Hydro Stack: Automated geospatial processing workflow for Water Security Planning

Shubham Kumar [1] and Aaditeshwar Seth [2,3]

[1,2]Department of Computer Science, Indian Institute of Technology Delhi
[3]Amar Nath and Sashi Khosla School of Information Technology, IIT Delhi

November 1, 2026

Abstract

Watershed and micro-watershed delineation underlies a wide range of water security and land management decisions; yet existing global hydrographic products such as HydroSHEDS are static, coarser, and not readily reproducible or adaptable to new regions or scales. We present Hydro Stack, an open-source, end-to-end workflow that automates micro-watershed delineation and hydrological characterization for any user-supplied area of interest. Given only a boundary vector, the pipeline resolves the appropriate projection, acquires and conditions elevation data, delineates micro-watersheds via a hydrologically consistent basin-merging procedure, and derives a unified set of layers, such as natural depressions, drainage networks with stream ordering, pour points, specific catchment area, catchment-level stream order, and inter-basin drainage connectivity. Built mostly on GRASS GIS and released as a containerized, script based pipeline, Hydro Stack makes every step of the analysis transparent, reconfigurable, and reproducible, providing a generalized foundation for local-level hydrological planning.

Keywords: Geospatial Analysis, Hydrological Analysis, Watershed Management, Computational Engineering, Software Engineering.

1 Introduction

Why does watershed analysis matter? A watershed (also called a catchment or drainage basin) is the area of land where all surface water from rainfall to snowmelt drains toward a common outlet, such as a river mouth, lake, or reservoir. Understanding how water moves across a landscape is fundamental to a wide range of real-world problems: predicting flood risk, planning irrigation and reservoir systems, siting infrastructure like bridges and culverts, managing soil erosion, tracking pollutant transport [1], and supporting ecological and conservation planning. Nearly every major decision about how to manage the land and water resources involves tracking the flow of water.

Traditionally, delineating watersheds and mapping stream networks required painstaking manual work with topographic maps. Today, this process is automated using Digital Elevation Models (DEMs), grids of elevation values sampled across a landscape, usually derived from satellite radar or laser (LiDAR) surveys combined with well-established hydrological algorithms that simulate how water flows downhill, cell by cell, across the terrain.

Based on the size of these hydrological units, they are termed as basin, sub-basin, catchment, sub-catchment, watershed, sub-watershed and micro-watershed. Micro-watersheds (MWS) are small, localized land unit, typically covering hundred to few thousand hectares, where all water runoff drains to a single, common point such as a stream, pond, or drain. Micro-watersheds are the smallest hydrological unit for environmental planning and they together constitute a watershed. So, these hydrological units are hierarchical in nature.

Why Hydrosheds and other projects have limitations? HydroSHEDS and similar global hydrographic products offer broad, consistent coverage and have become a standard reference for basin and stream

network delineation worldwide. However, being global in scope, they are necessarily generalized: derived at a fixed resolution and using globally uniform delineation thresholds, they are not tuned to the terrain characteristics or planning needs of any particular region. Their basin units are also released as static, versioned datasets that are suitable for broad-scale analysis, but not something a practitioner can easily regenerate, refine, or extend for a new area of interest, a different flow-accumulation threshold, or an updated elevation source.

Also, for watershed development planning we need other geospatial layers and information like natural depressions, catchment area, micro-watershed connectivity, etc. which these global hydrographic products do not forthrightly provide.

Because the underlying delineation pipeline is not exposed as a reusable, adaptable workflow, incorporating a locally relevant DEM, adjusting micro-watershed size, or reproducing the delineation logic for a specific study area is not straightforward. This motivates a complementary, open pipeline that keeps the same hydrological principles but makes every step like projection selection, DEM conditioning, thresholding, and basin merging, transparent and reconfigurable for the region and scale a given study actually requires.

Why there is a need of generalized architecture that is open and reproducible? The terrain conditions that govern a sensible delineation vary widely across regions: relief, drainage density, DEM quality, and the scale at which interventions are planned differ between mountain catchments, semi-arid plateaus, and alluvial plains. A workflow that bakes in the assumptions of a single region therefore does not transfer, and a generalized one must derive its working configuration (map projection, elevation source, and basin scale) from the area of interest and a small set of explicit parameters rather than from region-specific code. Such generality also matters because elevation data keep improving. A workflow that treats the DEM as an interchangeable input can absorb new sources as they become available, without redesigning the analysis around them.

Openness and reproducibility matter for a second reason: the derived layers feed decisions that are consequential and publicly accountable, such as where to site recharge structures or how to prioritize treatment under watershed development programmes. In this setting, a delineation is only as trustworthy as the ability of others to inspect how it was produced, re-run it, and challenge its choices against local knowledge or field evidence. An open, scripted workflow makes the treatment of depressions, the size of the delineated units, and the resolution of undersized basins explicit and revisable, so that disagreements can be settled by changing a stated parameter rather than by negotiating over an opaque dataset. It also lets the research community extend individual stages, for instance by substituting an alternative conditioning method, and compare the effect on downstream layers within a common framework.

Our contributions We present an end-to-end, open-source workflow for micro-watershed delineation and hydrological characterization that operates on any user-supplied area of interest, anywhere in the world, without manual intervention in the middle. Specifically, our contributions are as follows:

- An automated pipeline that, given only a boundary vector, resolves the appropriate UTM projection, fetches and mosaics the corresponding elevation data, and conditions it for hydrological analysis, requiring no region-specific configuration.
- A watershed-merging procedure that consolidates the fine-grained basins produced by standard flow-accumulation-threshold delineation into micro-watersheds of a specified minimum size, using a hydrologically consistent, vectorized merge that scales efficiently to large study areas.
- A unified set of derived hydrological layers such as natural depressions, micro-watershed boundaries, drainage lines with Strahler and Shreve ordering, pour points, specific catchment area, and catchment-level stream order, that are produced within a single reproducible run and exported in standard geospatial formats.
- An explicit representation of inter-basin drainage topology, connecting each micro-watershed to its upstream and downstream neighbours, generated natively at the same locally-chosen scale and threshold as the delineation itself, rather than inherited fixed from a pre-computed global product.
- A fully containerized, scripted implementation that makes the entire workflow reproducible end-

to-end, allowing results to be independently verified and the pipeline adapted to new regions or parameters.

Organization of the paper The remainder of this paper is organized as follows. Section 2 lays out the system architecture and Section 3 describes the Hydro Stack workflow in detail, covering projection selection, elevation data acquisition, DEM preprocessing, micro-watershed delineation, drainage network extraction, pour point computation, inter-basin connectivity, catchment area estimation, and catchment-level stream ordering. Section 4 presents experiments and evaluates the performance of the pipeline. Section 5 discusses the broader context and applications of the workflow. Section 6 concludes the paper, and reproducibility details and acknowledgements are provided afterwards. Section 9 reviews related work on watershed delineation and existing global hydrographic products.

2 System Architecture

Hydro Stack is organized as a single, linear pipeline built around three architectural layers: a data acquisition layer that resolves and retrieves the inputs needed for a given area of interest, a processing layer that performs all DEM conditioning and hydrological computation inside a GRASS GIS session, and an output layer that exports the derived rasters and vectors in standard geospatial formats. This separation keeps each layer independently reasoned about. The acquisition layer is concerned only with correctly resolving projection and elevation data for an arbitrary region, the processing layer assumes a well-conditioned, correctly projected DEM and focuses purely on hydrological computation, and the output layer is agnostic to how a given layer was derived.

