smallest hydrological feature that can be resolved; the vertical accuracy governs the reliability of derived flow paths. A 30 m SRTM DEM resolves first-order channels of approximately 60–90 m width, while a 1 m LiDAR DEM resolves rills, terraces, and minor channel structures. Selection of DEM resolution should match the scale of the hydrological question rather than the highest available resolution.

4.2 Drainage Basin and Watershed

A drainage basin is the area of land surface that drains to a common outlet through a connected stream network. The terms catchment, watershed, and drainage basin are used interchangeably in international literature; in Indian usage following the Central Water Commission, basin denotes the largest unit (e.g., the Krishna basin), sub-basin or watershed denotes an intermediate unit, and micro-watershed denotes a unit of approximately 500 to 2000 hectares used in soil and water conservation planning. The boundary of a basin is the drainage divide, which separates surface flow into two adjacent basins.

4.3 Pour Point and Outlet

A pour point (also called outlet or basin outlet) is the cell at which surface flow exits a drainage basin. In the Watershed tool, pour points are user-supplied as a point feature class or as a raster of designated cells. The accuracy of the resulting watershed depends critically on the precise placement of the pour point. A pour point placed even one cell off the main channel may produce a degenerate watershed of only a few cells. The Snap Pour Point tool addresses this issue by relocating the supplied point onto the highest-accumulation cell within a user-defined search radius.

4.4 Sinks and Spurious Pits

A sink is a cell whose elevation is lower than all of its eight neighbours, such that no surface flow direction can be assigned by the D8 method. Sinks may be genuine endorheic features (e.g., closed depressions in arid regions) or spurious artefacts arising from DEM interpolation, sensor noise, or vertical quantisation. Genuine sinks are rare in humid Indian conditions, and the standard practice is to fill all sinks before computing flow direction. The Sink tool reports the locations of sinks in an unfilled DEM and is recommended as a diagnostic step before the Fill operation.

4.5 Stream Network and Drainage Density

The stream network is the set of cells that exceed a flow-accumulation threshold and are therefore considered to carry channelised flow. The threshold (often denoted A_c or critical support area) is the smallest contributing area required to maintain a perennial or persistent channel. In Indian humid regions, A_c values of 0.5–1.0 km² are commonly used; in semi-arid regions, A_c values of 2–10 km² are appropriate. Drainage density (D_d) is defined as the total length of streams divided by the basin area and is expressed in km/km². D_d is sensitive to the chosen threshold and should always be reported alongside the threshold value.

5. Algorithms in the Hydrology Toolset

5.1 D8 Flow Direction Algorithm

The deterministic eight-direction (D8) algorithm assigns flow from each cell to one of its eight neighbours in the direction of steepest descent. The slope to each neighbour is calculated as the elevation difference divided by the inter-cell distance: 1 cell-width for the four cardinal neighbours and √2 cell-widths for the four diagonal neighbours. The neighbour with the maximum slope receives all the flow. ArcGIS Pro encodes the eight directions as powers of two: East = 1, Southeast = 2, South = 4, Southwest = 8, West = 16, Northwest = 32, North = 64, and Northeast = 128. The D8 algorithm is computationally efficient and exactly preserves drainage area, but introduces parallel-flow artefacts on planar surfaces and does not represent flow divergence.

Slope formula at cell c to neighbour n:

$$\text{Slope}(c, n) = (Z_c - Z_n) / d(c, n)$$

where Z is elevation and d(c, n) is 1 for cardinal neighbours and $\sqrt{2}$ for diagonal neighbours.

5.2 D-Infinity Flow Direction Algorithm

The D-Infinity (D∞) algorithm proposed by Tarboton (1997) addresses the planar-flow limitation of D8. Each 3×3 cell neighbourhood is partitioned into eight triangular facets, and the steepest downslope direction is computed as a continuous angle in the range $[0, 2\pi)$. Flow is then partitioned between the two D8 neighbours that bracket this angle, with weights proportional to the angular proximity of the flow direction to each neighbour. This produces smoother accumulation surfaces and reduces the parallel-flow artefacts of D8, at the cost of slightly higher computational expense and a more complex flow-direction encoding (a floating-point angle rather than an integer code).

