Climate and Upland Loading Vulnerability Evaluation and Risk Analysis Tool (CULVERT)

Comprehensive User Manual

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Access the web-application at culvert-at-risk.org

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1. Summary

The Climate and Upland Loading Vulnerability Evaluation and Risk Analysis Tool (CULVERT) is an integrated scientific software platform developed for comprehensive watershed analysis and hydrologic risk assessment. This user manual provides detailed operational procedures and methodological guidance for all software modules, including watershed delineation, regional frequency analysis, rational method calculations, graphical peak discharge estimation, culvert hydraulic capacity assessment, streambank erosion vulnerability analysis, Revised Universal Soil Loss Equation (RUSLE) implementation, and watershed debris flow modeling.

Key Features

The CULVERT software incorporates the following analytical capabilities:

- **Advanced Watershed Delineation**: Automated boundary extraction using digital elevation models and sophisticated flow direction algorithms
- **Multi-Method Hydrologic Analysis**: Integration of regional frequency analysis, rational method, and graphical peak discharge methodologies for comprehensive flood risk assessment
- **Hydro-geomorphologic Risk Evaluation**: Streambank erosion susceptibility analysis and debris flow hazard modeling tools
- **Interactive Visualization Platform**: Dynamic mapping interface with customizable display options and real-time analysis feedback
- **Professional Documentation**: Automated report generation with standardized formatting and comprehensive technical documentation
- **Data Management**: Support for multiple file formats with quality control validation and seamless data export capabilities

2. Introduction

Transportation infrastructure on national forest lands includes an extensive network of road culverts that facilitate water conveyance beneath roadways while maintaining ecological connectivity. The existing forest road infrastructure was engineered based on historical hydrologic conditions and design standards that may be inadequate under current and projected climate scenarios.

Climate change is intensifying hydrologic extremes, particularly precipitation patterns that exceed historical design parameters for transportation infrastructure. These evolving conditions present multiple hazards to culvert systems, including flood-induced overtopping, sediment accumulation, and flood induced debris flows. Culvert failures resulting from these hazards can compromise transportation networks, public safety, economic activities, and aquatic habitat connectivity.

2.1. Software Development and Purpose

The Climate and Upland Loading Vulnerability Evaluation and Risk Analysis Tool (CULVERT) represents a comprehensive web-based platform developed to address these emerging infrastructure vulnerabilities. This dynamic application systematically identifies culverts experiencing hydraulic inadequacy, erosion-induced sedimentation risk, and potential failure under extreme flow conditions.

The software serves resource managers, transportation engineers, and environmental professionals engaged in culvert vulnerability assessment across multiple hazard categories, including flooding due to undersized infrastructure, accelerated soil erosion, and debris flow scenarios.

2.2. Funding and Institutional Support

This research and development initiative is supported through collaborative funding from the U.S. Department of Transportation and the USDA Forest Service. The partnership reflects the critical intersection of transportation infrastructure resilience and natural resource management objectives.

2.3. Technical Framework

CULVERT operates as an automated hydro-geospatial modeling platform that integrates decision support capabilities with comprehensive risk assessment methodologies. An advanced watershed delineation is implemented first for identifying and mapping the drainage areas specific to each road-stream intersection. The system then evaluates culvert vulnerability through two distinct failure mechanisms: hydrologic risk assessment determined by chances of hydraulic overtopping resulting from inadequate hydraulic capacity, and obstruction due to sediment and debris accumulation that may necessitate infrastructure restoration or replacement.

2.3.1. Watershed Delineation

Watershed delineation is the process of identifying and mapping the drainage area that contributes surface water flow to a specific outlet point. This method utilizes digital elevation models (DEMs) and advanced flow direction algorithms to automatically determine watershed boundaries with high precision.

