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USUAL Watershed Tools: A new geospatial toolkit for hydro-geomorphic delineation

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ABSTRACT

Watershed and hydro-geomorphic delineation is a critical first step in most environmental and natural resource assessments, analyses, and research. While existing geospatial tools have provided exceptional advances, less attention has been put toward developing fully automated tools for subdividing landscapes into their constituent hydro-geomorphic units or discretizing river corridor features. Here, we present a new, open-source ArcGIS toolbox, called the Utah State University AppLied (USUAL) Watershed Tools. The USUAL Tools are a set of streamlined, easy-to-use ArcGIS toolboxes that automate the delineation of watersheds, sub-catchments, river-adjacent interfluves, and discretized river networks with the topological structure and feature attributes necessary for one-dimensional source-to-sink transport modeling through large watersheds. This novel geospatial toolset replaces the need for extensive delineation workflows, providing the Earth science, environmental science, and natural resources communities with the ability to rapidly and easily automate necessary but often time-intensive tasks in a format familiar to ArcGIS users.

1. Introduction

Watershed and hydro-geomorphic feature delineation is a fundamental step for geospatial research and analysis of natural resources across a variety of disciplines. Delineation of hydro-geomorphic landscapes are often performed using geospatial software to compartmentalize landscapes into functional units, which allows environmental parameters to be binned and modeled across discrete process domains. Breaking landscapes into functional hydro-geomorphic units can provide critical insights into natural resource conditions and processes. With respect to biology and ecology, hydro-geomorphic delineation can help inform the characterization of physical habitat (e.g.,Belletti et al., 2017), models evaluating the effects of physical habitat disturbance (e.g., Murphy et al., 2020), and the surveys and management of species (e.g., Wang et al., 2012). Additionally, hydro-geomorphic delineation can assist in natural resource planning and impact assessments (e.g., timber harvest; Fisher et al., 2021), especially when the dispersal and distribution of environmental effects are linked to surface hydrologic pathways and source-to-sink transport of matter, including but not limited to sediment, nutrients, and pollutants (e.g., Ahammad et al., 2021; Launay et al., 2015; Saleh et al., 2013). Finally, the hydro-geomorphic delineation of landscapes allows for more accurate modeling of the variable erosional processes that occur across the different geomorphic units within watersheds (e.g., Cavalli et al., 2013; Gannon et al., 2019; Gartner et al., 2014; Murphy et al., 2019; Staley et al., 2017; Wall et al., 2022).

Rivers and waterways control the surface transport of matter through landscapes from a point source to a downstream sink, whether that sink is local (e.g., reservoir or lake) or global (oceans). Tracking matter through a landscape often employs one-dimensional (1-D) routing models of water (e.g. David et al., 2011; Saleh et al., 2013), sediment (e.g. Ahammad et al., 2021; Czuba et al., 2017; Murphy et al., 2019; Viparelli et al., 2013), nutrients or pollutants (e.g., Launay et al., 2015), or any other material that can be entrained in water and moved through a river network. However, these methods rely on computing spatial metrics over the two-dimensional area of a watershed. This typically requires extensive, and often manual, geospatial analysis or the application of multiple tools developed specifically for morphometric

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characterization of rivers and hydrologic modeling (Clubb et al., 2014; Passalacqua et al., 2010, 2012; Schwanghart and Scherler, 2014; Schwenk et al., 2020; Tarboton, 1997) to extract the parameters from a watershed necessary to initialize the routing models (e.g., Czuba et al., 2017). For instance, the methods required for Murphy et al. (2019) to delineate and attribute a river network and hundreds of sub-catchments for analysis of post-wildfire erosion and sediment dynamics involved more than 50 ArcGIS tools interspersed with many manual steps, as well as passing data back and forth between external development environments to execute scripts and perform functions not available in ArcGIS. Hence, there is a need for a streamlined set of GIS tools designed specifically for hydro-geomorphic watershed delineation and attribution that serves the needs of natural resource management, environmental science, and source-to-sink modeling.

Several geospatial tools currently exist to delineate watersheds, river networks, sub-watersheds, and to compute spatial morphometrics. For instance, Topotoolbox delineates river networks, watersheds, and sub-watersheds (Schwanghart and Scherler, 2014). Additionally, TAK is a toolkit built on top of Topotoolbox which streamlines functions and removes the need for a Matlab license (Forte and Whipple, 2019). However, Topotoolbox and TAK were designed to compute topographic metrics for advanced longitudinal river profile analysis (channel steepness, chi-plots, etc.). Another commonly used tool, LSDtopotools (Clubb et al., 2014) is a Linux-based toolkit which primarily focuses on channel extraction and attribution. LSDtopotools also contains functionality to delineate fluvial features, such as floodplains and terraces (Clubb et al., 2017). LSDtopotools also incorporates components of GeoNet (Sangireddy et al., 2016), which uses advanced filtering techniques and attributes the network for high-resolution topographic data (i.e., lidar). Another tool, RivGraph (Schwenk et al., 2020; Schwenk and Hariharan, 2021) automates extraction of river networks and attributes (e.g., flow direction, reach length and width, branching angle, etc.) from binary images of river networks without the need for an underlying digital elevation model (DEM). Collectively, these tools have advanced our ability to conduct higher-order fluvial and landscape analysis, however all of these tools require knowledge of computational languages in potentially unfamiliar computing environments. Moreover, these tools are largely focused on delineating and extracting morphometrics specific to the river network alone.

In contrast, TauDEM (Tarboton, 1997) and SWAT (https://swat.tamu.edu/software/; QSSWAT and ArcSWAT) are examples of tools that were built with graphical user interfaces (GUI) in common GIS platforms (ArcGIS and QGIS) to provide methods for delineating rivers, watersheds, and sub-watersheds. Both TauDEM and SWAT were designed and developed to delineate watersheds for setting up common hydrologic routing schemes (e.g., Muskingum Method). Accordingly, it is important to recognize that they subdivide watersheds into hydrologic units, which both conceptually and functionally differ from hydro-geomorphic process domains. Specifically, in their sub-watershed delineation, neither TauDEM nor SWAT distinguish between interfluvial process domains, where hillslope runoff and erosion processes dominate, and tributary sub-catchments, where streamflow and fluvial processes dominate. Instead, TauDEM and SWAT subdivide watersheds into "sub-watersheds", which define all areas that directly contribute surface flow to each discretized reach of the delineated river network (Fig. 1A). As a result, this approach aggregates all tributary catchments and hillslope process domains along each river network reach into a single polygonal area. However, these different process domains contribute flow, sediment, and other materials to each reach by distinctly different processes and magnitudes. Aggregating process domains may work for hydrologic models, but these two tools are unsuitable for discretizing landscapes for many process-based hydro-geomorphic models. For example, the U.S. Geological Survey model for predicting debris flows within burned watersheds (Staley et al., 2017) is applied at the scale of first- and second-order tributary sub-catchments. The debris flow modeling domain does not include network-adjacent interfluves or reaches of the major river network, and the inclusion of these areas through the use of the sub-watershed extents produced by either TauDEM or SWAT would mischaracterize extracted model predictors and skew model predictions.

To date, existing delineation tools have focused primarily on hydrologic modeling, river channel extraction, and topographic

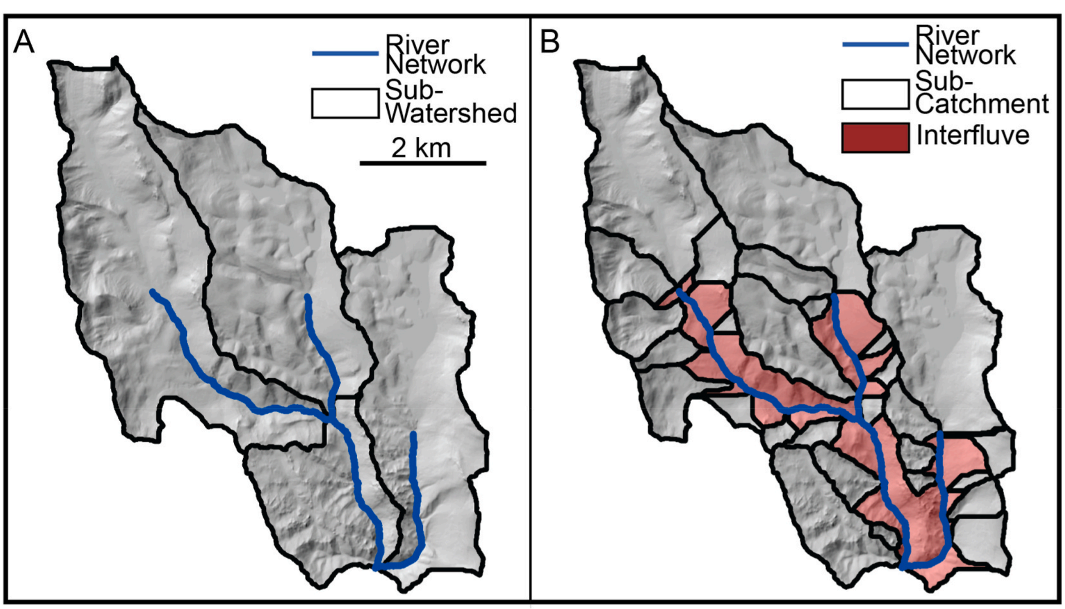


Fig. 1. Comparison of different delineation tools applied to the headwaters of the Logan River, Utah, USA. A) Sub-watershed and river network delineations generated by the existing GIS tool TauDEM. Note that "sub-watershed" extents in TauDEM extend across the channel and are aggregated as broad hydrologic units defined by the area that drains directly to each reach of the river network (here discretized between river confluences). B) Sub-catchment, interfluve, and river network delineations generated using USUAL Watershed Tools. In contrast, the "sub-catchments" of USUAL define the watershed extent for every tributary larger than a prescribed drainage area (i.e., the hillslope-channel threshold), and the interfluves as the areas below this threshold area between the sub-catchments. These are all delineated as discrete features, and their delineations are independent of the lengths or locations of the discretized river network reaches.