The pipeline is driven entirely by a single vector file describing the area of interest, with no other required input. From this file, the system determines the appropriate UTM projection, retrieves and mosaics elevation data for the corresponding extent, and initializes a GRASS GIS project scoped to the study area. All subsequent modules such as DEM conditioning, micro-watershed delineation, stream extraction, pour point computation, and connectivity and catchment analysis, operate within this single GRASS session, reading and writing intermediate rasters and vectors internally rather than relying on ad hoc file exchange between modules. This design keeps state implicit within the GRASS project rather than distributed across intermediate files, while still allowing every intermediate layer to be inspected or exported independently, since GRASS retains each named raster and vector until the session is closed.

Because acquisition and processing are decoupled, extending the pipeline to a different elevation source, projection strategy, or study area requires no change to the hydrological modules themselves. Similarly, because each hydrological module reads and writes named layers within the same GRASS session rather than being hard-wired to its immediate predecessor, individual modules can be reordered, reused, or extended. For instance, substituting a different depression-handling strategy or stream extraction threshold without altering the rest of the pipeline. The entire pipeline, along with its GRASS GIS dependency, is packaged as a Docker container, so that this architecture is reproducible independent of the host environment.

3 The Hydro Stack Workflow

Our analysis uses a GRASS GIS native approach where all the steps of the analysis are automated end-to-end using Python scripts. The input to the workflow could be an ESRI Shapefile, GeoJSON, GeoPackage, or KML/KMZ file describing the area of interest. The output of the workflow is natural depression map, micro-watershed delineation layer, drainage lines, catchment area raster, stream order raster, and pour points. These six layers form the bedrock for water security planning purposes and other local level hydrological planning.

3.1 Finding the Right Map Projection

Maps of the Earth's curved surface have to be flattened using a projection, and for accurate distance and area measurements. The pipeline uses the UTM (Universal Transverse Mercator) system, which divides the world into narrow zones, each with its own precise projection. This module return the local Coordinate Reference System (CRS) for that zone, which is used in the subsequent steps: downloading elevation data, reprojecting it, and running all the flow calculation in real-world units like meters and hectares.

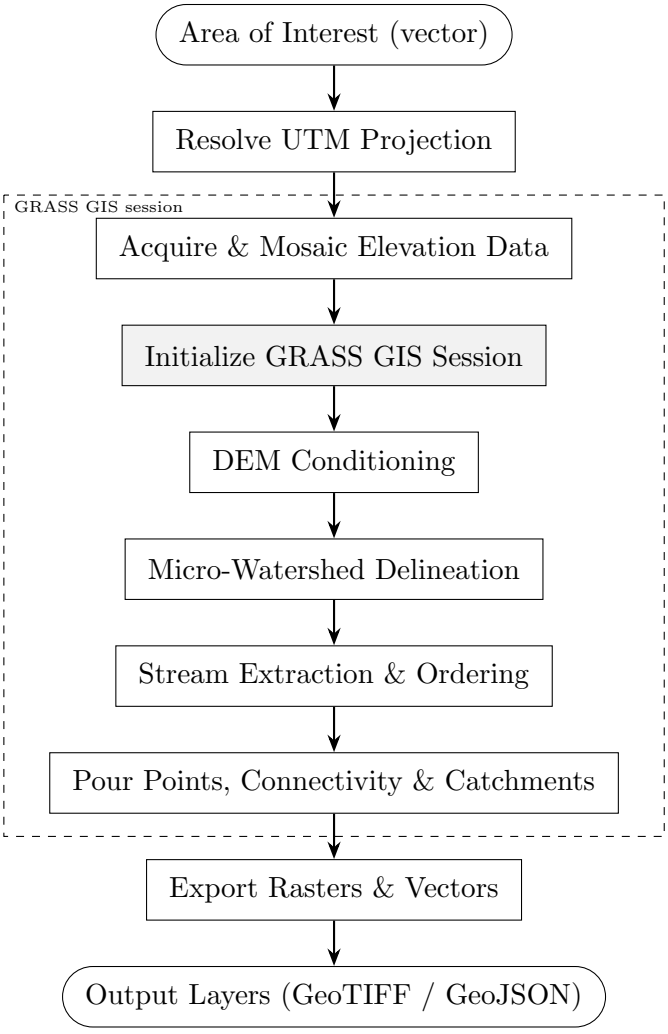


Figure 1: Layered system architecture of the Hydro Stack pipeline: data acquisition, GRASS-native hydrological processing, and export.

3.2 Elevation Data

Given an input vector covering area of interest, we download the corresponding elevation data which could be either a Digital Elevation Map(DEM) or Digital Surface Map(DSM) from OpenTopography. For our analysis, we chose SRTM 1 arc second data, but we provided options for SRTM 3 arc second, Copernicus DEM, NASADEM, ALOS World 3D, SRTM15+ bathymetry, etc. We first tiled the DEM and then fetched it in parallel from the portal. Downloaded tiles were cached, and for the given area of study, they were merged into a single GeoTIFF file for further topographical and hydrological processing. (See figure 2.)

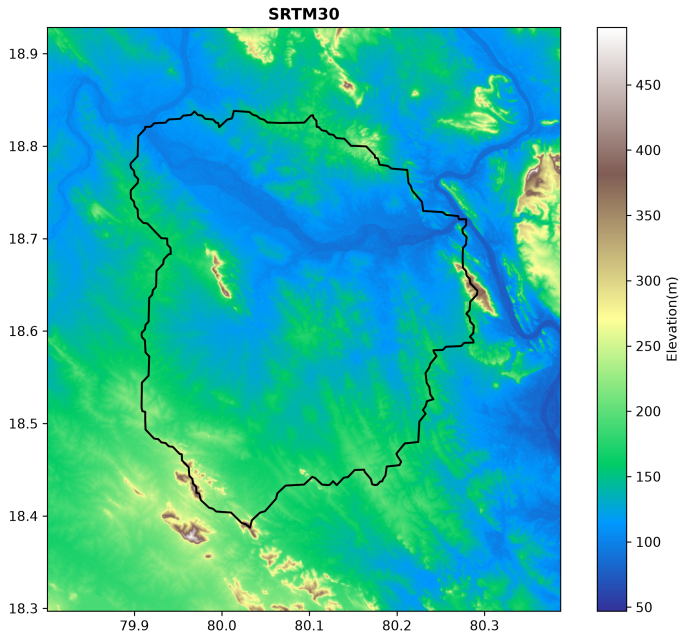


Figure 2: SRTM 30m DEM corresponding to the input vector of HydroSHEDS v1 level 5 basin with Hybas ID: 4051065250. This region lies south of Godavari river near Maharashtra-Telanga-Chhatisgarh border.

3.3 DEM Preprocessing

The DEM data contains natural and artificial sinks or depressions. For hydrological processing the depressions need to be treated. Various techniques exists for preprocessing the DEM like sink filling, dem breaching, etc. We used sink filling as implemented in richdem library.