Key Algorithms Used:

- D8 Flow Direction Algorithm
- Flow Accumulation Analysis
- Stream Network Generation
- Watershed Boundary Extraction

2.3.2. Hydrologic Vulnerability Assessment

The platform addresses hydraulic inadequacy through a comprehensive suite of hydrologic modeling techniques designed to quantify peak discharge characteristics under various return period scenarios:

1. **Regional Frequency Analysis (RFA)**: Statistical modeling of extreme flow events in gauged and ungauged watersheds by incorporating temporal trends and climate variability to account for changing hydrologic conditions in non-stationary settings.
2. **Rational Method (RM)**: Simplified peak discharge estimation for small gauged and ungagued watersheds using rainfall intensity, runoff coefficients, and watershed characteristics
3. **Graphical Peak Discharge Method (GPDM)**: Unit hydrograph-based approach for medium-scale gauged and ungauged watersheds incorporating synthetic storm distributions and rainfall-runoff transformation processes

The modular architecture supports integration of additional hydrologic methods and models to accommodate evolving analytical requirements and emerging methodologies.

2.3.3. Hydro-geomorphological Vulnerability Assessment

Sediment and debris obstruction vulnerability is evaluated through an ensemble modeling approach that aggregates risk scores derived from multiple hydro-geomorphological assessment techniques:

1. **Streambank Erosion Vulnerability Assessment (SBEVA)**: Evaluation of channel stability and erosion potential based on hydraulic stress, bank material properties, and vegetation characteristics
2. **Revised Universal Soil Loss Equation (RUSLE)**: Quantitative assessment of watershed-scale soil erosion rates incorporating rainfall erosivity, soil erodibility, topographic factors, and land cover management practices
3. **Watershed Debris Flow Modeling (WDFM)**: Debris flow hazard assessment utilizing extreme precipitation, watershed characteristics, soil and geologic properties, and debris availability mapping.

The ensemble methodology synthesizes vulnerability scores from each assessment technique to generate composite risk ratings for road-stream crossing infrastructure, providing a comprehensive evaluation framework for sediment-related failure mechanisms.

The web application incorporates both static analytical outputs and interactive dashboard visualization tools, providing users with flexible access to assessment results through integrated online interfaces.

2.4. System Requirements

The CULVERT web application operates as a browser-based platform with specific hardware and software prerequisites to ensure optimal performance and functionality.

2.4.1. Table Hardware Specifications

Component	Minimum Requirement	Recommended Specification
Storage	2 GB available disk space for output data download and storage for a relatively small area of interest.	5 GB for output data download and storage for a relatively larger area of interest.
Network	Broadband internet connection	High-speed connection for large dataset processing

2.4.2. Operating System Compatibility

- Windows: Version 10 or later
- macOS: Version 10.14 (Mojave) or later
- Linux: Ubuntu 18.04 LTS or equivalent distributions

2.4.3. Browser Requirements

The application requires a modern web browser with JavaScript enabled and WebGL support:

- Google Chrome: Version 90 or later (recommended)
- Mozilla Firefox: Version 88 or later
- Safari: Version 14 or later
- Microsoft Edge: Chromium-based version 90 or later

2.4.4. Additional Considerations

- Internet Connection: Required for data access, cloud processing, and real-time analysis updates
- Security: Pop-up blockers should allow the CULVERT domain for proper functionality

2.5. Getting Started

2.5.1. Initial Access and Navigation

Upon successful authentication, login and application launch, users access the project dashboard interface, which serves as the central hub for creating new or accessing existing projects. The app is hosted at https://culvert-at-risk.org. Users upon landing on the this page can access the home page as shown in Figure 2.5.1.