5.3 Multiple Flow Direction (MFD)

The Multiple Flow Direction algorithm (Quinn et al., 1991) distributes flow from each cell to all downslope neighbours, with the partition weights proportional to the slope to each neighbour raised to a power p (commonly p = 1.1 in ArcGIS Pro). MFD is appropriate for representing divergent flow on hillslopes and ridge tops, and is widely used for soil erosion modelling and topographic wetness index (TWI) calculations. It is less appropriate for delineating discrete channel networks, where convergent flow is the dominant signal.

5.4 Strahler and Shreve Stream Ordering

Stream ordering schemes assign an integer rank to each segment of a channel network. Two schemes are implemented in the Stream Order tool. In the Strahler (1957) method, headwater (first-order) streams have order 1; when two streams of order n meet, the resulting downstream segment has order n+1; when two streams of different order meet, the downstream segment retains the higher of the two orders. In the Shreve (1966) method, headwater streams have magnitude 1; at every confluence the magnitudes of the joining streams are summed. Strahler order is more widely used for morphometric analysis and is the default in most Indian morphometric studies; Shreve magnitude is more sensitive to network density and is used in network-topology research.

6. Data Sources for Hydrological Analysis

DEM data form the principal input for all tools in the Hydrology toolset. The selection of the appropriate DEM should consider the spatial scale of the basin, the vertical accuracy required, the temporal currency of the surface (post-event versus pre-event), and the licensing terms applicable to academic and commercial use.

Source	Coverage	Spatial Resolution	Vertical Accuracy	Access
SRTM 1 Arc-Second Global	60° N to 56° S	~30 m	± 16 m (LE90)	USGS EarthExplorer (free)
ASTER GDEM v3	83° N to 83° S	~30 m	± 17 m (LE95)	NASA Earthdata (free)
ALOS PALSAR RTC	Global	~12.5 m	± 10 m	ASF Vertex (free, registration)
CartoDEM v3 R1	India only	30 m	± 8 m (RMSE)	ISRO Bhuvan (registration required)
Copernicus DEM (GLO-30)	Global	30 m	± 4 m (LE90)	Copernicus Data Space (free)
NASADEM	60° N to 56° S	30 m	± 5–10 m	NASA Earthdata (free)
LiDAR (state DEM)	Selected Indian states	1–5 m	± 0.15–0.5 m	State remote sensing centres / Survey of India
UAV Photogrammetry	Project-specific	0.05–0.5 m	± 0.05–0.20 m	User-acquired

For Indian river basins, Copernicus GLO-30 and CartoDEM v3 R1 are the recommended baseline products, with LiDAR or UAV-derived DEMs preferred where available for sub-basin and micro-watershed studies. SRTM 1 Arc-Second remains useful for regional analysis owing to its long temporal stability and global homogeneity, although vertical artefacts in vegetated and steep terrain may require post-processing.

PART II: STEP-BY-STEP HYDROLOGY WORKFLOW IN ArcGIS PRO

7. Data Acquisition and Preparation

7.1 Obtaining DEM Data

Step 7.1.1: Identify Data Source

Select a DEM whose resolution is appropriate to the scale of the study basin. For river basins exceeding 1000 km², Copernicus GLO-30 or SRTM 30 m are suitable. For sub-basins below 100 km² and for urban drainage studies, a 5–10 m DEM derived from CartoDEM, ALOS PALSAR, or LiDAR is preferable.

Step 7.1.2: Download and Mosaic

DEM tiles should be downloaded in the native projection (typically Geographic WGS 84 for global products) and mosaicked using the Mosaic to New Raster tool (Data Management Tools > Raster > Raster Dataset). Specify the cell size of the input tiles, the pixel type (32-bit floating point), and the number of bands as 1.

Step 7.1.3: Reproject to UTM

Reproject the mosaicked DEM to the appropriate UTM zone using the Project Raster tool (Data Management Tools > Projections and Transformations). For peninsular India, the relevant zones are UTM 43N (EPSG:32643) for longitudes 72°–78° E, UTM 44N (EPSG:32644) for 78°–84° E, and UTM 45N (EPSG:32645) for 84°–90° E. Use the bilinear resampling method for elevation data.

7.2 DEM Pre-processing

Step 7.2.1: Clip to Study Area

Clip the projected DEM to a rectangular extent that encloses the study basin with a buffer of approximately 10 percent on each side. The buffer prevents edge effects in flow-direction computation. Use the Extract by Mask tool with a polygon feature class as the mask.

Step 7.2.2: Inspect and Document

Examine the histogram of elevation values to identify outliers, no-data regions, and vertical artefacts. Document the DEM source, acquisition date, native resolution, projected resolution, vertical datum (typically EGM96 or EGM2008 for global products), and CRS in the methodology section of the project.