3.4 Natural Depressions

Depression filling, as used to condition the DEM for flow routing, treats every sink as an artifact to be removed so that flow can be traced continuously to the edge of the study area. This is necessary for hydrological processing, but it also discards information: many of these depressions are not artifacts of the elevation data at all, but real topographic features — natural ponds, sinkholes, and closed basins — that are themselves relevant to water security planning as potential sites for water harvesting or recharge.

We therefore retain the depression-filling step as a source of information rather than discarding it after conditioning. By comparing the filled DEM against the original, unfilled surface, we recover the depth of

every depression that was removed, cell by cell, giving a continuous natural depressions layer over the full study area. This layer is exported independently of the conditioned DEM, providing a map of candidate natural storage locations that can be examined directly, rather than requiring these features to be re-derived separately from the raw elevation data. The conditioned DEM produced alongside it — with depressions filled and flat regions resolved — then serves as the input to all subsequent flow-routing steps.

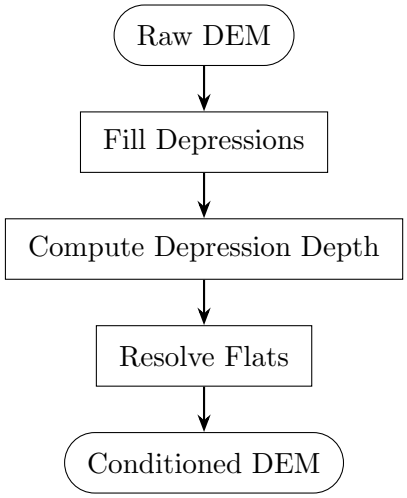


Figure 3: DEM preprocessing workflow.

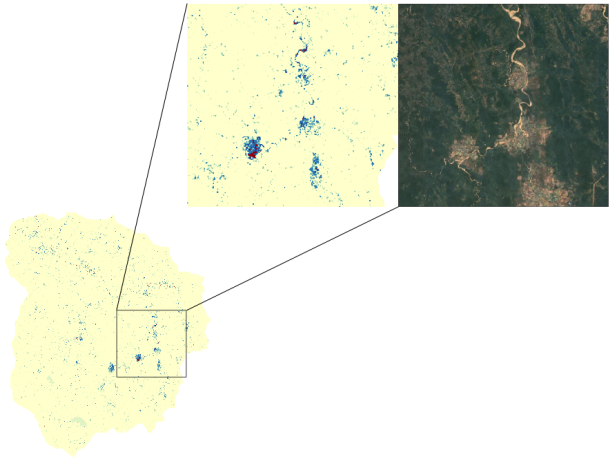


Figure 4: Natural depressions map (including pseudo depressions) for the same HydroSHEDS basin. Also path of the river channel comes naturally in this depressions map.

3.5 Micro-Watershed Delineation and Consolidation

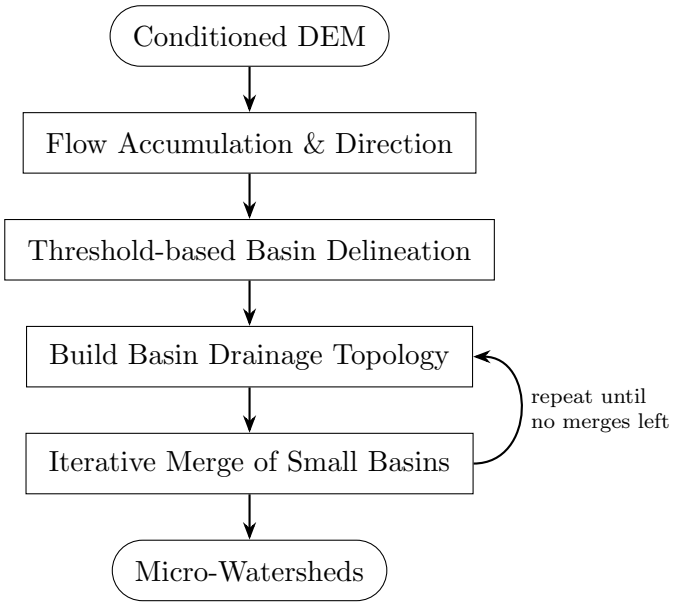


Figure 5: Micro-watershed delineation and consolidation workflow.

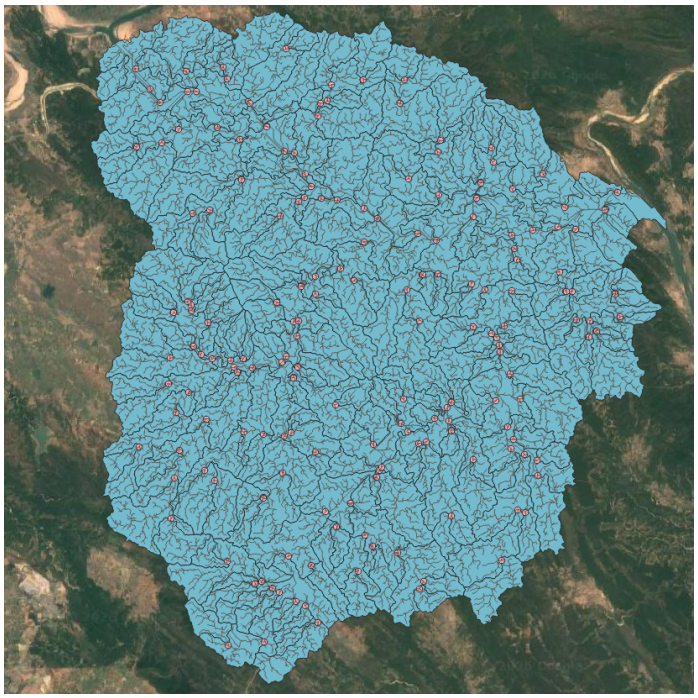


Figure 6: Micro-watershed delineation corresponding to the HydroSHEDS basin. Further drainage network and pour points are laid over it.

Micro-watersheds are first delineated using the standard flow-accumulation-threshold approach: basins are cut wherever the accumulated flow exceeds a fixed threshold (chosen 1200 cells for 30 m DEM resolution), producing a fine-grained partition of the landscape along with the flow direction and accumulation fields needed to relate one basin to another. This threshold, however, is a computational convenience rather than a hydrologically meaningful boundary, and the resulting basins are typically far smaller and more numerous than what is useful for planning purposes.

We therefore consolidate these initial basins into micro-watersheds of a minimum target size (we set this to 500 ha) through an iterative merging procedure. (Algorithms 1 and 2) Merging is driven by the drainage structure rather than by spatial adjacency alone: a basin that is too small is absorbed into the basin it drains into, so the hydrological connectivity of the network is preserved. Only when this is impossible, because the downstream basin is missing or would exceed the size limit (set to 1500 ha), is the basin merged into one of the basins that drain into it, starting with the largest. Basins are processed from smallest to largest, so the tiniest fragments are resolved first and may grow enough to need no further merging. Because a merge can change which basins are neighbours, the topology is rebuilt and the procedure repeated until a full pass produces no merge. Basins for which no admissible neighbour exists are left unchanged, which guarantees termination.

The downstream neighbour of a basin is determined from its effective outlet, the boundary cell carrying the highest accumulated flow, so that minor leakage across the basin boundary does not alter the drainage relationship. All of this is computed over the whole raster at once rather than basin by basin, so the cost of rebuilding the topology grows with the number of cells rather than with the number of basins, and repeated passes remain affordable on large study areas.