morphometrics. However, less attention has been given to delineation of watersheds at the sub-catchment and interfluve scale (Fig. 1B), which is critical for accurately computing localized geospatial metrics and modeling runoff and erosion within hydro-geomorphic process domains, specifically for source-to-sink models. Therefore, we introduce the Utah State University AppLied (USUAL) Watershed Tools (or for brevity, USUAL). The USUAL Watershed Tools are an open-source, Python-based toolkit for ArcGIS that have been designed to: delineate watersheds, sub-catchments, interfluves, and river networks; discretize river networks and extract attributes necessary for fluvial network routing; and provide new GIS functions for feature extraction and attribution. USUAL has an ArcGIS Graphical User Interface (GUI) to make the toolkit easy to use and familiar for users with experience in ArcGIS software. However, we have also made the underlying Python scripts available for advanced users who wish to adapt and modify the tools. Novel attributes of the USUAL Watershed Tools include: (1) Delineating both interfluves and sub-catchments (Fig. 1B). (2) Providing the ability to exclude user-defined regions of the topography that would traditionally yield erroneous delineations (e.g., delineating catchments and interfluves across waterbodies). (3) Automating the identification and generation of pour points required to delineate sub-catchments and interfluves. (4) Automating the discretization and attribution of a river network for 1-D routing. (5) Automating the computation of reach-averaged widths from fluvial features (e.g., river, floodplain, valley bottom). Hence, the USUAL Watershed Tools automate many frequently required and labor intensive steps in watershed delineation and generates outputs that seamlessly integrate with state-of-the-art 1-D routing models (e.g., Czuba, 2018; Pfeiffer et al., 2020; Tangi et al., 2019).

Herein, we introduce the components of the USUAL Watershed Tools, describe how each works, detail all required and optional inputs, and describe the final GIS products output from each tool (Section 2). We then explore and demonstrate how USUAL handles: (1) variable DEM resolution, (2) shallow vs. steep gradient landscapes, (3) watersheds of varying channel complexity, and (4) the computational efficiency of feature delineation (Section 3). Finally, we provide an example application of the USUAL Watershed Tools in the Logan River, Utah to demonstrate its utility for evaluating common models of soil erosion and delivery, as well as its capability to inform sediment routing models (Section 4).

2. Toolkit description

The USUAL Watershed Tools are a set of Python-based scripts built on the ESRI ArcGIS platform, developed using ArcGIS Pro version 2.9, and available for download on GitHub (*see Software and Data Availability for link*). The toolkit requires a basic ArcGIS Pro license, as well as Spatial Analyst and 3-D Analyst licenses. USUAL provides users with the familiar, easy-to-use ArcGIS toolbox GUIs and is constructed as a suite of toolboxes that can be executed independently or in sequence (Fig. 2). However, the underlying Python code can also be opened and executed in ArcGIS or externally using any Python Integrated Development Environment (IDE; e.g., Spyder, Jupyter Notebook).

USUAL is comprised of four main tools used for extracting, delineating, and attributing spatial metrics across different morphologic features in watersheds (Fig. 2). Additionally, USUAL contains two optional sub-toolkits each containing two tools to extract additional attributes (Fig. 2). Broadly, the toolkit will delineate a watershed, a river network, all sub-catchments draining to the network, the interfluves between the sub-catchments and adjacent to the river network (Fig. 3), and compute and attribute spatial metrics for the delineated features. Running the primary workflow for the USUAL Watershed Tools requires a minimum of just two data inputs: a DEM raster, and a “pour point” shapefile identifying the downstream-most point for the watershed. However, in the following subsections, we will outline and describe all the required and optional inputs and parameters, functionality, and outputs from each tool.

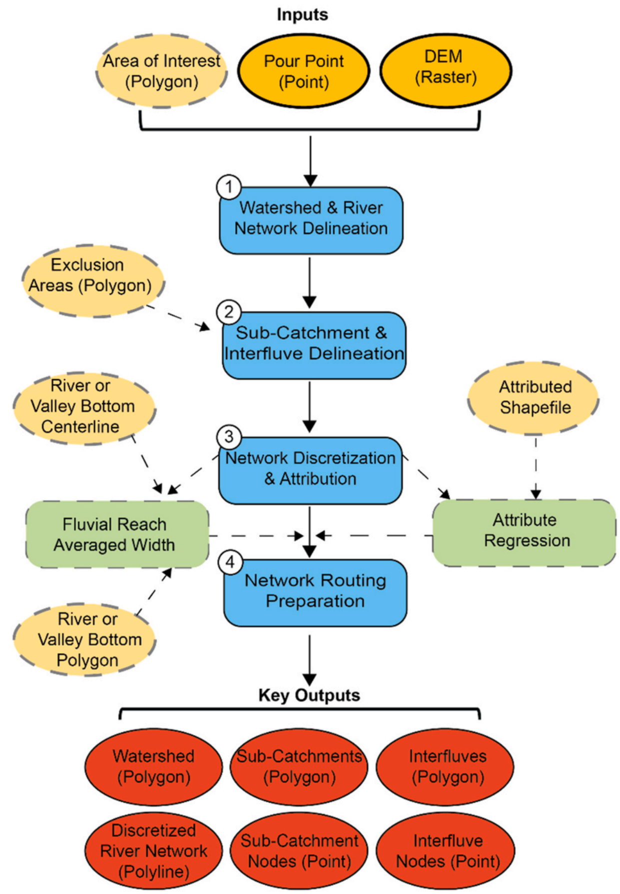


Fig. 2. The model workflow for the USUAL Watershed Tools. Rectangles represent individual tools and ovals represent inputs and outputs. Blue rectangles and solid arrows represent the minimum workflow and tools required to delineate a DEM into a watershed, its sub-catchments and interfluves features, and to generate a river network prepared for routing applications (1,2,3,4). When following this simplified workflow, the outputs generated by each tool are used as inputs for the next, with the exception of optional exclusions areas for delineation of sub-catchments and interfluves. Dark yellow ovals represent required inputs and light-yellow ovals with dashed borders represent optional inputs. Green rectangles and dashed lines represent optional workflows and sub-toolkits that allow for the generation of additional attributes, such as reach-averaged river or valley bottom widths or attributes predicted based on regressions of other attributes. Optional sub-toolkits could be run independently or in any position within the overall workflow, but we show them in the order recommended if regressed attributed are based on network attributes generated by tool #3. Red ovals represent the primary data outputs generated by the USUAL Watershed Tools workflow, whether including optional tools or not. Optional tools do not generate new layers but only add attribute fields to existing output features.

2.1. Watershed and river delineation

The first tool in the USUAL workflow - the Watershed and River Delineation Tool - delineates the watershed extent and river network upstream of a user-specified point in a landscape (pour point) based on topography and surface hydrologic pathways. This tool is essentially a wrapper script that streamlines the standard order of operations within the ESRI Hydrologic Toolbox for basic watershed delineation and river network delineation, but with some critical additional functionality to handle more complex but commonly encountered watershed scenarios.

The Watershed and River Delineation Tool requires just two inputs (Table S1): a watershed pour point (specified as a point feature) and a topographic raster representing the DEM. Additionally, the user must specify a river network drainage area threshold value. In hydro-

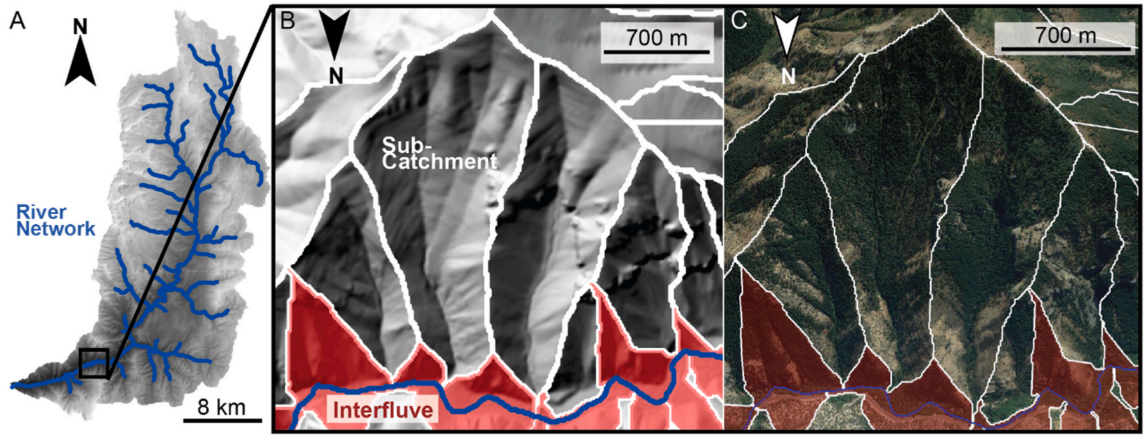


Fig. 3. Example of watershed hydro-geomorphic features delineated by USUAL. A) Example of extracted watershed and river delineated on the Logan River, Utah, USA. B) Zoomed in example of delineated sub-catchments, interfluves, and river network. C) Features overlain on Google Earth Imagery with an oblique view highlighting USUAL's ability to delineate interfluves and sub-catchments.

geomorphology, this typically defines the minimum drainage area marking the transition point between hillslopes and river channels in the landscape (Montgomery and Foufoula-Georgiou, 1993; Tarboton et al., 1991). However, as the USUAL Watershed Tools can be used to generate river networks for 1-D routing, this threshold can also be viewed more simply as defining the extent of the network intended for modeling fluvial material transport. Although the lower order tributaries may be important for some models, users may not want to include the full network in a large-scale watershed routing analysis. In the USUAL framework, this threshold also inherently defines the maximum drainage area of tributary channels that are delineated as sub-catchments (see Section 2.2.1).