8. Setting Up the GIS Environment

Step 8.1: Geodatabase Configuration

Create a file geodatabase (.gdb) within the project workspace using the Create File Geodatabase tool. All raster intermediate outputs and the final stream and watershed feature classes will be stored in this geodatabase. The recommended folder structure is: Project/Data (for input data), Project/Workspace (for the geodatabase and scratch outputs), and Project/Outputs (for final maps and reports).

Step 8.2: Environment Settings

Open the Geoprocessing Environments dialogue (Analysis tab > Environments) and configure the following globally:

- Workspace: Project/Workspace/hydrology.gdb
- Scratch Workspace: Project/Workspace/scratch.gdb
- Output Coordinate System: WGS 1984 UTM Zone 44N (EPSG:32644) or appropriate zone
- Cell Size: same as input DEM (e.g., 30 m for SRTM)
- Snap Raster: the input DEM (ensures all output rasters are co-registered)
- Extent: same as DEM extent

Step 8.3: Enable Spatial Analyst

Verify that the Spatial Analyst extension is enabled in Project > Licensing. Without this extension, the Hydrology toolset is not available.

9. Step 1: Fill Sinks

Tool: Spatial Analyst Tools > Hydrology > Fill

Purpose: The Fill tool removes spurious sinks from the input DEM by raising the elevation of each sink cell to the elevation of its lowest pour point. The output is a hydrologically conditioned DEM in which every cell drains to a basin outlet.

Step 9.1: Open the Fill Tool

Locate the Fill tool in the Geoprocessing pane (Analysis tab > Tools > Spatial Analyst Tools > Hydrology > Fill). Set the input as the projected, clipped DEM. Leave the Z limit parameter blank to fill all sinks; specify a Z limit (in vertical units of the DEM) only when a known maximum depression depth should be preserved.

Step 9.2: Run and Verify

Set the output filename as DEM_fill.tif (or in the geodatabase as DEM_fill). After execution, compute the cell-wise difference between the filled and unfilled DEM using the Raster Calculator: "DEM_fill" − "DEM_raw". The resulting raster should show small positive values (typically less than 1–2 m) at locations of filled sinks and zero elsewhere. Large filled regions may indicate data voids or systematic DEM errors and should be investigated before proceeding.

Output: a hydrologically conditioned DEM in which all cells drain to the basin outlet.

10. Step 2: Flow Direction

Tool: Spatial Analyst Tools > Hydrology > Flow Direction

Purpose: Encodes the direction of steepest descent from each cell to one of its eight neighbours (D8) or partitions flow among neighbours (D-Infinity, MFD).

Step 10.1: Configure the Tool

Parameter	Setting	Notes
Input surface raster	DEM_fill	Filled DEM from Step 1
Output flow direction raster	FlowDir_D8	Integer raster of flow codes
Force all edge cells to flow outward	Checked	Prevents edge artefacts
Output drop raster	(optional)	Records the drop in elevation along the flow path
Flow direction type	D8	Use MFD for divergent flow studies; D-Infinity for TWI

Step 10.2: Interpretation of D8 Codes

The output is an integer raster with the following values: 1 = East, 2 = Southeast, 4 = South, 8 = Southwest, 16 = West, 32 = Northwest, 64 = North, 128 = Northeast. Cells with no defined flow direction (typically the basin outlet at the DEM edge) receive a value of zero.

Step 10.3: Validate

Display the flow-direction raster with a unique-values symbology and overlay the DEM. The codes should follow the topographic gradient: cells on a south-facing slope should display values dominated by 4 (South). Anomalies indicate residual sinks or DEM errors.

11. Step 3: Flow Accumulation

Tool: Spatial Analyst Tools > Hydrology > Flow Accumulation

Purpose: Computes, for each cell, the number of upstream cells that drain into it. The flow-accumulation raster is the basis for stream-network extraction and for computing the topographic wetness index.

Step 11.1: Configure

Parameter	Setting	Notes
Input flow direction raster	FlowDir_D8	From Step 2
Output accumulation raster	FlowAcc	Counts of upstream cells
Input weight raster	(optional)	Use for weighted accumulation, e.g., rainfall-weighted
Output data type	Float	Use Integer only for unweighted small basins
Flow direction type	D8	Must match Step 2

Step 11.2: Display

The raw accumulation raster is dominated by zero-valued hillslope cells and a small number of high-valued channel cells, producing a histogram with extreme right-skew. For visualisation, apply a log-transform to the symbology: in Layer Properties > Symbology, set the stretch type to Standard Deviation with n = 2, or apply a logarithmic stretch. The channel network will appear as bright lines against a dark hillslope background.