Algorithm 1: Flow-aware consolidation of micro-watersheds

Input : Basin raster B, flow direction D, flow accumulation A, minimum area $a_{\min}$, maximum area $a_{\max}$
Output: Consolidated basin raster B'

$n_{\min} \leftarrow a_{\min}$/cell area
$n_{\max} \leftarrow a_{\max}$/cell area
repeat
  $(area, down, up) \leftarrow$ `BuildTopology(`B, D, A`)`
  $S \leftarrow$ basins with $area < n_{\min}$, sorted by increasing area
  if $S = \emptyset$ **then break**
  $parent \leftarrow \emptyset$
  foreach *basin* $b \in S$ **do**
    if b *was already absorbed or* $area[b] \geq n_{\min}$ **then continue**
    `// Candidate targets: downstream neighbour first, then upstream neighbours by decreasing area`
    $K \leftarrow \big(down[b]\big)$ followed by live basins of $up[b]$ sorted by decreasing area
    `// Take the first candidate that keeps the merged basin within the size limit`
    $t \leftarrow$ first $k \in K$ with $area[k] + area[b] \leq n_{\max}$
    if *no such* t *exists* **then** leave b unmerged; **continue**
    $area[t] \leftarrow area[t] + area[b]$
    redirect all links to b in *down* and *up* towards t
    $parent[b] \leftarrow t$
  if $parent = \emptyset$ **then break**
  relabel every cell of B with the final target reached by following *parent*
until *no merge was performed in the last pass*
relabel the remaining basins with compact sequential identifiers
return B

Algorithm 2: BuildTopology: basin areas and drainage neighbours

Input : Basin raster B, flow direction D, flow accumulation A
Output: Basin areas, downstream map, upstream map

$area[b] \leftarrow$ number of cells labelled b, for every basin b
$C \leftarrow$ cells whose $D8$ neighbour lies in a different basin or off the grid
foreach *basin* b **do**
    $c^* \leftarrow$ cell of C in b with the highest $|A|$
    if c^* *drains off the grid or into an undefined cell* **then**
        $down[b] \leftarrow$ none
    else
        $down[b] \leftarrow$ basin containing the $D8$ neighbour of c^*
$up \leftarrow$ inverse of $down$
return $(area, down, up)$

3.6 Stream Network Extraction and Ordering

While the micro-watershed delineation step establishes basin boundaries, the drainage lines themselves — the actual stream channels along which water is concentrated — are extracted separately, directly from the conditioned DEM and its accumulated flow field. A cell is classified as part of the stream network once its contributing flow exceeds a specified accumulation threshold, and the connected cells satisfying this condition are traced into a stream raster and a corresponding vector line network, together with the flow direction field consistent with this extraction.

Each segment of the resulting stream network is then assigned a position within the overall drainage hierarchy. We compute both the Strahler order, which reflects the branching structure of the network by increasing only where two channels of equal order converge, and the Shreve order, which instead reflects the cumulative number of upstream channel segments. These two measures capture complementary aspects of a stream segment's place in the network — topological prominence versus contributing channel count — and are attached to the stream vector along with descriptive attributes distinguishing stream type. Together, they allow the drainage network to be queried and symbolized by hierarchical importance, rather than treated as an undifferentiated set of line segments.

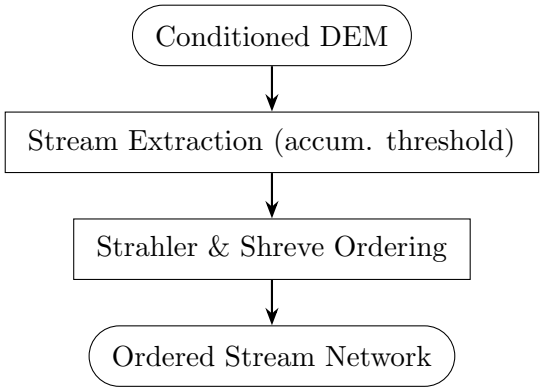


Figure 7: Stream network extraction and ordering workflow.



Figure 8: Drainage network corresponding to the HydroSHEDS basin alonwith the stream order map.

3.7 Pour Points

The pour point of a micro-watershed is the single cell through which all of its accumulated runoff exits, and it is the natural reference location for characterizing that unit, whether for reporting its total contribut-

ing area, linking it to a downstream monitoring point, or anchoring it within the broader drainage network. While the basin boundary describes the full extent of a micro-watershed, the pour point identifies the specific cell through which the entire basin's runoff exits — the only location where connectivity to a neighbouring basin can actually be established. Its correct identification is therefore a direct prerequisite for the connectivity analysis that follows.

For each micro-watershed, the pour point is identified as the boundary cell with the highest accumulated flow among those where the flow direction leads either into a different micro-watershed or off the edge of the study area — both being signatures of the cell through which the basin actually drains outward. This condition distinguishes true outlets from interior cells that, despite carrying high accumulation, still drain onward within the same basin. The resulting set of pour points is exported as a point layer, with each point carrying its parent basin's identifier and the flow accumulation value at that location, providing a compact, per-basin reference for all subsequent connectivity and catchment computations.

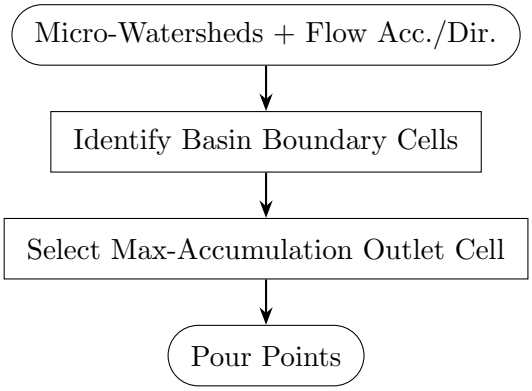


Figure 9: Pour point computation workflow.

3.8 Micro-Watershed Connectivity

Individual micro-watersheds are not hydrologically meaningful in isolation: runoff from one unit passes into a neighbouring one, and this chain of hand-offs ultimately converges at the outlet of the watershed. Capturing this drainage topology — which micro-watershed feeds into which — is essential for any analysis that must be propagated across the landscape, such as routing pollutant loads or aggregating upstream catchment characteristics at a point of interest.

This topology is derived from the pour point of each micro-watershed. Tracing the flow direction one step beyond a pour point identifies the receiving micro-watershed, yielding a directed edge between the two; units with no such downstream neighbour are treated as terminal nodes. The result is a directed graph over all delineated micro-watersheds, consistent with the underlying flow direction field.

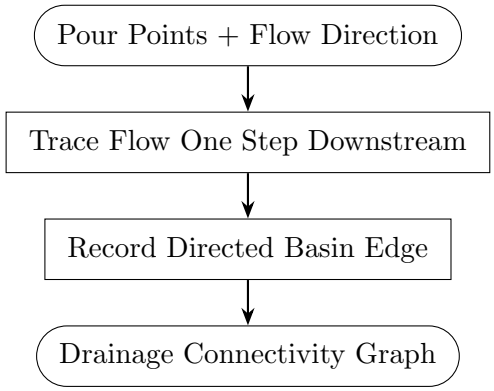


Figure 10: Micro-watershed connectivity workflow.