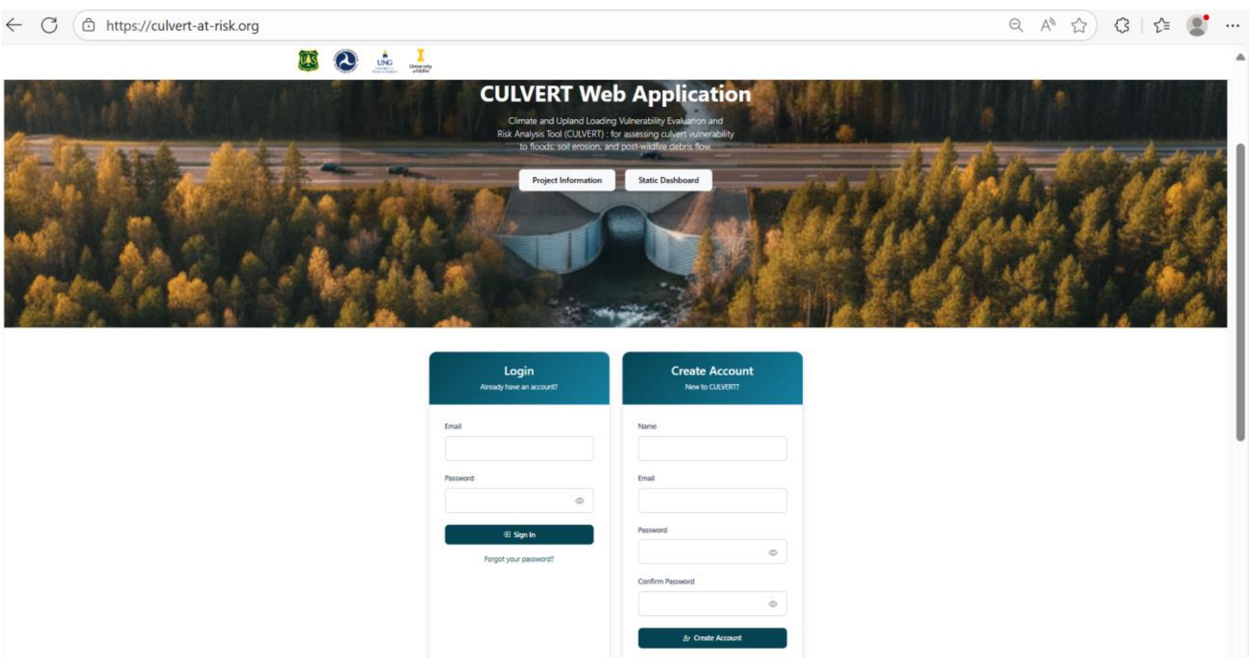

Figure 2.5.1. Snapshot of the home page.

2.5.2. Modular Architecture

The CULVERT platform employs modular software architecture designed to accommodate diverse analytical workflows and user expertise levels. This design philosophy enables users to:

- Execute Individual Analyses: Perform standalone assessments using specific methodological approaches
- Integrate Multiple Workflows: Combine complementary analysis techniques for comprehensive vulnerability assessment
- Customize Analysis Sequences: Adapt analytical procedures to match project-specific requirements and data availability
- Scale Computational Complexity: Progress from simplified screening-level assessments to detailed engineering analyses

2.5.3. User Interface Organization

The main interface incorporates the following functional components:

- Project Management Panel: Tools for creating, saving, and managing analysis projects as shown in Figure 2.5.3.
- Data Input Interface: Streamlined data import and validation procedures
- Analysis Module Selector: Access to hydrologic and hydro-geomorphological assessment tools
- Results Visualization: Interactive mapping and graphical output displays
- Report Generation: Automated documentation and export capabilities