Step 11.3: Convert Counts to Area

To express accumulation as contributing area in m², multiply the accumulation raster by the cell area (cell size squared) using the Raster Calculator: "FlowAcc" * 900 for a 30 m DEM. To express in km², divide further by 1,000,000.

12. Step 4: Stream Definition (Threshold)

Tool: Spatial Analyst Tools > Map Algebra > Raster Calculator (with Con expression)

Purpose: Extracts the stream-cell network by thresholding the flow-accumulation raster. Cells with accumulation greater than or equal to the critical support area are classified as streams; all other cells receive NoData.

Step 12.1: Choose the Threshold

The threshold (T) should match the smallest channel that the analyst wishes to represent, expressed in number of upstream cells. For a 30 m DEM:

Climate / Terrain	T (cells, 30 m)	Equivalent Area (km²)	Resulting Network
Humid tropical (Western Ghats)	500–1000	0.45–0.90	Dense; includes 1st-order rivulets
Sub-humid (Deccan Plateau)	1000–2000	0.90–1.80	Moderate; perennial 1st-order
Semi-arid (Rayalaseema, Marathwada)	5000–10000	4.50–9.00	Sparse; ephemeral channels excluded
Arid (Thar)	10000–20000	9.00–18.00	Trunk channels only

Step 12.2: Run the Conditional Statement

In Raster Calculator, enter:

```
Con("FlowAcc" >= 1000, 1)
```

This produces a raster in which stream cells have a value of 1 and all other cells are NoData. Save the output as Stream_raw.

Step 12.3: Sensitivity Analysis

Generate stream networks at three thresholds (e.g., T = 500, 1000, 2000) and overlay them on the topographic map and on Survey of India 1:50,000 sheets where available. Choose the threshold that best matches the mapped blue-line streams in the SOI sheet for the dominant terrain type. Document the chosen T in the methodology and report drainage density at this T.

13. Step 5: Stream Link

Tool: Spatial Analyst Tools > Hydrology > Stream Link

Purpose: Assigns a unique integer identifier to each segment of the stream network between successive junctions or between a headwater and a junction.

Step 13.1: Configure

- Input stream raster: Stream_raw (from Step 4)
- Input flow direction raster: FlowDir_D8 (from Step 2)
- Output: StreamLink

Step 13.2: Verify

Display the output with a unique-values symbology. Each stream segment should appear in a distinct colour. Segments terminate at every confluence and at the basin outlet. The total number of segments equals the number of unique values in the attribute table.

14. Step 6: Stream Order

Tool: Spatial Analyst Tools > Hydrology > Stream Order

Purpose: Assigns a numeric order to each stream segment using either the Strahler or the Shreve scheme.

Step 14.1: Configure

- Input stream raster: Stream_raw
- Input flow direction raster: FlowDir_D8
- Method: STRAHLER (recommended for morphometric analysis)
- Output: StreamOrder_S

Step 14.2: Inspect Order Statistics

Open the attribute table of the output raster and record the maximum order, the count of segments at each order, and the total length of streams at each order (the latter requires conversion to features in Step 7). For typical Indian sub-basins of 100–1000 km², expected maximum Strahler order ranges from 4 to 6.

15. Step 7: Stream to Feature

Tool: Spatial Analyst Tools > Hydrology > Stream to Feature

Purpose: Converts the stream raster to a polyline feature class with attributes preserving stream order and link identifier.

Step 15.1: Configure

- Input stream raster: StreamOrder_S
- Input flow direction raster: FlowDir_D8
- Simplify polylines: Checked (reduces vertex count without changing topology)
- Output: StreamNetwork (polyline feature class)

Step 15.2: Compute Geometry Attributes

Open the attribute table of the output and use Calculate Geometry to add a Length_m field in metres. Aggregate this field by stream order using Summary Statistics to report total stream length per order class. These values feed directly into morphometric analysis (bifurcation ratio, stream-length ratio, drainage density).