This connectivity is recorded in two complementary forms. First, it is exported as a GeoJSON network connecting basin centroids, giving a compact visual representation of the drainage structure. Second, and more importantly, it is embedded directly into the micro-watershed vector layer's attribute table — each unit is tagged with its downstream neighbour, its upstream contributors, and the compass bearing of flow toward its downstream neighbour. This makes the drainage network directly queryable by attribute lookup rather than graph traversal, providing the structural backbone for cascading, basin-to-basin analyses central to water security planning.

3.9 Catchment Area

The catchment area at a given cell is the total surface area of land upstream of it that contributes runoff to that location, and is one of the most fundamental derived quantities in hydrological analysis — it underlies stream network extraction, flood risk estimation, and the sizing of hydraulic structures alike. While flow accumulation expresses this contributing area in units of cell counts, it is not directly interpretable across

datasets of differing resolution and offers little physical meaning on its own.

We therefore convert the flow accumulation raster into a specific catchment area raster expressed in square metres, by scaling each cell's accumulated cell count by the ground area of a single cell under the working projection. This yields, for every cell in the study area, the true upstream contributing area in physical units, directly comparable across studies and consistent with the resolution of the input DEM.

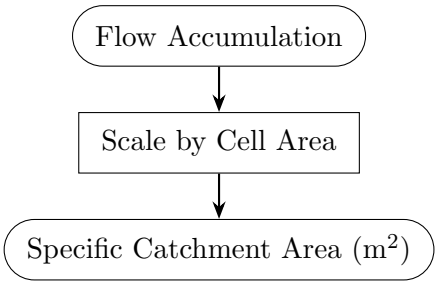


Figure 11: Catchment area computation workflow.

3.10 Catchment Ordering

Stream order — the Strahler hierarchy assigned to each segment of the extracted stream network — indicates the relative position of a stream within the overall drainage network, distinguishing small headwater channels from the larger, higher-order streams they eventually join. For many planning purposes, however, this ordering needs to be known not just along the stream itself, but for every point in the landscape that drains into a given segment.

To this end, each stream segment is used to delineate its own contributing catchment, and the Strahler order of that segment is then assigned to every cell within it. The result is a catchment-level stream order raster, in which each cell carries the order of the stream segment it ultimately drains into. This reframes stream order — ordinarily a property of the channel network alone — as a spatially continuous attribute of the landscape, enabling planning decisions to be prioritized by the order of the drainage a given parcel of land feeds into, rather than by proximity to the stream network alone.

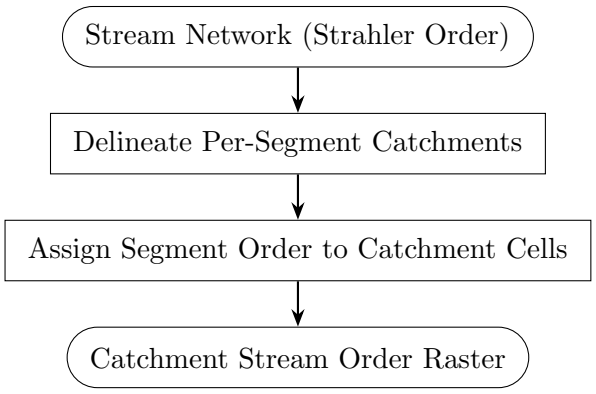


Figure 12: Catchment ordering workflow.

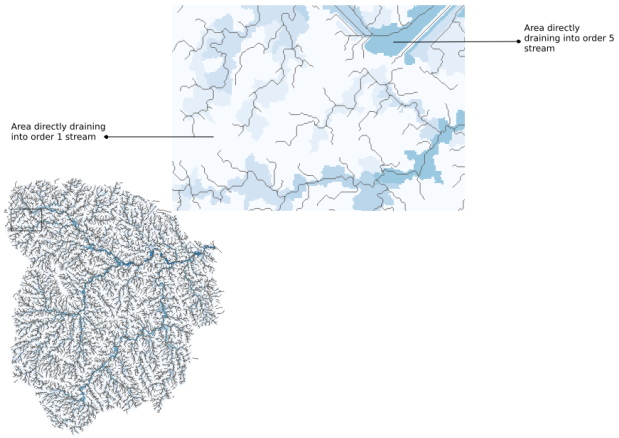


Figure 13: Catchment with stream ordering map for Masalia block, Jharkhand, India. Each cell/ region is assigned the stream order of the immediate stream it drains into.

4 Experiments and Performance Evaluation

4.1 Hardware Used for Experiments

Although the workflow can run on any x86 64-bit or ARM based architecture, but lower computational resource would only permit small level analysis. For larger level analysis such as ours we used DELL Precision 5860 Tower Workstation (a high performance computing facility) with 128 GB of RAM and 6 cores (12 logical processors) with a clock speed of 2.11 GHz.

4.2 Performance Metric on basins of different sizes

We ran the workflow on HydroSHEDS v1 basins at level 5, intersecting with India. There are a total of 125 basins at level 5 intersecting with India and they are of different sizes. We picked the basins at deciles and kept them as the benchmark for our workflow and any algorithmic and implementational improvement in it. (See table 1)

Thus, our workflow can process basins of size nearly 167,000 sq.kms. at 30 m resolution in few hours.

Percentile	Area (sq. km)	DEM Tiles	Execution time
0	28.4	1	15.43 s
10	6,020.16	4	1 min 56.25 s
20	10,247.24	4	4 min 45.62 s
30	13,929.36	6	5 min 51.70s
40	18,601.2	9	8 min 9.12 s
50	23,549.7	6	8 min 44.81 s
60	29,665.54	12	15 min54.37 s
70	36,816.38	9	11 min 56.92 s
80	58,586.3	19	24 min 37.83 s
90	91,072.6	58	3 hr 53 min 52.86 s
100	166,655.9	56	1 hr 10 min 57.75 s

Table 1: Execution time (end-to-end) by percentile of area

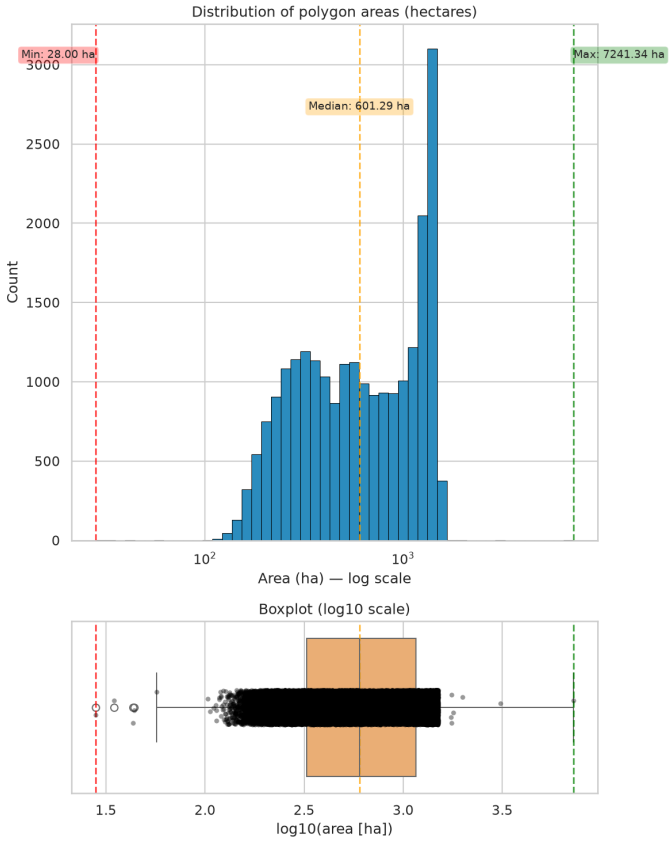


Figure 14: Distribution of areas of micro-watersheds in 100th percentile basin at level 5 intersecting with India

4.3 Size distribution of micro-watersheds

For local level planning, our level of analysis focused on micro-watersheds as the hydrological unit. Each basin was delineated into micro-watersheds and made to fall into sizes between few hundreds of hectares to few thousands.