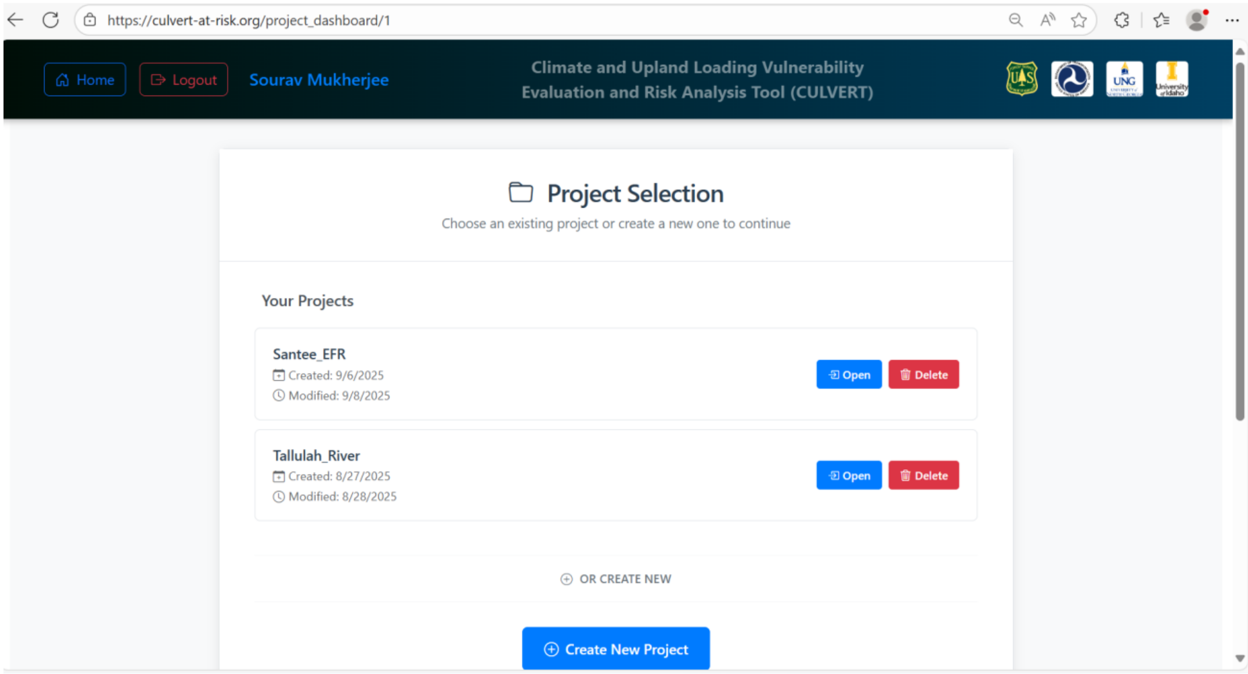

Figure 2.5.3. Snapshot of the project management page.

This organizational structure facilitates efficient navigation between analytical components while maintaining workflow continuity and data integrity throughout the assessment process.

3. Watershed Delineation

3.1. Definition and Methodological Framework

Watershed delineation serves as the foundational step in flood modeling, as it defines the spatial boundaries within which surface water flows converge toward a common outlet, directly influencing runoff patterns, peak discharge calculations, and flood risk assessments. Accurate watershed boundaries are essential for hydrologic modeling because they determine the contributing area, channel network characteristics, and flow accumulation patterns that drive flood generation processes (Jenson & Domingue, 1988; O'Callaghan & Mark, 1984). The precision of watershed delineation directly impacts the reliability of flood models used to evaluate infrastructure vulnerability, as misrepresented drainage areas can lead to significant errors in discharge estimates, flood extent mapping, and subsequent risk assessments for critical infrastructure such as bridges, culverts, and urban developments (Garbrecht & Martz, 1997; Tarboton et al., 1991).
This computational process leverages high-resolution digital elevation models (DEMs) in conjunction with sophisticated flow direction algorithms to automatically extract watershed boundaries with sub-pixel precision and hydrologic accuracy.

The methodology employs terrain analysis principles to simulate surface water flow patterns across the landscape, accounting for topographic controls on drainage networks and catchment boundaries. The automated approach ensures consistency and reproducibility while significantly reducing the time and expertise requirements associated with manual delineation techniques.

Computational Algorithms

The watershed delineation module incorporates a suite of established hydrologic modeling algorithms:

Flow Direction Analysis:

- **D8 Flow Direction Algorithm**: Single-direction flow routing methodology that assigns flow from each grid cell to one of eight neighboring cells based on steepest descent
- **D-Infinity Flow Direction**: Multiple flow direction algorithm that distributes flow proportionally across downslope neighbors for enhanced representation of divergent flow patterns

Hydrologic Network Processing:

- **Flow Accumulation Analysis**: Computational procedure that calculates the upslope contributing area for each grid cell, serving as the foundation for stream network identification
- **Stream Network Generation**: Threshold-based extraction of drainage channels using flow accumulation values and topographic convergence indices
- **Watershed Boundary Extraction**: Geometric processing that defines catchment perimeters based on drainage divides and flow direction patterns

Quality Assurance Procedures:

- **Depression Filling**: Automated correction of artificial sinks in elevation data that impede natural flow routing
- **Boundary Smoothing**: Post-processing algorithms that refine watershed perimeters while maintaining topographic accuracy
- **Connectivity Validation**: Verification procedures ensuring proper hydrologic connectivity between upstream areas and designated outlets

3.2. Steps to perform watersheds delineation

After creating a new project or opening an existing project from the project dashboard the users are directed to the watershed delineation page, as shown below in Figure 3.2. The analysis follows eight main phases: data preparation, road network processing, optional hydro-enforcement, hydrologic modeling, pour point processing, watershed delineation, characterization, and quality control.