16. Step 8: Snap Pour Point

Tool: Spatial Analyst Tools > Hydrology > Snap Pour Point

Purpose: Relocates user-supplied outlet points onto the cell of highest flow accumulation within a specified search radius. This step is essential before running the Watershed tool.

Step 16.1: Create Outlet Points

Create a point feature class named Outlets in the same projection as the DEM. Add a unique integer field named PourID. Use the Editor toolbar to digitise outlet locations: a basin gauge station, a culvert, the inlet of a reservoir, or any other location where a watershed boundary is required. Each point must have a unique PourID.

Step 16.2: Configure Snap

- Input raster or pour point feature data: Outlets
- Pour point field: PourID
- Input accumulation raster: FlowAcc
- Snap distance: 100 m (3–4 cells for a 30 m DEM)
- Output: SnappedOutlets (raster)

Step 16.3: Verify Snap

Display the snapped output as a point raster (or convert to feature class with Raster to Point) and overlay the original outlet points and the FlowAcc raster. Each snapped point should sit exactly on a high-accumulation channel cell. If a snap distance of 100 m is insufficient, increase to 250–500 m, but check that the snapped point still corresponds to the intended channel and not to an adjacent tributary.

17. Step 9: Watershed Delineation

Tool: Spatial Analyst Tools > Hydrology > Watershed

Purpose: Delineates the upslope contributing area for each snapped pour point. The output is a raster in which all cells draining to a single pour point share the PourID of that point.

Step 17.1: Configure

- Input flow direction raster: FlowDir_D8
- Input raster or feature pour point data: SnappedOutlets
- Pour point field: Value (for raster) or PourID (for features)
- Output: Watershed_raster

Step 17.2: Convert to Polygon

Convert the watershed raster to a polygon feature class using the Raster to Polygon tool (Data Management Tools > Raster > Raster to Other Format). Set Simplify Polygons = false to preserve the cell-wise boundary; check the option to dissolve adjacent polygons of the same value. The result is a polygon feature class with one polygon per watershed.

Step 17.3: Compute Basin Area

Add an Area_km2 field and calculate using Calculate Geometry (set the area unit to square kilometres). For very small watersheds (< 5 cells), suspect an unsnapped pour point and re-run Steps 8–9 with a larger snap distance.

18. Step 10: Basin Tool (All Basins)

Tool: Spatial Analyst Tools > Hydrology > Basin

Purpose: The Basin tool delineates all natural drainage basins from the flow-direction raster without requiring user-supplied pour points. Each basin terminates at a flow-direction sink (typically the DEM edge or an internal drainage point).

Step 18.1: Configure

- Input flow direction raster: FlowDir_D8
- Output: Basin_raster

Step 18.2: Use Cases

The Basin tool is appropriate when the analyst wishes to delineate all sub-basins within a study area without pre-defining outlets, for example in regional drainage characterisation or in initial reconnaissance of an unfamiliar terrain. The output is a raster in which each cell carries the integer ID of the basin to which it drains. Convert to polygons using Raster to Polygon for cartographic display and area computation.

Note: The Basin tool typically produces many small basins along the DEM edge that have no hydrological meaning. Filter these by computing area and removing polygons smaller than a project-specific threshold (e.g., 1 km²).

19. Cartographic Presentation of Hydrological Outputs

Hydrological maps prepared for academic publication should follow the cartographic conventions specified in the Indian Society of Remote Sensing journal guidelines and the IAHS scientific publication standards.

19.1 Symbology

Layer	Symbology	Notes
DEM	Hillshade overlay with elevation colour ramp (terrain)	Apply 50% transparency to elevation

Layer	Symbology	Notes
Stream Network	Polyline graduated by Strahler order	Width: 0.3–1.5 mm; colour: blue (CMYK 100,50,0,0)
Watershed Boundary	Polygon outline only	Width: 1.0 mm; colour: black or dark red
Pour Points / Outlets	Triangle marker	Size: 4–6 pt; colour: red
Sub-basins (from Basin tool)	Unique values, qualitative palette	Use ColourBrewer Set3 or Pastel1

19.2 Required Map Elements

- Title: descriptive of basin name, year of DEM, and metric displayed
- North arrow
- Scale bar in metric units (km)
- Legend with all classes labelled
- Inset map showing the basin within the state and within India
- Coordinate grid in DMS or decimal degrees on all four sides
- Data source attribution (DEM source, year, resolution)
- CRS / EPSG code in margin (e.g., “WGS 1984 UTM Zone 44N (EPSG:32644)”)
- Author and date of map preparation
- Export at 300 DPI in TIFF or PDF format for publication