The tool also accepts three additional optional inputs (Table S1): an area of interest (polygon feature), a pour point snapping tolerance (numeric input), and an option to conduct a nested watershed delineation. The area of interest (AOI) polygon clips the input DEM to the extent of the AOI before running the ESRI Hydrology tools, which helps improve computational efficiency if the input DEM is not pre-clipped and significantly larger than the watershed being delineated. The pour point snapping tolerance defines a radius (in map units) that feeds into

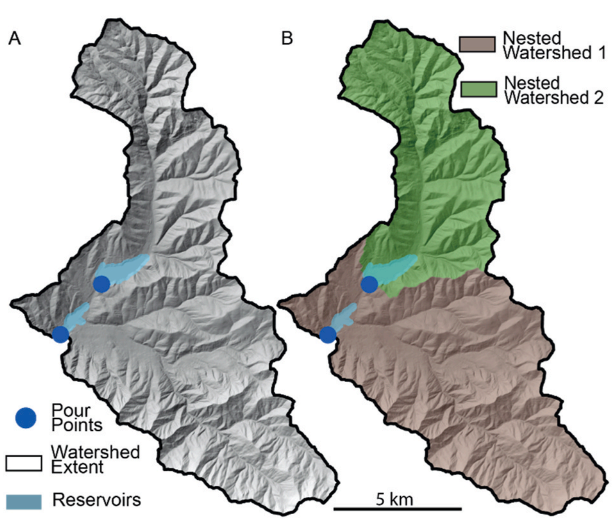


Fig. 4. Example of nested watershed analysis for the Mountain Dell Reservoir, UT (downstream; brown) and the Little Dell Reservoir (upstream; green) watersheds. Using two input pour points (blue dots), USUAL splits the entire watershed into the respective nested watersheds (panel B) while maintaining a continuous river network (not shown).

the ESRI 'Snap Pour Point' tool and moves the pour point location to the highest flow accumulation cell within the search radius to ensure the point falls within the river channel. The nested analysis option allows users to define and input multiple pour points for a watershed (Fig. 4A) and allows the tool to delineate multiple nested watersheds inside the primary watershed (Fig. 4B).

First, the tool delineates the entire watershed extent based on the prescribed pour point. Using ESRI Hydrology Toolset, it fills small hydrologic depressions (sinks) in the DEM, computes flow direction (D8 algorithm) and flow accumulation across the DEM, and finally delineates the extent of the entire watershed as a polygon feature. Next, the tool delineates the river channel network by reclassifying the flow accumulation raster based on the prescribed river drainage area threshold and applies the ESRI 'Stream to Feature' tool to convert the reclassified binary raster into a stream network polyline.

In many watersheds there may be reservoirs upstream and within the larger watershed extent. The presence of these "nested" reservoirs can influence network routing modeling and analysis (i.e., they represent significant sinks along flow paths), as well as the assessment and modeling of dispersal for aquatic populations. The Watershed and River Network Delineation Tool could be run individually for each of these "nested" watersheds, however rectifying the entire watershed delineation would require subsequent manual merging of the multiple watersheds and networks. While this provides a relatively simple solution to produce a visually satisfactory GIS product, the simple merging of features would not result in the creation of a single and functional routing network with consistent and linked attributes that would allow for modeling material transport or migratory behavior through the entire watershed.

To address the common issue of nested watersheds, we incorporated the option to run a "nested analysis". This function does not automatically identify the presence of nested watersheds or generate pour points for any potential nested reservoirs; rather, the user must input multiple pour points to the tool. The tool first delineates the larger scale watershed that encompasses all the reservoirs upstream from the downstream-most pour point and then delineates the nested watersheds based on the natural drainage divides and clips them by the delineated watersheds of upstream reservoirs (Fig. 4). Although delineating the nested watersheds as separate features, the tool still generates a single continuous river network for the entire watershed extent that maintains accurate drainage area attributes for each reach (i.e., the drainage area calculated immediately below a nested reservoir is not inaccurately identified as a drainage boundary with no contributing upstream area). The tool also outputs sub-networks for each nested watershed in case the user has a need for these features.

Outputs from the Watershed and River Delineation Tool include (Table S1): (1) a watershed polygon delineating the extent of the watershed, (2) a river network polyline mapping out the extent of the river network, (3) rasters for the filled DEM, flow accumulation, flow direction, and river channel clipped to the watershed extent. If a nested analysis is performed, the tool will output all the above features for the full watershed, as well as for each of the nested watersheds.

2.2. Sub-catchment and interfluve delineation

The Sub-Catchment and Interfluve Delineation Tool comes second in the primary workflow and subdivides and delineates the watershed into two feature groups: (1) sub-catchments that define the drainage areas for all tributaries that flow directly to the delineated river network and (2) the interfluves between sub-catchments that are directly adjacent to and along the river network (Figs. 3B & 5). Although interfluves are smaller in area relative to the sub-catchments within the watershed and often not included in other delineation tools, the interfluves are directly stream adjacent and comprise a significant percentage of the river network length. Accordingly, interfluves can be a significant source of direct material inputs to the river network in some watersheds (Fisher et al., 2021; Kelly and Belmont, 2018; Vaughan et al., 2017). Furthermore, compartmentalizing the landscape into discrete components creates a geospatial framework where every geomorphic process domain across the landscape that may serve as a point source input can be evaluated or modeled as a potential source and associated with spatially explicit locations of delivery to the river network.

The Sub-Catchment and Interfluve Delineation Tool requires five input datasets, all of which are generated by, and output from, the Watershed and River Delineation Tool (Table S2): (1) filled DEM, (2) flow direction raster, (3) flow accumulation raster, (4) river network shapefile, and (5) watershed polygon. Additionally, the user must prescribe a sub-catchment drainage area threshold, which defines the minimum drainage area for delineated sub-catchments (the upper limit for sub-catchment drainage area is set by the river network drainage area threshold value). For example, if the river network drainage area threshold value was set to 5 km^2 and the sub-catchment drainage area threshold value was set to 1 km^2, then the drainage area of every sub-catchment delineated in the watershed would be between 1 and 5 km^2. It is worth noting that while this tool can conveniently be run using the outputs from the previous Watershed and River Delineation Tool, the outputs from other tools (e.g., a GeoNet or RivGraph derived network) could also be used as input data.

The tool also contains a novel function for handling "exclusion areas" within the watershed. These are regions of topography that would be included in standard ESRI delineations and other delineation tools but which result in the creation of erroneous sub-catchment and interfluve extents that are not a reflection of reality and could result in the mischaracterization of extracted properties from those domains (e.g., zonal statistics). For example, a standard delineation of sub-catchments draining directly into a waterbody (e.g., lake or reservoir) extend out across the surface of the waterbody (Fig. 5A), thus including large areas that are not representative of the actual sub-catchment topography (Fig. 5B). Typically, correcting this issue requires selecting or adjusting pour point locations for each of these sub-catchments by hand. Our exclusion area function eliminates this tedious and time-intensive step by automatically identifying and generating sub-catchment pour points at the perimeter of the exclusion area before feature delineation. Additionally, the tool will correctly delineate the interfluves with downslope boundaries that terminate at the perimeter of the exclusion area (Fig. 5A and B). To utilize this function, the Sub-Catchment and Interfluve Delineation Tool includes an optional input of a polygon shapefile that encompasses the extent of exclusion area (e.g., reservoir, urban area, valley bottom). The input feature can contain a single polygon or multiple polygons. Additionally, the tool contains an optional input allowing the user to define a number of cells to buffer the input polygons,

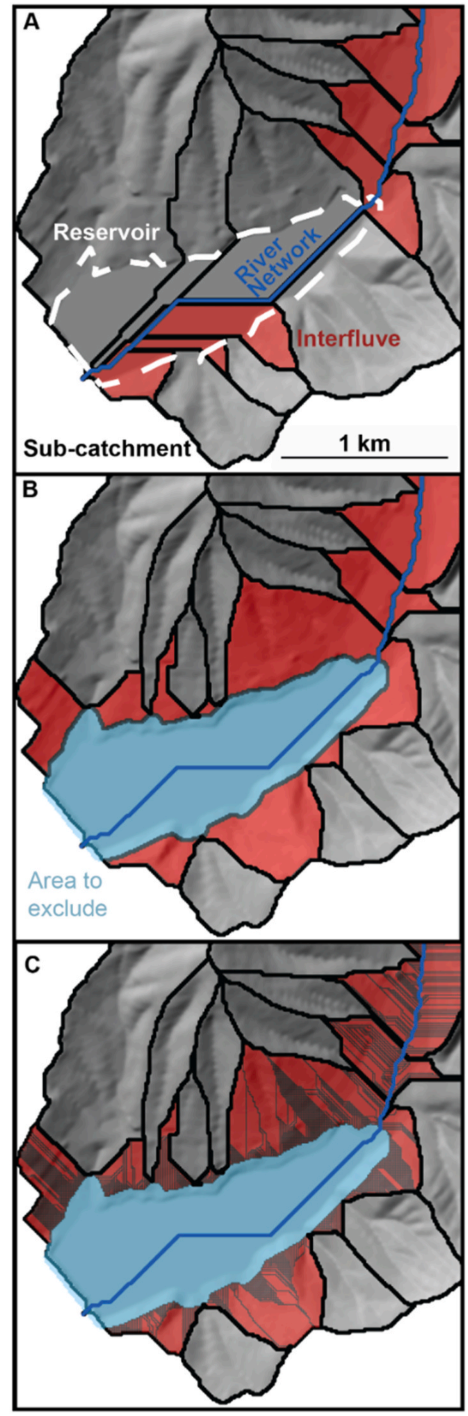


Fig. 5. Examples of sub-catchment (black outlines) and interfluve (red polygons) delineation with and without inputting an exclusion area of a reservoir. A) Example of sub-catchment and interfluve delineation without including the reservoir polygon as an exclusion area (reservoir perimeter shown with a dashed white line). B) Example of sub-catchment and interfluve delineation using the reservoir polygon (blue) as an exclusion area. Note that the exclusion area function not only avoids sub-watershed delineations extending into reservoir, but fundamentally changes the locations and extent of interfluves. Additionally, this approach results in the more accurate delineation of multiple sub-watersheds that are combined when the pour point is incorrectly placed within the exclusion area (here the reservoir). C) Example output of a high-resolution interfluve delineation, where grey lines indicate the edges of contributing areas for the individual interfluve flow paths to the river or reservoir.