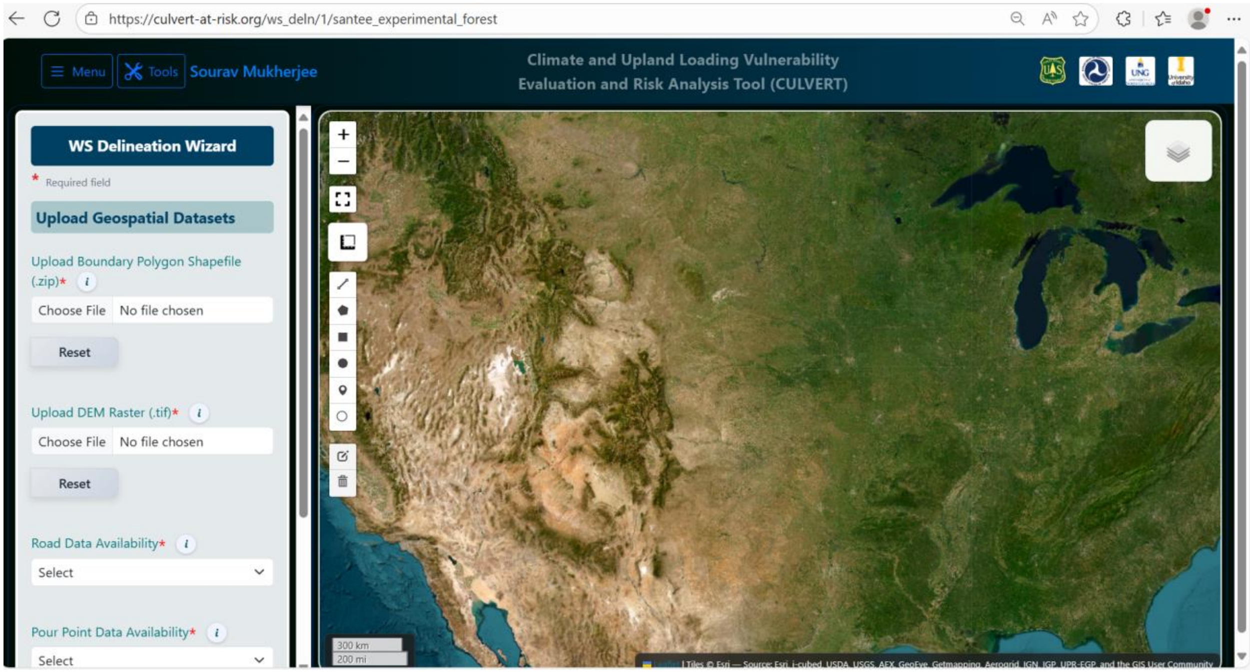

Figure 3.2. Snapshot of the watershed delineation page.

3.2.1. Step1: Upload Geospatial Dataset

The input data selection for availability and uploads, and acceptable data formats required for delineating the watersheds using the CULVERT v01 application is demonstrated below.

3.2.1.A. Upload boundary and elevation data:

The Watershed delineation methodology implemented in CULVERT v01 is a systematic geospatial workflow that begins with user data uploading including region boundary polygon shapefiles and DEM raster data (Figure 3.2.1.A.).

Boundary Shapefile: Accepted format:

- Upload a ZIP file containing boundary polygon files: `.shp`, `.shx`, `.dbf`, and `.prj`.
- Ensure the total ZIP file size does not exceed 25 MB.
- The boundary must be located within the USA.
- The maximum area allowed for the boundary is 120,000 hectares.

Sample Data Download: here

LiDAR DEM Data: Accepted format:

- Upload a valid DEM raster file in `.tif` format with elevation values in `m`.
- The DEM should cover an area larger than the boundary shapefile to ensure proper watershed delineation.
- Make sure the DEM resolution is suitable for user's analysis.
- If the DEM leaves out any part of the boundary, an error will be displayed.