PART III: APPLICATIONS, VALIDATION, AND REFERENCES

20. Applications of Hydrological Analysis

Application Domain	Description
Watershed Management Planning	Delineation of watersheds and sub-watersheds for prioritisation under the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) and Integrated Watershed Management Programme (IWMP)
Flood Hazard Assessment	Extraction of channel networks and contributing areas as inputs to HEC-HMS, HEC-RAS, and MIKE 11 hydrodynamic models
Soil Erosion Modelling	Computation of slope length and steepness (LS) factor for the Revised Universal Soil Loss Equation (RUSLE) using flow-accumulation-derived flow length
Groundwater Recharge Studies	Identification of zones of high topographic wetness index (TWI) for delineation of recharge potential in lateritic and alluvial aquifers
Sediment Yield Estimation	Sediment routing through stream networks using contributing area and slope-derived sediment delivery ratios
Reservoir and Dam Site Selection	Identification of suitable reservoir sites by combining basin area, slope, and storage capacity computations
Drainage Density and Morphometric Analysis	Quantification of basin morphometry (drainage density, bifurcation ratio, ruggedness number, hypsometric integral) for tectonic and geomorphic interpretation
Environmental Flow Assessment	Identification of channel network connectivity for ecological flow studies in regulated rivers
Landslide Hazard Mapping	Computation of contributing area as a predictor variable in physically-based slope stability models (e.g., SHALSTAB, SINMAP)
Urban Drainage and Stormwater Planning	Sub-catchment delineation for SWMM (Storm Water Management Model) inputs in urban hydrology

21. Common Errors and Troubleshooting

Error / Issue	Possible Cause	Solution
Watershed contains only a few cells	Pour point not snapped to a high-accumulation cell	Run Snap Pour Point with a larger snap distance (250–500 m). Verify that the snapped point coincides with a channel.
Stream network appears as parallel lines on flat terrain	D8 algorithm artefact on planar surfaces	Switch to D-Infinity or MFD; or apply minor noise to the DEM (± 0.01 m) using Raster Calculator before flow direction.

Error / Issue	Possible Cause	Solution
Fill tool runs but produces unchanged DEM	DEM has no sinks (rare) or Z limit is too low	Verify by running the Sink tool first. Set Z limit to a high value or leave blank to fill all sinks.
Watershed boundary cuts across a known basin	Pour point placed off the channel; or DEM edge effect	Re-snap the pour point. Buffer DEM extent by 10 percent and re-run the workflow.
Stream network is too dense or too sparse	Inappropriate flow-accumulation threshold for terrain	Test thresholds at half and double the initial value. Compare with Survey of India 1:50,000 sheets.
Output projection differs from input	Environment settings not applied	Set Output Coordinate System and Snap Raster in Geoprocessing Environments before each tool run.
No-data values in flow accumulation	DEM contains no-data cells inside basin	Fill no-data using Focal Statistics with mean filter, then re-run the workflow.
Stream Order tool returns blank raster	Input stream raster has values other than 1	Re-run the Con expression to ensure stream cells equal 1 and all other cells are NoData.
Slow performance on large DEM (> 10000 × 10000 cells)	Insufficient memory or unoptimised raster format	Convert input to .tif with LZW compression; tile the DEM and process by sub-basin.
Watershed polygon has irregular jagged boundary	Raster cell-wise boundary preserved	Apply a moderate smoothing using the Smooth Polygon tool with PAEK algorithm and tolerance of 1–2 cell sizes.

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Appendix: Complete Tool and Morphometric Formula Reference

A.1 Hydrology Toolset — Tool Reference

Step	Tool Name	Inputs	Output	Toolbox Path
1	Fill	Raw DEM	Filled DEM	Spatial Analyst > Hydrology > Fill
2	Flow Direction	Filled DEM	Flow direction raster (D8 codes)	Spatial Analyst > Hydrology > Flow Direction
3	Flow Accumulation	Flow direction	Accumulation raster (counts)	Spatial Analyst > Hydrology > Flow Accumulation
4	Con (Map Algebra)	Accumulation raster	Stream raster (1/NoData)	Spatial Analyst > Map Algebra > Raster Calculator
5	Stream Link	Stream raster, Flow direction	Link IDs	Spatial Analyst > Hydrology > Stream Link
6	Stream Order	Stream raster, Flow direction	Order raster (Strahler/Shreve)	Spatial Analyst > Hydrology > Stream Order
7	Stream to Feature	Stream order, Flow direction	Polyline feature class	Spatial Analyst > Hydrology > Stream to Feature
8	Snap Pour Point	Outlets, Accumulation	Snapped points (raster)	Spatial Analyst > Hydrology > Snap Pour Point
9	Watershed	Flow direction, Snapped pour points	Watershed raster	Spatial Analyst > Hydrology > Watershed
10	Basin	Flow direction	All-basins raster	Spatial Analyst > Hydrology > Basin