which helps correct flow paths between interfluves and sub-catchments converging at the edge of the exclusion area. However, buffering an irregularly shaped polygon can create holes in the buffered exclusion area polygon (Fig. S1). To overcome this the toolkit also contains an option to fill any holes in an exclusion area polygon (Fig. S1).

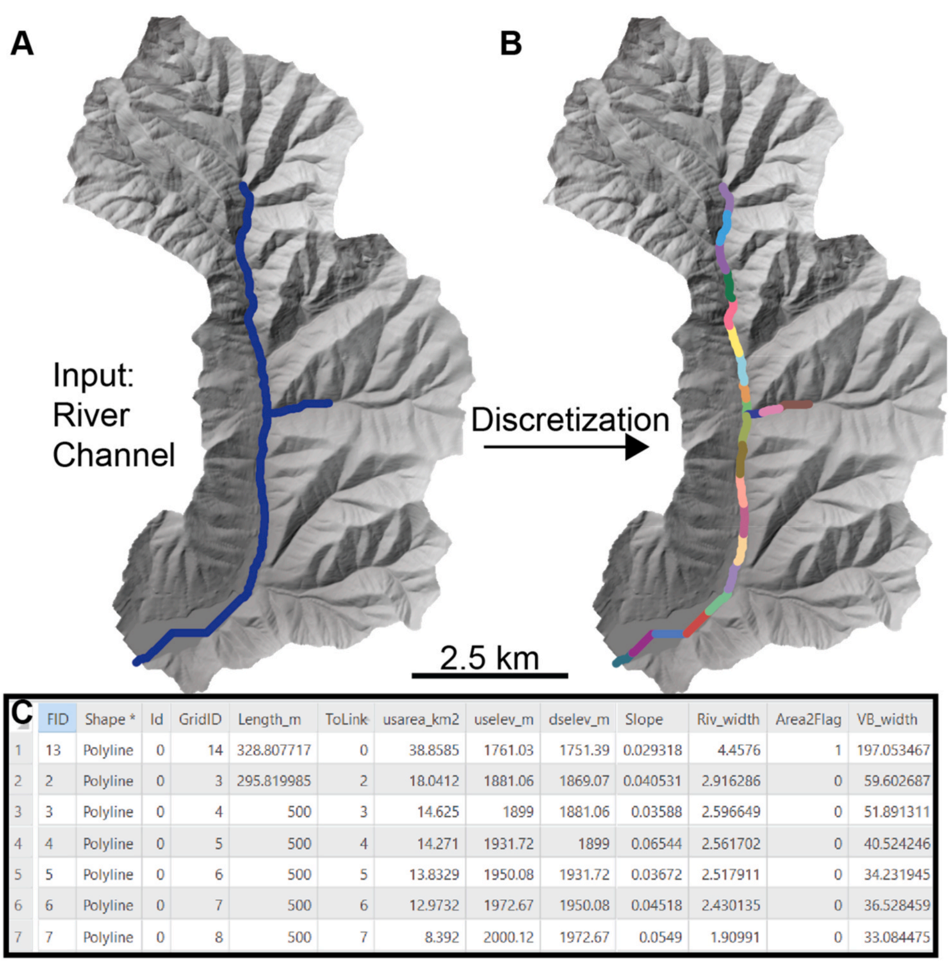
The Sub-Catchment and Interfluve Delineation Tool contains up to three options for outputs (Table S2): (1) sub-catchments, (2) interfluves at fine resolution, and (3) interfluves at a coarse resolution. By default, the toolbox outputs all three, however the ArcGIS toolbox contains tick boxes (Booleans in the code), which allow users to select or suppress outputs for any of the three features. In the following two subsections, we outline how each is delineated and their respective outputs.

2.2.1. Sub-catchment delineation

Sub-catchment pour points are internally identified by first creating a binary raster where flow accumulation cells equal to or above the sub-catchment drainage area threshold value are given a value of one and cells below the threshold are given a value of zero. Second, if an area to exclude polygon is provided, the portions of the input binary network raster (one for river cells, zero otherwise) inside this area are converted to a value of one. Raster calculator is then used to subtract the binary network raster (with exclusion area) from the binary flow accumulation raster (above the sub-catchment drainage area threshold value). The result is a binary raster (all negative values are set to zero) indicating which cells flow directly into (but are not in) the river network. Those raster cells are then converted to pour points directly adjacent to the river channel and exclusion area and input to the ESRI 'Watershed' tool to delineate the contributing area of each sub-catchment (Fig. 5A and B). The tool outputs a polygon shapefile with all sub-catchment polygons and a shapefile of the pour points used to extract each sub-catchment. Each sub-catchment and its associated pour point are assigned a unique identifier, which is written to their attribute tables, so they can be linked for source-to-sink modeling.

2.2.2. Interfluve delineation

Interfluve delineation can be performed in two ways: at a coarse (Fig. 5B) and fine (Fig. 5C) resolution. Interfluve pour points are identified by locating all flow accumulation cells adjacent to the river network, as well as around the perimeter of any optional exclusion areas that have contributing areas greater than zero but less than the defined sub-catchment drainage area threshold value. These pour points are then used in the ESRI 'Watershed' tool to delineate the contributing area of every interfluve flow path (Fig. 5C). This fine-scale resolution of interfluves may be beneficial for users modeling and tracking non-channelized flow paths of potential point-source inputs to the river network (e.g., soil erosion or nutrient runoff from agricultural fields). However, if a user were interested in coarser scale delineation of interfluves for morphometric calculations the tool can also aggregate and merge all of the fine-scale interfluves between the sub-catchments to create coarse resolution interfluves (Fig. 5B). For this latter case, the tool does not output pour points because the coarse resolution interfluves are intended for broader scale environmental parameter characterization rather than source-to-sink modeling. Additionally, the tool provides an optional input to delete all coarse interfluves containing less than a user defined number of cells, thus filtering out all small coarse resolution interfluves.



	FID	Shape *	Id	GridID	Length_m	ToLink	usarea_km2	uselev_m	dselev_m	Slope	Riv_width	Area2Flag	VB_width
1	13	Polyline	0	14	328.807717	0	38.8585	1761.03	1751.39	0.029318	4.4576	1	197.053467
2	2	Polyline	0	3	295.819985	2	18.0412	1881.06	1869.07	0.040531	2.916286	0	59.602687
3	3	Polyline	0	4	500	3	14.625	1899	1881.06	0.03588	2.596649	0	51.891311
4	4	Polyline	0	5	500	4	14.271	1931.72	1899	0.06544	2.561702	0	40.524246
5	5	Polyline	0	6	500	5	13.8329	1950.08	1931.72	0.03672	2.517911	0	34.231945
6	6	Polyline	0	7	500	6	12.9732	1972.67	1950.08	0.04518	2.430135	0	36.528459
7	7	Polyline	0	8	500	7	8.392	2000.12	1972.67	0.0549	1.90991	0	33.084475

Fig. 6. Example of river network discretization and attribution. A) Example of an input river network. B) Resulting USUAL discretized river network, where each color indicates a different reach segment. Here we applied a maximum discretization length of 500 m. C) The attribute table shows an example of output attributes: unique segment identifier (GridID), reach length (Length_m), the unique segment identifier of the reach immediately downstream (ToLink), upstream drainage area (usarea_km2), upstream and downstream elevations of each reach (uselev_m and dselev_m, respectively), reach-averaged slope (Slope), river width (Riv_width), flagged areas of interest (Area2flag), and valley bottom width (VB_width). Note the flagged areas of interest, river width, and valley bottom width attributes are generated using the tools discussed in section 2.4, 2.5, and 2.6, respectively.

2.3. Network discretization and attribution

The Network Discretization and Attribution Tool discretizes the river network polyline into discrete reaches based on a user-defined maximum length and consideration of geometric constraints from tributary junctions in the river network (Fig. 6). Additionally, it computes and attributes key fluvial routing parameters to each associated reach, including upstream drainage area, reach length, and reach-average slope (Fig. 6). Discretizing river networks is a necessary step for calculating reach-averaged morphometrics (e.g., channel width, valley bottom width, river slope), creating topologic networks through which numerical models can route flow and other materials, and characterizing the conditions of discrete patches of aquatic habitat.