Sample Data Download Link: here

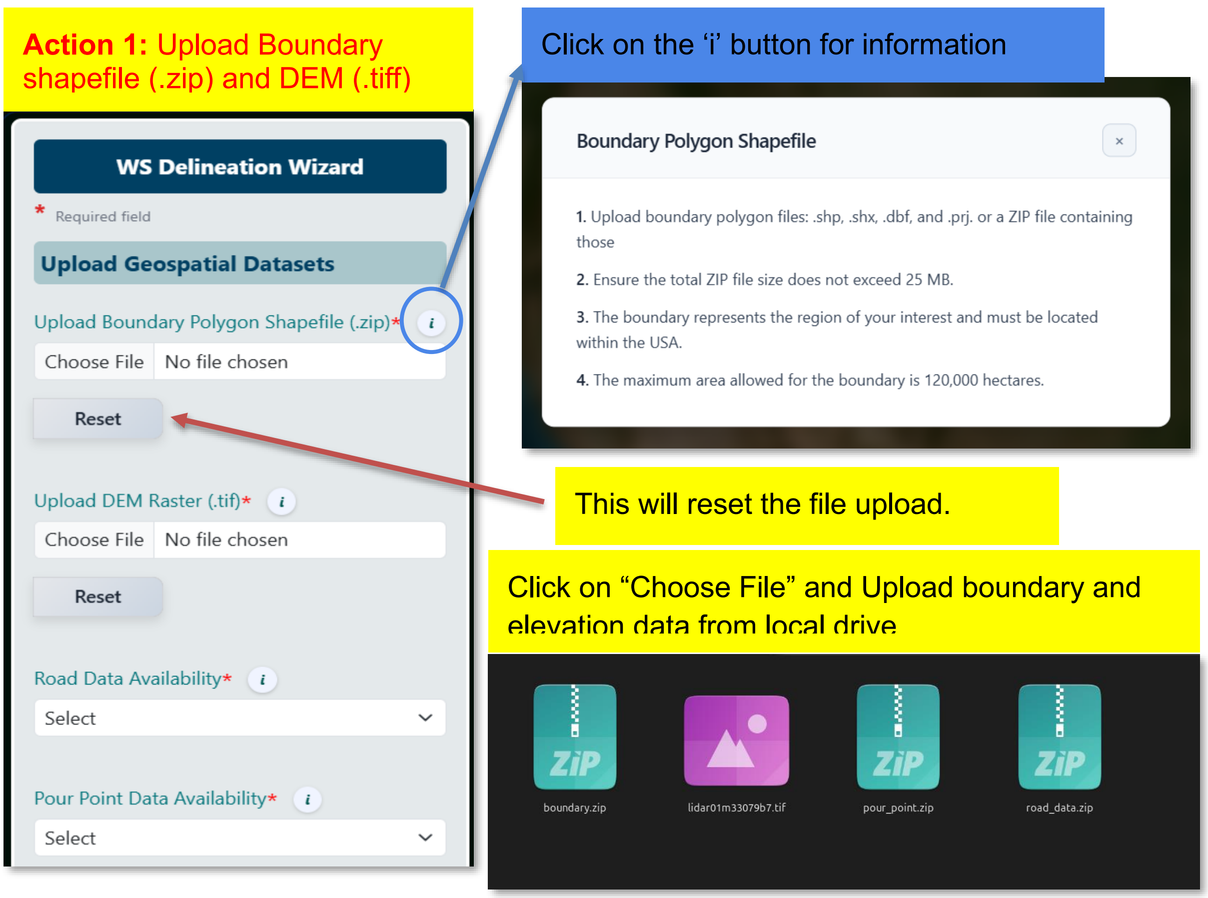

Figure 3.2.1.A. Schematic illustrating the steps for boundary and elevation data upload.

3.2.1.B. Road data availability and upload:

Road network data can either be uploaded manually by the user or, if unavailable, automatically retrieved from the OpenStreetMap (OSM) API. The supported data formats, along with the procedure for selecting road data availability options and uploading custom road network files, are illustrated in Figure 3.2.1.B.