A.2 Flow Direction Encoding (D8)

Direction	Code	Direction	Code
East	1	West	16
Southeast	2	Northwest	32
South	4	North	64
Southwest	8	Northeast	128

A.3 Morphometric Parameter Formulas

Derived from outputs of the Hydrology toolset and used in standard morphometric analysis (Horton, 1945; Strahler, 1957; Schumm, 1956).

Parameter	Symbol	Formula	Unit
Stream Order	U	Hierarchical (Strahler/Shreve)	Dimensionless
Stream Number	N_u	Total count of segments of order u	Count
Stream Length	L_u	Total length of segments of order u	km
Mean Stream Length	L_um	L_u / N_u	km
Stream Length Ratio	R_L	L_u / L_(u−1)	Dimensionless
Bifurcation Ratio	R_b	N_u / N_(u+1)	Dimensionless
Drainage Density	D_d	Σ L_u / A	km/km^2
Stream Frequency	F_s	Σ N_u / A	1/km^2
Drainage Texture	R_t	Σ N_u / P	1/km
Form Factor	R_f	A / L_b^2	Dimensionless
Circulatory Ratio	R_c	4πA / P^2	Dimensionless
Elongation Ratio	R_e	(2/L_b) × √(A/π)	Dimensionless
Compactness Coefficient	C_c	0.2841 × P / √A	Dimensionless
Relief Ratio	R_h	H / L_b	Dimensionless
Ruggedness Number	R_n	H × D_d (with H in km)	Dimensionless

Where A = basin area (km^2); P = basin perimeter (km); L_b = basin length (km); H = basin relief, the difference between maximum and minimum elevation (km); u = stream order.

A.4 Recommended Flow-Accumulation Thresholds (30 m DEM)

Climate / Terrain	Cells	Area (km^2)
Humid tropical (Western Ghats, North-East India)	500–1000	0.45–0.90
Sub-humid (Deccan, Eastern Ghats)	1000–2000	0.90–1.80
Semi-arid (Rayalaseema, Marathwada, Saurashtra)	5000–10000	4.50–9.00
Arid (Thar, Kachchh)	10000–20000	9.00–18.00
Urban / Engineered drainage	100–500	0.09–0.45

A.5 Python (arcpy) Script Skeleton

The following script automates Steps 1–7 of the workflow. Library versions: ArcGIS Pro 3.2 with Spatial Analyst extension; Python 3.9 (bundled arcpy).

```
# Hydrology workflow automation — ArcGIS Pro 3.x import arcpy from arcpy.sa import *
arcpy.CheckOutExtension('Spatial') arcpy.env.workspace = r'C:/Project/Workspace/hydrology.gdb'
arcpy.env.overwriteOutput = True  dem = 'DEM_raw' threshold = 1000  # cells  # Step 1: Fill dem_fill
= Fill(dem); dem_fill.save('DEM_fill')  # Step 2: Flow Direction (D8) flowdir =
FlowDirection(dem_fill, 'NORMAL', '', 'D8'); flowdir.save('FlowDir_D8')  # Step 3: Flow Accumulation
flowacc = FlowAccumulation(flowdir, '', 'FLOAT', 'D8'); flowacc.save('FlowAcc')  # Step 4: Stream
Definition streams = Con(flowacc >= threshold, 1); streams.save('Stream_raw')  # Step 5: Stream Link
```

```
link = StreamLink(streams, flowdir); link.save('StreamLink')  # Step 6: Stream Order (Strahler) order
= StreamOrder(streams, flowdir, 'STRAHLER'); order.save('StreamOrder_S')  # Step 7: Stream to Feature
arcpy.sa.StreamToFeature(order, flowdir, 'StreamNetwork', 'SIMPLIFY')
arcpy.CheckInExtension('Spatial') print('Hydrology workflow complete.')
```

— End of Document —

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