Percentile	MWS	Min	Median	Max
0	2	765.83	912.67	1059.5
10	836	52	553.43	1500.46
20	1435	88.8	586.63	2017.28
30	1837	124.12	642.90	1499.39
40	2600	37.40	599.67	1500.02
50	3358	89.67	554.03	1503.39
60	4149	94.28	589.97	1621.21
70	5003	106.71	632.14	1548.46
80	8026	26.67	566.24	8024.21
90	12611	25.21	591.59	2327.3
100	22922	28	601.29	7241.39

Table 2: Descriptive statistics on area distribution of the micro-watersheds. All units of area are in hectares.

Specifically we wanted to set the micro-watersheds to fall mostly between 500 ha and 1500 ha. We achieved our objective to a large extent(See table 2 and figure 14). Some of the micro-watersheds still remained between 100 ha and 500 ha becuase no merge candidate was found for them or their merging lead to larger size micro-watersheds. Only a small fraction of the micro-watersheds remain below 100 ha because they were slivers and were not removed as the sliver removal threshold was set to 25 ha. (5 % of 500 ha).

Few of the micro-watersheds were significantly beyond 1500 ha in area and that was because these regions were flat and thus it took lot of traversal for enough flow accumulation to aggregate. leading to larger sized polygons.

5 Broader Context and Applications

Hydro Stack is being used to generate the base layers of CoRE (Commoning for Resilience and Equity) Stack [2], a digital public good built to empower communities and help them in planning and making interventions related to local level watershed management. With the help of applications like Commons Connect [3] built on the top of the core geospatial layers that includes micro-watershed layers, these tools help the local communities and Civil Society Organizations (CSO) in generating demands from local government bodies.

6 Conclusion

We presented Hydro Stack, an open, containerized workflow that takes a boundary vector for any area of interest and produces a consistent set of layers for local-level water planning: natural depressions, micro-watersheds, stream networks with Strahler ordering, pour points, specific catchment area, catchment-level stream order, and explicit inter-basin connectivity. Its central methodological element is a flow-aware consolidation step that merges the fine-grained basins from threshold-based delineation into planning-scale units, so that the threshold seeds the delineation and the target unit size is set separately.

Run on HydroSHEDS level-5 basins intersecting India, the workflow processed basins of up to roughly 167,000 km^2 (about 185 million cells at 30 m) in under few hours on a single workstation, and produced micro-watersheds with most of the micro-watersheds between 100 ha and 1500 ha. The workflow now supplies the base micro-watershed layers of CoRE Stack, where they support community-level planning of water interventions.

Several limitations remain. The initial delineation threshold is currently a fixed constant based on heuristics, and the framework has not yet been validated against reference delineations or field-mapped drainage. Depression handling is limited to filling, and large RAM requirement for running the workflow on larger basins suggest that tiling or parallelization would be needed for continental-scale runs. Future work will address these points: coming up with better set of parameters based on sound reasoning, adding breaching and hybrid conditioning options, evaluating the delineations against existing micro-watershed atlases and global products, and extending the workflow for continental level analysis and augmenting other hydrological layers of interest.

7 Reproducibility Statement

All of the workflow is designed to run in a containerized environment using Docker. The repository for the workflow along with instructions to set up and run the workflow can be found at `https://github.com/mastershubham/hydro_stack/`.

8 Acknowledgements

We would like to acknowledge the financial and advisory support of Tower Research Capital India, Asankhya Trading, and R Systems International without which the project would not have succeeded.

9 Appendix A: Literature Review

9.1 DEM-based Hydrological Modeling

The shift from manual, map-based watershed delineation to automated, grid-based computation began with the recognition that a DEM could be treated as a discrete surface over which flow paths are determined purely by local elevation differences. O'Callaghan and Mark [4] formalized this with the deterministic eight-direction (D8) flow model, in which each cell routes its entire flow to the single steepest-descent neighbour among its eight adjacent cells; this single-flow-direction assumption, together with the accumulation step that sums contributing area downstream along these paths, remains the computational core on which most subsequent watershed and stream-network extraction methods, including ours, are built. Jenson and Domingue [5] extended this into a practical, full pipeline for DEM-based drainage analysis, coupling D8 flow direction and accumulation with automated basin and stream network delineation, and establishing much of the processing sequence — fill, direction, accumulation, threshold, delineate — that later tools, GRASS's own `r.watershed` included, continue to follow.

The D8 model's restriction to a single downslope neighbour was quickly identified as a source of systematic error on convex, divergent terrain, where flow in reality disperses across multiple downslope cells rather than concentrating along one direction. Quinn et al. [6] addressed this with a multiple-flow-direction (MFD) model that partitions each cell's flow across all downslope neighbours in proportion to slope, better capturing dispersive flow on hillslopes at the cost of a less crisply defined single drainage path. Freeman [7] proposed a related weighted multiple-flow-direction scheme, while Tarboton [8] introduced the D-infinity model, which allows flow to be routed along a continuous angle between the two nearest downslope neighbours rather than being constrained to eight fixed directions, offering a middle ground between the directional precision of D8 and the dispersion of MFD approaches. Comparative evaluations of these flow-routing schemes have generally found that the choice matters most on gentle or convex terrain, with D8 remaining adequate — and computationally preferable — for channelized, convergent flow, which is the regime most relevant to stream and micro-watershed delineation as opposed to hillslope-scale dispersion modelling. This is consistent with our use of the D8 scheme as implemented in GRASS's `r.watershed`, single-flow-direction routing being sufficient once the DEM has been properly conditioned and the analysis is focused on concentrated drainage rather than sheet flow.

9.2 DEM Conditioning: Sinks, Depressions, and Flats

Raw DEMs, particularly those derived from satellite radar, contain spurious sinks and flat regions that disrupt flow routing if left untreated . Two broad strategies address this: depression filling, which raises sink cells to the elevation of their lowest outlet, and depression breaching, which instead carves a drainage path through the obstruction. The choice between filling and breaching is not merely a computational preference: each alters the DEM's surface differently, and these alterations propagate into the derived hydrology. Lindsay and Creed [9] directly compared the two strategies and showed that filling tends to widen and flatten depressions, artificially enlarging flat regions and distorting flow paths near the treated sink, whereas breaching preserves the original terrain more faithfully by cutting a narrow channel through the obstruction, at the risk of carving drainage paths that do not correspond to any real hydrological feature. Lindsay [10] later proposed hybrid strategies that apply breaching where it suffices and fall back to filling only where necessary, aiming to combine the terrain fidelity of breaching with the guaranteed drainability of filling. These comparative findings motivate treating the depressions removed during conditioning as informative rather than incidental, since the same filling step that enables flow routing also determines how much of the original surface is altered in the process — a trade-off directly relevant to our decision to retain depression depth as a derived output rather than discarding it.