Inputs for this tool include (Table S3): (1) a polyline feature of the river network, (2) the flow accumulation raster, and (3) a filled DEM. Additionally, the user defines a maximum discretization length of the network reaches (in map units). The tool initially splits the sections of river network between each of the network confluences into segments at the user-defined maximum length starting from the upstream extent and moving downstream. However, in this first pass, discretized reaches that are considerably shorter than the user defined length are typically generated, as it is rare that a length of river between confluences is perfectly divisible by the defined discretization length. These short reaches (sometimes just a few meters in length) are often not long enough to reliably characterize reach-averaged morphometrics or habitat conditions. They can also be problematic as inputs to network routing models (e.g., if modeled transport lengths exceed reach lengths over the scale of one time-step, it can lead to numerical instabilities). To address this issue, USUAL identifies all reaches less than one-half of the maximum length and merges each with the next upstream reach. The tool then splits the newly merged reach at the midpoint to avoid creating reaches longer than the user-defined maximum.

For attribution of reach parameters (Fig. 6), one required input by the Network Discretization and Attribution Tool is a minimum river reach slope. The tool extracts the upstream and downstream elevations (m) of each reach, as well as the reach length (m), and then computes the average slope (m m^{-1}) along each reach as the difference between the maximum and minimum elevations divided by the length. Derived from a filled DEM, it is possible the river network may include reaches with zero slope, or the network may pass through extremely flat regions, such as lakes or reservoirs. These extremely low or zero slope reaches can cause numerical instabilities in 1-D network routing models. Therefore, the defined minimum threshold value is used to replace any reach slope values less than this value. If a user does not wish to replace derived slopes, they can set the minimum value to less than or equal to 0.

The tool outputs (Table S3) a new, updated river network shapefile that is discretized and includes an attribute table containing a unique reach ID, reach length, upstream and downstream elevations, reach-average slope, and a field identifying the ID of the next reach downstream (Fig. 6), which is critical information for network routing.

2.4. Network routing preparation

The last tool in the main workflow of the USUAL Watershed Tools (Fig. 1) is the Network Routing Preparation Tool. The tool ensures all pour points and the river network contain the necessary attributes to be applied for 1-D network routing. The tool has two functions: 1) snapping all pour points (sub-catchments and interfluves) to the river network, and 2) flagging any network reaches that intersect polygonal areas of interest (e.g., water bodies, urban areas, vegetation types or land cover).

Snapping the pour points for all of the interfluves and sub-catchments to the river network both functionally and spatially links the potential flow and material input locations throughout the watershed to points along the river network. The pour points produced from the Sub-Catchment and Interfluve Delineation Tool are all generated at flow accumulation cells immediately upstream or upslope but not directly on or intersecting the river network or perimeter of exclusion areas. This is required for the proper delineation of these features; however, to use these locations as spatially explicit point source nodes of material delivery to the river network, it is necessary the pour points intersect the river polyline and can be functionally linked to the appropriate reach or waterbody. The tool uses the ESRI 'Snap' function to move the points onto the river network and then writes all of the attributes of the associated river reach to their respective snapped pour points.

The second function to flag river reaches provides the user the option to identify reaches of the river network that may be of interest for subsequent applications or analysis. One example would be a river network delineated upstream of a dam that includes reaches delineated across the reservoir surface (e.g., Fig. 4). For 1-D routing applications, these reaches would not be appropriate locations to apply fluvial transport equations, and thus valuable to identify as unique from other reaches. Other examples could include characterizing which reaches flow through urban areas or through the extent of a wildfire. Regardless of the intended application, the tool uses a binary notation to identify which reaches in the river network intersect a user-specified polygon of interest (=1) and which do not (=0) (Fig. 6C).

The tool outputs (Table S4) new shapefiles of snapped pour points for both interfluves and sub-catchments and leaves the original, unsnapped pour point shapefiles unmodified. Additionally, all network attributes, including those added to the network in this tool (i.e., flagging), are appended to the attribute table of each newly snapped pour point shapefile.

2.5. Data regression tools

The USUAL Watershed Tools contain an additional sub-toolkit, Attribute Regression Tools, which houses two tools for data regression within ArcGIS based on fields within a shapefile's attribute table. The first tool, Scaling Relationship Generator Tool, computes a univariate regression between two variables, and the second tool, Scaling Relationship Extrapolator Tool, applies the regression, writing predicted values to a new field in the attribute table. Typically, this type of data analysis would require exporting the attribute table data to conduct regressions in external software and then reading the data back into ArcGIS to continue any geospatial analysis. An example application for this tool would be using a discretized river network that contains upstream drainage areas (e.g., output from the River Network Discretization and Attribution Tool) augmented with a field of river widths manually measured at select locations in the watershed to develop a drainage area-river width scaling relationship using the Scaling Relationship Generator Tool. The Scaling Relationship Extrapolator Tool applies the regression across the entire network attributing all links with river width based on an upstream drainage area.

The Scaling Relationship Generator Tool uses any attributed shapefile as an input (i.e., this does not need to be a shapefile created by USUAL). The user then specifies the attribute field (Table S5) containing the dependent dataset and the field containing the independent dataset and specifies one of three types of regressions to be applied: linear, exponential, or power. If the appropriate regression type to be applied is unknown, the user should initially plot the data using the ESRI Chart Tools to visually determine the most appropriate trend to be applied before using the tool. The Scaling Relationship Generator Tool regresses the data and appends the coefficient values to the shapefile attribute table with fields (coefficient a and b) defining the two regression coefficients. If the tool is run multiple times on the same input dataset, the tool will overwrite the coefficients previously written to the shapefile. Finally, the tool includes an option to output a scatter plot to a user-defined file directory that displays the input data, regression line, r^2 value, and the regression equation.

The second tool is the Scaling Relationship Extrapolator Tool. This tool allows a user to apply one of the three regression types to generate a new attribute field of predicted values within a shapefile based on identified fields for a dependent variable and coefficients. Returning to the above drainage area-river width relationship, a regression could be applied to the upstream drainage area field of the discretized network to estimate river widths for every reach (Fig. 6C and example application shown in section 4.1). The tool requires (Table S6) an input shapefile and requires the user define an output field name, as well as identify the input attribute fieldnames for the dependent variable, coefficients a & b, and the regression type associated with the coefficients (exponential, power law or linear). The tool then applies the fit and writes the predicted values to the output field.

2.6. Fluvial Reach-Average Width Tools

The USUAL Watershed Tools contain a sub-toolkit called the Fluvial Reach-Average Width Tools to measure reach-average widths along an elongate polygon (e.g., river channel or valley bottom). This functionality addresses a common need in characterizing reach-scale morphometrics, as well as the generation of initial conditions often needed in 1-D network routing.

The first tool in the set – the Fluvial Polygon Transects – generates a high-density of nodes and transects that connect across the opposite sides of the elongate polygon feature. The tool requires (Table S7): an input polygon, a user-defined transect spacing (in map units) and a polygon “centerline” (Fig. 7). This centerline does not necessarily have be exactly centered through the polygon but must intersect the polygon at the tips and only at the tips. While a river network could work, generating a centerline manually or using the Polygon to Centerline tool (requires the ESRI Production Mapping extension) ensures the outlined criteria. The elongate polygon (e.g. river, floodplain, valley bottom) needs to be generated externally from USUAL either by manual delineation or using existing tools (e.g., Clubb et al., 2017; Gilbert et al., 2016; Roux et al., 2015; Schwenk and Hariharan, 2021). Alternatively, centerlines can be generated using non-ESRI tools and methods (e.g., Dilts, 2015; Lewandowicz and Flisek, 2020; Roux et al., 2015; Schwenk and Hariharan, 2021). Regardless of the approach, one critical condition of any centerline used for these tools in USUAL is that it must extend to the polygon perimeter at all “tips” of the elongate polygon (Fig. 6A–C). This is required because the tool relies on this intersection point of the line and polygon to identify and split the elongate polygon into “left” and “right” segments.

Starting at the intersection point of the polygon and the centerline, the tool generates points along the edges of the two halves of the polygon at the defined transect spacing (Fig. 7B–D). A kd-tree is applied to each point to identify the closest point on the opposite side of the polygon and to generate point pairs. The paired points are then converted into lines, producing a series of transects spanning the width of the elongate polygon (Fig. 7B–D).

There are two additional, optional inputs: 1) a search radius applied around the points where the centerlines intersect the polygon to exclude points from transect generation (Figs. 7B), and 2) a polygon feature to allow users to prescribe specific areas to exclude from transect generation (Fig. 7C). These two options are intended for the exclusion of perimeter points at the upstream and downstream-most “tips” of the polygon (Fig. 7 B&C) where generating transects across flat edges, corners, or tapered edges may result in unrepresentative polygon width calculations. Regardless of whether the optional exclusion functions are used, the tool outputs (Table S7) a polyline shapefile containing transects that extend across the polygon with lengths calculated and attributed to each line feature (Fig. 7B–D).