The flat regions produced by filling raise a related but distinct problem: cells assigned identical elevation have no defined downslope direction, so flow direction cannot be resolved from elevation alone. Garbrecht and Martz [11] addressed this by imposing an artificial two-pass gradient across each flat — one pass biasing flow away from higher terrain, the other toward the eventual outlet — ensuring a unique, drainable flow direction is assigned to every flat cell without perceptibly altering the surrounding topography. This flat-resolution step is now standard practice alongside depression filling, and is the technique underlying the flat-handling stage of our own DEM conditioning.

9.3 Watershed and Stream Network Delineation

Threshold-based delineation extends the D8 accumulation framework directly: a cell is classified as belonging to the channel network once its contributing area exceeds a chosen accumulation threshold, and the set of cells satisfying this condition is traced into a stream network, with the divides between adjacent channels giving the corresponding basin boundaries. Jenson and Domingue [5] established this threshold-and-trace approach as the standard basis for automated stream and basin extraction from a conditioned DEM, and it remains the mechanism underlying GRASS's own `r.watershed` and `r.stream.extract`, which our pipeline builds directly on.

The threshold itself, however, is not a hydrologically fixed quantity: because it is specified in units of contributing cells rather than physical area or discharge, its effect depends on DEM resolution, and even

at fixed resolution, varying it materially changes both basin size and stream density. Tarboton [8] showed that plotting basin or network properties against the accumulation threshold reveals a characteristic scaling behaviour, from which a threshold consistent with the real, visually identifiable channel network can be identified rather than chosen arbitrarily. Montgomery and Foufoula-Georgiou [12] further linked this threshold to the physical transition between hillslope (diffusive) and channelized (concentrated) flow, showing that the appropriate threshold varies systematically with local slope and terrain type rather than being a single constant applicable everywhere. This sensitivity is precisely why our own pipeline treats the initial threshold as a coarse, over-segmenting parameter, deferring the determination of a hydrologically meaningful minimum basin size to the merging step that follows delineation.

Once delineated, individual stream segments are commonly organized into a drainage hierarchy using one of two classical ordering schemes. Strahler [13] assigns order strictly by branching structure: a segment's order increases only when two channels of equal order converge, making Strahler order a measure of a segment's topological prominence within the network. Shreve [14] instead defines order additively as the cumulative count of upstream first-order channels feeding a segment, giving a measure more directly proportional to expected discharge and total contributing channel count. Both schemes are widely used for identical networks and yield different, complementary rankings of the same segments, which is why our pipeline computes both rather than committing to a single ordering convention.

Comparatively less attention has been given to the step our pipeline relies on most directly: consolidating the many small, threshold-delineated basins into fewer, larger units suitable for planning use. Most existing tools stop at threshold-based delineation and leave basin size implicitly determined by the chosen threshold, rather than treating consolidation as a distinct, explicitly controlled step. Where basin merging is addressed, it is typically framed as an aggregation over an already-delineated basin hierarchy, rather than as a flow-direction-aware relabelling of the underlying raster basins themselves, as performed in our merging procedure — suggesting this remains a comparatively underexplored step in the DEM-based delineation literature relative to flow routing and network extraction.

9.4 Open-Source Hydrological GIS Tools

The algorithmic primitives described above — flow direction, accumulation, threshold-based delineation, and stream ordering — are implemented, with varying design choices, across several open-source GIS packages. GRASS GIS provides these through its native raster modules, principally `r.watershed`, `r.stream.extract`, and `r.stream.order`, which support both D8 and, in `r.watershed`, a multiple-flow-direction option, and integrate directly with GRASS's broader raster and vector processing environment. TauDEM takes a more specialized, hydrology-focused approach, built around the D-infinity flow model [8] and designed explicitly for parallel execution on large DEMs, making it well suited to continental- or global-scale terrain processing. WhiteboxTools offers a comparable breadth of flow-routing and basin-delineation algorithms — including D8, D-infinity, and MFD variants — packaged as a lightweight, dependency-minimal command-line library, with an emphasis on ease of scripting and integration into external workflows rather than a full GIS environment.

These packages differ less in the hydrological algorithms they implement, which by and large trace back to the same lineage surveyed above, than in how they are meant to be used: GRASS GIS is a full geospatial processing environment within which hydrological analysis is one of many capabilities, TauDEM is a specialized, performance-oriented toolkit for large-scale terrain analysis, and WhiteboxTools prioritizes a minimal, scriptable interface. None of the three, however, ships with an end-to-end, region-agnostic pipeline that takes an arbitrary area of interest and autonomously resolves projection, acquires elevation data, and proceeds through delineation to a consolidated set of planning-ready outputs; in each case, this remains the responsibility of the user to script around the underlying modules. Our pipeline is built natively on GRASS GIS specifically because it offers both the flow-routing modules needed for delineation and a full vector and attribute-table processing environment for the connectivity and catchment-ordering steps that follow, allowing the complete workflow — from raw boundary vector to final micro-watershed layers — to be expressed as a single reproducible script rather than a set of tools invoked separately.

9.5 Global Hydrographic Products

HydroSHEDS [15] was among the first global hydrographic products to make consistently derived basin and stream network layers available at near-global coverage, built from void-filled and hydrologically conditioned SRTM elevation data at 3 arc-second (roughly 90 m) resolution. Its derivation follows the same conditioning-and-flow-routing lineage surveyed above — depression filling, D8 flow direction and accumulation, and threshold-based stream and basin extraction — but applied once, at a single fixed set of thresholds and resolution, to produce a uniform, versioned set of layers covering river networks, basin boundaries at multiple nested scales, and flow direction and accumulation rasters themselves distributed as static downloads.

More recent products have extended this same paradigm rather than departing from it. MERIT-Hydro [16] improves on HydroSHEDS's underlying elevation data by correcting known SRTM error sources — vegetation bias, stripe noise, and absolute bias — before applying a broadly similar conditioning and flow-routing pipeline at finer, 3 arc-second resolution globally. MERIT-Basins [17] in turn builds a global basin and river-reach delineation on top of the MERIT-Hydro flow direction layer, again released as a fixed, pre-computed dataset rather than a reproducible pipeline that a user can re-run with a different threshold or region-specific elevation source.

This pattern is common to all three products: each substantially improves the fidelity or coverage of its predecessor's input elevation data or derived layers, but each is released as a static, one-time computation rather than as an adaptable workflow. The thresholds governing stream and basin delineation are fixed globally, chosen to be broadly reasonable across highly varied terrain rather than tuned to any particular region's drainage characteristics; the resulting layers are versioned snapshots rather than something a practitioner can regenerate with an updated elevation source or a locally appropriate minimum basin size; and none of the three exposes the underlying pipeline as a script a user can point at an arbitrary new area of interest. These are precisely the limitations — fixed thresholds, static releases, and lack of regional adaptability — that motivate the open, region-agnostic pipeline presented in this paper.

9.6 Applications in Water Security and Local Planning

Basin- and sub-basin-scale hydrography, of the kind produced by HydroSHEDS and similar global products, is well suited to broad-scale analysis — regional water balance, transboundary river management, large-scale flood modelling — but is coarser than what most local-level planning decisions actually require. Programs concerned with irrigation scheduling, groundwater recharge structure siting, soil and water conservation, or watershed development more generally operate at the scale of individual fields, clusters of villages, or single drainage lines, which is precisely the micro-watershed rather than the basin or sub-basin.