The second tool is Fluvial Reach Averaged Width, which computes and attributes average widths for a discretized line feature within the elongate polygon. The intended application is to compute average widths of river channels or valley bottoms along each reach of the discretized river network, but there could be other potential applications. The tool densifies transect vertices, converts them to points, and assigns the transect length (i.e., local polygon width) to each. These attributed points are used to generate a TIN, which is then converted to a raster (of the user-defined resolution) with values representing the local polygon width (Fig. 7E). Finally, the ESRI ‘Zonal Statistics’ tool is applied to calculate the average width value from the raster along each reach of the discretized polyline and write this value to the new output field in the

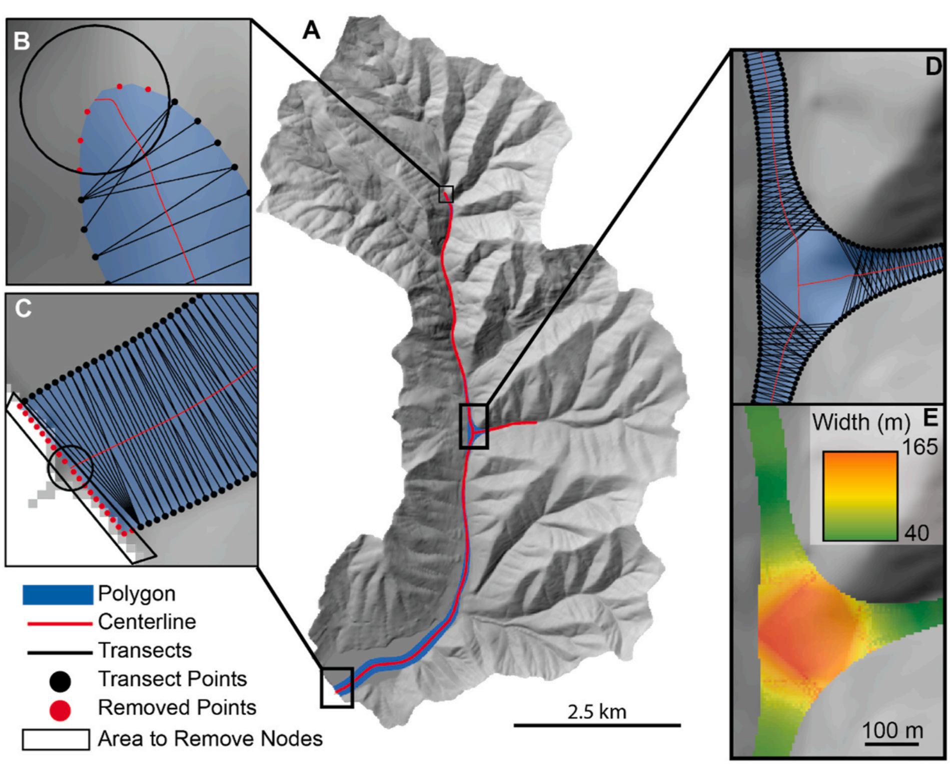


Fig. 7. Example of automated Fluvial Reach-Average Width tools. A) DEM hillshade of the watershed overlaid with a polygon of valley bottom extent (blue) and associated valley centerline (red). B) Example of a search radius generated around the intersection of the polygon and polyline and used to identify points to remove at the “tips” (red dots) before generating transects. C) Example of a user-defined polygon used to identify and remove points (red dots) at a flat terminus of a polygon. D) Points and transects generated at a polygon confluence. E) Raster generated within the polygon area and with colors scaled by width calculated from interpolating attributed transects.

attribute table (Table S8).

2.7. Model structure and data management

Overall, the USUAL Watershed Tools require a minimum of just two input datasets (a watershed pour point and a DEM) to delineate a watershed boundary, generate a discretized and attributed river network, delineate all sub-catchment and interfluve extents, and identify their associated point source input locations along the river network (Fig. 2). Moreover, each tool in USUAL can be run independently using inputs created by other toolkits. The additional tools provided in USUAL can also be applied to a variety of geospatial applications beyond watershed and network delineation.

Key outputs from USUAL (Fig. 2) are written to a user-defined folder. Additionally, the output folder will include a 'temp' subfolder to house all intermediate outputs, within which each tool creates its own subfolder of organized outputs. The inclusion of this intermediate data is intended to help users troubleshoot problems, and this folder structure makes it easy to delete all intermediate files if the final results are satisfactory. If applying a nested analysis, the output folder contains an additional folder with outputs for each nested watershed that is based on an optional user naming structure.

3. Evaluation, testing, and limitations

In this section, we demonstrate the capabilities of the USUAL Watershed Tools. We test the toolkit in watersheds with varying DEM resolutions, topographic relief, and river channel complexity, and evaluate the computational efficiency of USUAL. Additionally, we discuss potential limitations and considerations when running USUAL for different scenarios.

3.1. DEM resolution

To demonstrate the applicability of the USUAL tools across sites with variable resolution of available DEM datasets, we explored three sites: 1) the highest resolution site was the Big Walnut Creek (125 km^2 watershed) near North Salem, Indiana, USA (Fig. 8A) with a 1.5-m lidar-derived DEM (https://maps.indiana.edu), 2) the intermediate resolution site was Dells Creek (41 km^2 watershed) upstream of Little Dell Reservoir, UT, USA (Fig. 8B) with a 10-m USGS DEM (https://apps.nationalmap.gov/), and 3) the coarsest resolution site was the Fraser River between Lytton, BC, Canada and the southern end of Edge Hills Provincial Park, BC (Fig. 8B; 5852 km^2 watershed) with a 30-m DEM from TRIM (https://catalogue.data.gov.bc.ca/dataset/).

To delineate Big Walnut Creek, we used a river network threshold of 0.2 km^2 and a sub-catchment threshold of 0.05 km^2. The Dell Creek delineation used a river network threshold of 5 km^2 and a sub-catchment threshold of 0.1 km^2. For the Fraser River (Fig. 8C), we used a river network threshold of 5 km^2 and sub-catchment threshold of 0.1 km^2. Additionally, along the Fraser River, we input a pour point that was not at the mouth of the river and a DEM that intentionally did not cover the entire extent of the watershed (which covers ~25% of British Columbia; Rennie et al., 2018) to demonstrate the applicability and limitations of USUAL when applied to large rivers with input DEMS that do not cover the entire watershed.

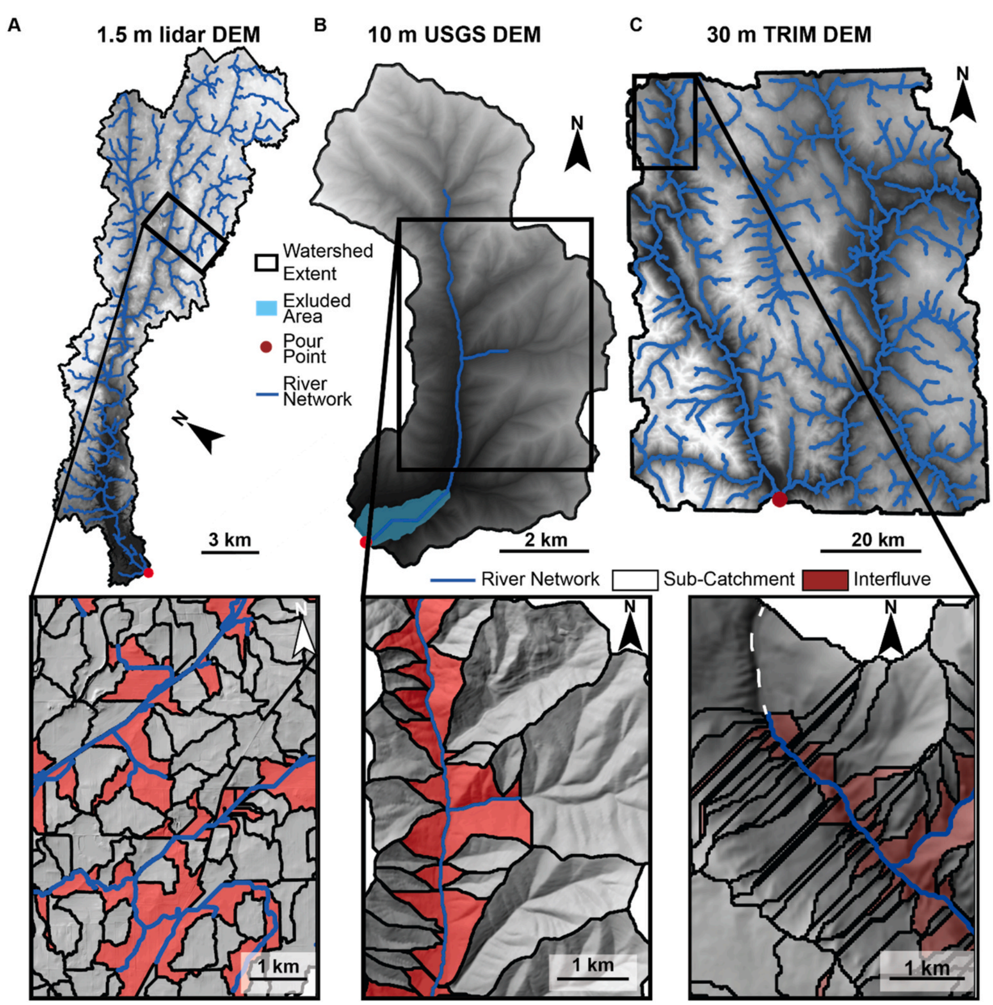


Fig. 8. Example of applying the USUAL Watershed Tools to delineate rivers, sub-catchments, and interfluves using high (A), moderate (B), and low resolution DEMs (C). The upper images show the input data for our delineations overlaid on hillshades derived from DEMs and the insets at the bottom show zoomed in results from the USUAL delineation. The dashed white line in zoomed in portion of C denotes the location where the Fraser River should be delineated but was not due to the prescribed drainage area threshold and DEM not covering the entire extent of the watershed.

Outputs from our delineations (Fig. 8) reveal that the USUAL Watershed Tools can be applied to delineate features from a variety of data sources and across a wide range of DEM resolutions. Furthermore, our delineation of the Fraser River DEM that did not cover the entire watershed extent (Fig. 8C) reveals that the landscape delineations are still successful. The interfluves and sub-catchments are still correctly delineated, because their pour points are based on drainage areas adjacent to the river channel. However, the upstream most reach of the Fraser River was not delineated (Fig. 8C) due to significantly lower than accurate flow accumulation values throughout the Fraser River reaches caused by the truncated extent of the DEM. Hence, if inputting a DEM to USUAL that does not span the full watershed, a user should ensure that the DEM at least extends well beyond the upstream most river reach of interest. Additionally, if applying the River Network Discretization and Attribution Tool, users should beware that the drainage areas attributed to truncated watersheds and segments of larger rivers will be smaller than the real upstream drainage areas.

3.2. Topographic relief and channel complexity

To demonstrate the capability of the USUAL Watershed Tools for delineating features in landscapes of varied topographic complexity, we compared subsets of the Fraser River and Big Walnut Creek, which reasonably represent end members of complexity. The Fraser River is a large river traversing a series of canyons (Rennie et al., 2018) containing high topographic relief (Fig. 9A) and a complex network of tributaries (Fig. 8C). Big Walnut Creek is located in the central till plain of Indiana (Gray, 2000), which contains minimal topographic relief (Fig. 9C). In our AOI, Big Walnut Creek's downstream portion is a meandering river with well-developed riparian vegetation, whereas the headwaters are mostly small agricultural ditches representing a variety of anthropogenic influences (e.g., channel straightening and constructed levees) in the channel network (Fig. 9C).

Our results show that the USUAL Watershed Tools are capable of delineating features in both steep, mountainous terrain (Fig. 8C; Fig. 9 A&B) and relatively flat landscapes (Figs. 8A and 9 C& D). This is because the terrain processing tools operate on elevation differences between neighboring cells. Therefore, the USUAL Watershed Tools work well on any DEM with sufficiently high resolution that captures the topographic variability in detail. Additionally, our analysis illustrates the utility of USUAL in landscapes with natural (Fig. 9A) and anthropogenic complexity (Fig. 9C). However, one limitation of USUAL in low-gradient landscapes is that advanced topographic filters (Passalacqua et al., 2012; Sangireddy et al., 2016) are not included in the river network delineation, which can help overcome problems introduced by bridges and other human-engineered features. Hence, in order to use USUAL in these settings, a user must first pre-condition the DEM for delineation by manually lowering the elevations of these features to match the river network. An additional limitation we note is that network delineation in USUAL was developed to handle single threaded channels, and may not work as expected in braided or anabranching river systems.

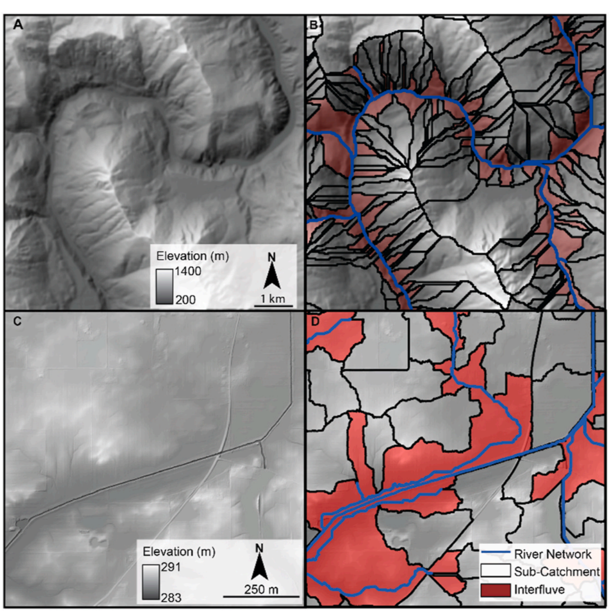


Fig. 9. Examples of delineations with different channel and topographic complexity. The left images are hillshades overlain on DEMs, and the right images show the delineation extents of the river channel, interfluves, and sub-catchments. A) Example of the Fraser River containing high topographic relief and a wide, sinuous channel. B) Delineated river, interfluves, and sub-catchments in the Fraser Canyon. C) Example of Big Walnut Creek, an agricultural headwater channel that has been straightened and leveed. D) Delineated river, interfluves, and sub-catchments along Big Walnut Creek.

3.3. Computational efficiency

To evaluate computational efficiency, we performed a series of repeated delineations on Toroda Creek, Washington, USA with varying DEM resolutions. Toroda Creek is located in mountainous north-central Washington State, with a watershed area of 175 km^2 (Fig. 10A). The input DEM was 1-m resolution and derived from lidar (https://lidarportal.dnr.wa.gov/). The DEM was then resampled to resolutions ranging from 1 to 10-m at 1-m increments and from 10 to 100-m at 10-m increments, giving a total of 19 different DEM resolutions (Fig. 9B). The Watershed and River Delineation Tool and Sub-Catchment and Interfluve Delineation Tool were run and timed for each DEM resolution. To account for any potential computational variability, we ran each tool 10 times at each resolution and present the average computation time. For our simulations, we used an AOI that extended just beyond the drainage divides (Fig. 10A), a river network threshold of 5 km^2 Fig. 10A), and a sub-catchment threshold value of 0.1 km^2.

Simulations were performed on a consumer grade laptop containing i7-7700HQ (quad-core 2.8 GHZ), 24 GB DDR3 ram, and a NVIDIA GTX 1050Ti graphics card. Each tool was called and parameterized using Spyder IDE and timed using the perf_counter in the time module. Results from this watershed indicate that DEM resolutions of 10-m (here ~1.8×10^6 cells) or less ran both tools in under 1 min, and DEM resolutions less than 4-m (here ~11.3×10^6 cells) ran in less than 5 min. For the highest resolution 1-m lidar DEM, running both tools took 30 min (here ~175.5×10^6 cells) (Fig. 10B). For a full break down, see Tables S9 and S10 (supplementary information).

4. Example application

In this section, we provide an example application of the USUAL Watershed Tools to delineate watershed features, discretize and attribute a river network, and apply the outputs to a 1-D network routing model. Specifically, we applied USUAL to the Logan River watershed upstream (555 km^2 watershed) of the First Dam Reservoir in Logan, Utah, USA, and use this site to demonstrate the utility of USUAL for an application of source-to-sink watershed modeling and analysis. The USUAL delineated hydro-geomorphic features were used as inputs to model spatially explicit soil erosion and delivery across the watershed, initialize a 1-D sediment transport model, and to evaluate the soil erosion model by comparing modeled and pre-existing, field-based estimates of sedimentation rate at the downstream reservoir.

4.1. USUAL application to the Logan River

We first applied the Watershed and River Delineation Tool to the Logan River (Fig. 11A). For our delineation, we used 10-m USGS DEM, specified an AOI that extended just beyond the drainage divides, used a

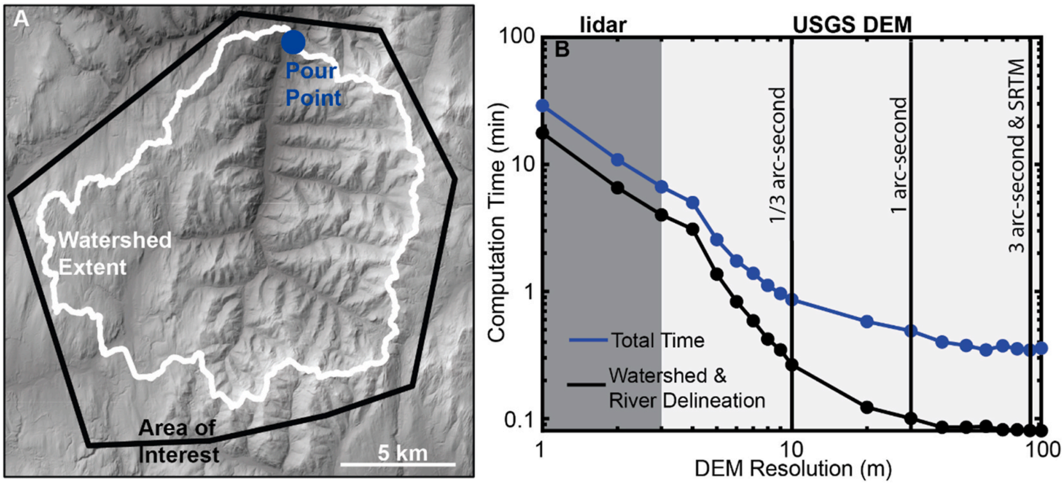


Fig. 10. Demonstration of USUAL's computational efficiency. A) Input data and computed watershed extent for Toroda Creek, WA, USA. B) Run times for the USUAL delineation tools on a consumer grade laptop delineating the watershed extent, sub-catchments, interfluves and river network in a ~175 km^2 watershed at different DEM resolutions.