India's watershed development programs are among the most extensive applied examples of planning organized explicitly at this scale. Soil and Land Use Survey of India [18] describes how national watershed guidelines adopt micro-watersheds of a few hundred to a few thousand hectares as the fundamental unit for treatment planning, on the grounds that a unit of this size is both hydrologically coherent — draining to a single, identifiable point — and small enough to be locally governed and treated as a coherent intervention area by a village community or implementing agency. Groundwater recharge structure siting depends on this same scale for a related but distinct reason: identifying where a check dam, percolation tank, or recharge trench will actually intercept and retain runoff requires knowing the specific drainage line and contributing area at that point, not merely which larger basin the site falls within. Irrigation planning imposes a similar requirement, since command area delineation and water availability assessment are naturally organized around the same small, locally drained units that a farmer or irrigation scheme actually operates within.

Across these applications, the common requirement is a delineation fine enough to be locally actionable, together with drainage topology that is explicit and traceable — a micro-watershed cannot be planned in isolation from what lies immediately upstream and downstream of it, since inteventions in one unit affect runoff and recharge in its neighbours. This is precisely what basin- or sub-basin-scale global products do not provide, and what motivates a workflow that delineates directly at the micro-watershed scale while retaining explicit inter-basin connectivity, as described in this

paper.

References

[1] Alan S Kolok, Cheryl L Beseler, Xun-Hong Chen, and Patrick J Shea. The watershed as a conceptual framework for the study of environmental and human health. *Environ. Health Insights*, 3:1–10, February 2009.

[2] Shivani A Mehta et al. *CoRE Stack: Commoning for Resilience and Equity - Geospatial Data Layers*. ICTD Lab, IIT Delhi, February 2025. Available at https://drive.google.com/file/d/1ZxovdpPThkN09cB1TcUYSE2BImI7M3k_/view.

[3] Shivani A Mehta, Aila Dutt, Ajay Tannirkulam, Akshay Pratap Singh, Aman Verma, Anamitra Singha, Ananda Sreenidhi, Ananjan Nandi, Ankit, Ankit Kumar, Atharv Dabli, Athira P, Balakumaran Ramachandran, Chahat Bansal, Chintan Sanjaybhai Sheth, Craig Dsouza, Deepak Kumar, Dharmisha Sharma, Harshita, Jaskaran Singh, Kapil Dadheech, Ksheetiz Agrahari, Om Krishna, Pooja Prasad, Priyadarshini Radhakrishnan, Ramita Sardana, Rittwick Bhabak, Ruptirumal Sai Bodavula, Saketh Vishnubhatla, Samitha Haldar, Sanjali Agrawal, Shiv Prakash Maurya, Shruti Kumari, Siddharth S, Sukriti Kumari, Vishnu S, and Aaditeshwar Seth. Initial observations from field testing of a digital participatory tool to improve water security in rural india. In *Proceedings of the 13th International Conference on Information & Communication Technologies and Development*, ICTD '24, page 337–364, New York, NY, USA, 2025. Association for Computing Machinery. ISBN 9798400710414. doi: 10.1145/3700794.3700816. URL https://doi.org/10.1145/3700794.3700816.

[4] John F O'Callaghan and David M Mark. The extraction of drainage networks from digital elevation data. *Computer Vision, Graphics and Image Processing*, 28(3):323–344, December 1984.

[5] Susan Jenson and Julia Domingue. Extracting topographic structure from digital elevation data for geographic information-system analysis. *Photogrammetric Engineering and Remote Sensing*, 54(11):1593–1600, 1988. URL https://pubs.usgs.gov/publication/70142175.

[6] P. Quinn, K. Beven, P. Chevallier, and O. Planchon. The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. *Hydrological Processes*, 5(1):59–79, 1991. doi: https://doi.org/10.1002/hyp.3360050106. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/hyp.3360050106.

[7] T.Graham Freeman. Calculating catchment area with divergent flow based on a regular grid. *Computers Geosciences*, 17(3):413–422, 1991. ISSN 0098-3004. doi: https://doi.org/10.1016/0098-3004(91)90048-I. URL https://www.sciencedirect.com/science/article/pii/009830049190048I.

[8] David G. Tarboton. A new method for the determination of flow directions and upslope areas in grid digital elevation models. *Water Resources Research*, 33(2):309–319, 1997. doi: https://doi.org/10.1029/96WR03137. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/96WR03137.

[9] John B. Lindsay and Irena F. Creed. Removal of artifact depressions from digital elevation models: towards a minimum impact approach. *Hydrological Processes*, 19(16):3113–3126, 2005. doi: https://doi.org/10.1002/hyp.5835. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/hyp.5835.

[10] John B. Lindsay. Efficient hybrid breaching-filling sink removal methods for flow path enforcement in digital elevation models. *Hydrological Processes*, 30(6):846–857, 2016. doi: https://doi.org/10.1002/hyp.10648. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/hyp.10648.

[11] Jurgen Garbrecht and Lawrence W Martz. The assignment of drainage direction over flat surfaces in raster digital elevation models. *Journal of Hydrology*, 193(1):204–213, 1997. ISSN 0022-1694. doi: https://doi.org/10.1016/S0022-1694(96)03138-1. URL https://www.sciencedirect.com/science/article/pii/S0022169496031381.

[12] David R. Montgomery and Efi Foufoula-Georgiou. Channel network source representation using digital elevation models. *Water Resources Research*, 29(12):3925–3934, 1993. doi: https://doi.org/10.1029/93WR02463. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/93WR02463.

[13] A.N. Strahler. Quantitative analysis of watershed geomorphology. *Eos, Transactions American Geophysical Union*, 38(6):913–920, 1957. doi: https://doi.org/10.1029/TR038i006p00913. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/TR038i006p00913.

[14] Ronald L Shreve. Statistical law of stream numbers. *J. Geol.*, 74(1):17–37, January 1966.

[15] Bernhard Lehner, Kristine Verdin, and Andy Jarvis. New global hydrography derived from spaceborne elevation data. *Eos, Transactions American Geophysical Union*, 89(10):93–94, 2008. doi: https://doi.org/10.1029/2008EO100001. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2008EO100001.

[16] Dai Yamazaki, Daiki Ikeshima, Jeison Sosa, Paul D. Bates, George H. Allen, and Tamlin M. Pavelsky. Merit hydro: A high-resolution global hydrography map based on latest topography dataset. *Water Resources Research*, 55(6):5053–5073, 2019. doi: https://doi.org/10.1029/2019WR024873. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019WR024873.

[17] Peirong Lin, Ming Pan, Hylke E. Beck, Yuan Yang, Dai Yamazaki, Renato Frasson, Cédric H. David, Michael Durand, Tamlin M. Pavelsky, George H. Allen, Colin J. Gleason, and Eric F. Wood. Global reconstruction of naturalized river flows at 2.94 million reaches. *Water Resources Research*, 55(8):6499–6516, 2019. doi: https://doi.org/10.1029/2019WR025287. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019WR025287.

[18] Soil and Land Use Survey of India. Microwatershed atlas of india, 2017. URL https://slusi.da.gov.in/mwa.pdf.