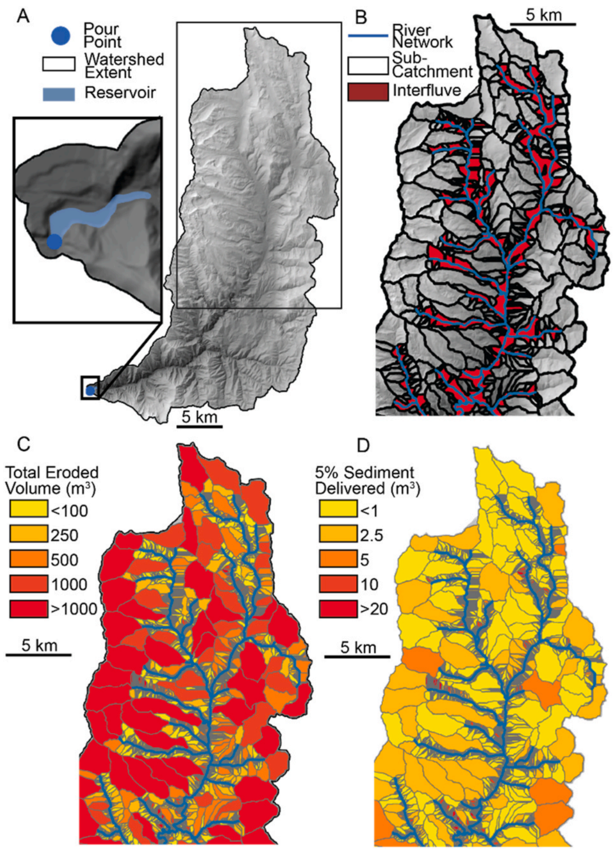


Fig. 11. Logan River watershed delineation with modeled sediment erosion and delivery. A) Input data to run USUAL for the Logan River watershed. B) Subset of USUAL river network, sub-catchment, and interfluve delineations. C) RUSLE-derived annual soil erosion volumes calculated for each sub-catchment and interfluve. D) Estimated annual sediment delivery to the river network by each sub-catchment and interfluve after enforcing a 95% reduction to the predicted SDR equations.

river network threshold of 5 km^2, and specified a pour point at the outlet of First Dam. Sub-catchments and interfluves (Fig. 11B) were then generated with the Sub-Catchment and Interfluve Delineation Tool using a sub-catchment threshold value of 0.1 km^2. The River Network Discretization and Attribution Tool was applied using a maximum discretization length of 500 m and a minimum slope threshold of 0.01 m/m. To attribute the network with river widths, we used the Regression Application Tool and applied a power-law relationship to scale drainage area to river width based on coefficients derived for the continental United States (Wilkerson et al., 2014):

$$b = 1.41A^{0.462} \tag{1}$$

where, b is the bankfull width (m) and A is the drainage area (km^2). Finally, the Network Routing Preparation Tool was run to produce a river network ready for routing analysis.

To model spatially explicit sediment inputs to the Logan River, we used the Revised Universal Soil Loss Equation (RUSLE), models of sediment delivery, and the USUAL delineated features (see supplementary information for more detailed methods). Applying RUSLE across the watershed, we generated a 10-m raster output of annual erosion rate. We then applied a sediment delivery ratio (SDR) equation based on flow path length to the river network to predict what fraction of soil eroded in each raster cell would be delivered to the river network (Gannon et al., 2019; Wagenbrenner and Robichaud, 2014). The SDR raster was then multiplied by the RUSLE raster to predict the volume of soil delivered to the river network each year from each raster cell. The delineated interfluves and sub-catchments from USUAL were then used to run the ESRI Zonal Statistics tool to sum the volume of sediment (Fig. 11C) eroded and delivered to the river network from each feature polygon. Using the unique IDs linking polygons to pour points, the modeled sediment input volumes were then written as attributes to the snapped pour points for each feature.

4.2. Application of 1-D sediment routing

The delineated river network and snapped interfluve and sub-catchment pour points from USUAL feed directly into 1-D network routing models, such as the Network Sediment Transporter (NST; Pfeiffer et al., 2020). The NST model uses a Lagrangian framework to simulate the transport of sediment under space- and time-variable flow conditions on a river network (Czuba, 2018). In the model framework, each reach of a discretized river network serves as a link through which sediment is routed and the snapped and attributed pour points for sub-catchments and interfluves generated by the USUAL Watershed Tools function as sediment input locations to the network.

The modeled sediment delivery volumes at each interfluve and sub-catchment pour point inform the annual sediment loads supplied to the

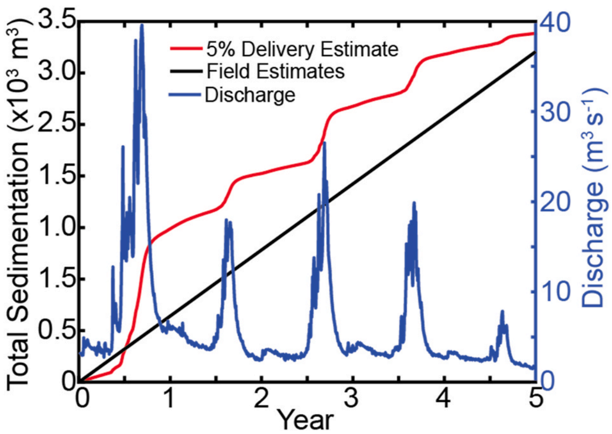


Fig. 12. Modeled vs. field-estimated sedimentation for First Dam Reservoir, Logan, Utah. The red line shows the total volume of sediment over time predicted by the NST routing model using 5% of the estimated sediment volume delivery to the river network. The black line shows the field estimated annual sedimentation, assuming a steady and continuous rate of sedimentation. The blue line shows the daily discharge over the 5-year simulation.

Logan River network (Fig. 11D). Sediment loads were divided into two grain size fractions, sand and fines (<2 mm), based on soils data from STATSGO (Reybold and TeSelle, 1989). The fine fraction was treated as suspended load and was delivered to the reservoir based on a sediment rating curve. The sand fraction was routed with NST using a mixed-size sediment transport equation (Wilcock and Crowe, 2003). Simulations were run for five water years using daily discharges (Fig. 12) measured just upstream of First Dam (USGS gage 10109000; 10/1/2016 –9/30/2021) and scaled to each reach based on its upstream drainage area. At the beginning of each month, one-twelfth of the predicted annual sediment delivery at each pour point was supplied to the river network and routed through the Logan River.

4.3. Results and discussion

Our initial simulations indicated annual sedimentation in the reservoir was 2.5 orders of magnitude greater than the field measured volumes of 641 $m^3\ yr^{-1}$ (Utah Division of Water Resources (UDWR), 2010). While sediment routing models have the potential to over- or under-estimate transport volumes, the magnitude of disparity in these results likely reflects over predictions in soil erosion and delivery by RUSLE and/or the SDR equations. A possible source of error in the RUSLE calculations is the inherent limitations in the accuracy of geospatial data and uncertainty in factor parameterization (Kampf et al., 2020). In particular, the cover-management factor has been shown to span up to 3 orders of magnitude (Larsen and MacDonald, 2007). Further, although RUSLE is commonly applied at landscape-scales, it has previously been shown to over-predict erosion for sub-catchments or watersheds larger than 0.01 km^2 (Kampf et al., 2020). Additionally, we evaluated a range of potential SDR equations for our analysis (e.g. Ebrahimzadeh et al., 2018), and we chose the SDR model that resulted in the lowest magnitude of sediment delivery to the river network. Depite this effort, we ultimately found that we had to impose a 95% watershed-wide reduction to predicted sediment delivery volumes (Fig. 11D) in order to produce a model with annual reservoir sedimentation rates that approximated field estimates (modeled sedimentation rate of 669 $m^3\ yr^{-1}$; Fig. 12).

This example underscores the utility of USUAL for broad applications in watershed analysis, and more specifically, an example of how USUAL can be used to evaluate and run watershed-scale source-to-sink models. Additionally, while it is more difficult to quantify and demonstrate here, the use of USUAL for this application eliminated the time-intensive steps typically required for delineating and extracting attributes for hydro-geomorphic modeling. The labor and computational time required to develop functional workflows, to execute the >150 ArcGIS functions required for the hydro-geomorphic delineation of just a single watershed (see supplementary information for USUAL workflows), and to code the interspersed, non-ArcPy steps necessary to fully prepare a watershed for analysis and hydro-geomorphic modeling can represent weeks of work for a single project (e.g., Murphy et al., 2019). In contrast, the USUAL Watershed Tools requires executing only 4 ArcGIS toolboxes, does not necessitate exporting and re-importing data to ArcGIS (i.e., does not involve any steps that require software or scripts external to ArcGIS), does not require any manual adjustments to ensure proper feature delineation, and for a moderate sized watershed like the Logan River was completed with less than 15 min of effort. USUAL represents a simple and streamlined approach for delineating watersheds, thus providing researchers more time to focus on analysis and evaluation of their results, rather than time-intensive geospatial pre-processing.

5. Concluding remarks

We have introduced the USUAL Watershed Tools, a new Python-based ESRI toolkit for delineating hydro-geomorphic features, including watersheds, rivers, interfluves, and sub-catchments. Along river networks, USUAL extracts relevant attributes, such as upstream drainage area, reach length, average channel slope, and the downstream connectivity of links. Additionally, USUAL can develop and apply regressions between shapefile attributes within the ArcGIS environment, and automate the measurement of a reach-averaged river or valley-bottom widths. Furthermore, the USUAL Watershed Tools serve as a geospatial pre-processor for network-based models, as the outputs can be directly fed into and used to run 1-D routing models (e.g., Pfeiffer et al., 2020). USUAL delineates and generates commonly needed hydro-geomorphic geospatial features that typically require time-intensive ArcGIS methods. Reducing geospatial processing times by using USUAL will: 1) provide users the potential to drastically scale up watershed-based analyses and modeling to evaluate a significantly greater number of landscapes in less time, and/or 2) allow users to focus their efforts more on research (e.g., model development, sensitivity testing, and analysis) than landscape delineation. Furthermore, USUAL allows users to easily extract, evaluate, and/or model environmental metrics at appropriate hydro-geomorphic scales and process domains by delineating landscapes into watersheds, river networks, sub-catchments, and interfluves. Finally, USUAL is capable of delineating features across a diverse range of watersheds with variable drainage area, topographic complexity, and relief, as well as with topographic data of varying spatial resolution.

Software availability

Name of Software: Utah State University AppLied (USUAL) Watershed Tools.
Contact Information: scott.david@usu.edu.
Year First Available: 2022.
Program Language: Python.
Software Requirements: ArcGIS Pro 2.9 and higher.
License: GNU GPL-3.0.
Availability: https://github.com/WatershedsWildfireResearchCollaborative/USUAL.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Availability: https://github.com/WatershedsWildfireResearchCollaborative/USUAL

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envsoft.2022.105576.

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