Road Polyline Shapefile: Accepted format

- Upload a ZIP file containing boundary polygon files: `.shp`, `.shx`, `.dbf`, and `.prj`.
- Ensure the total ZIP file size does not exceed 25 MB.
- The road layer must be located within the USA.

Sample Data Download: [here]

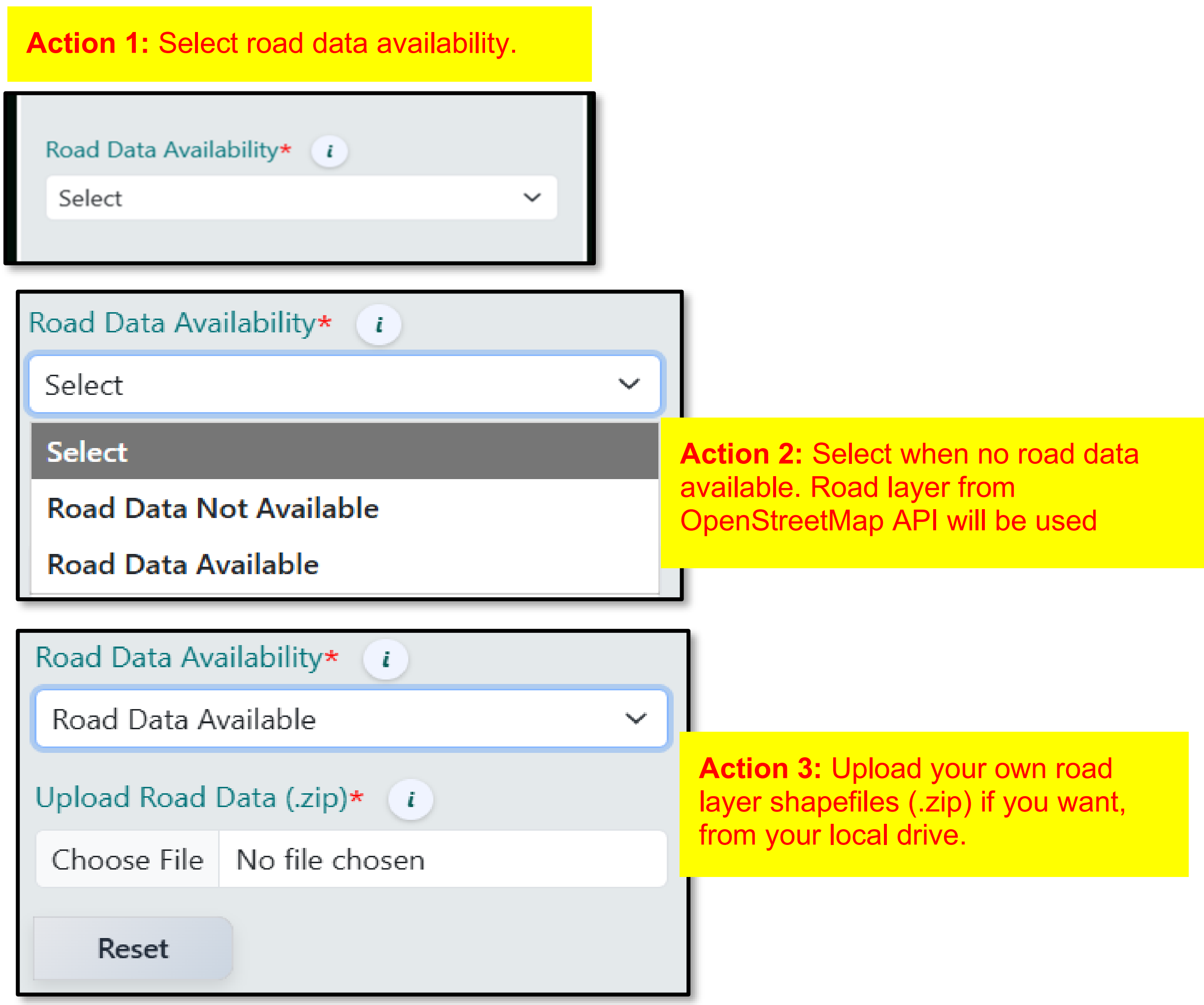

Figure 3.2.1.B. Schematic illustrating the steps for road network data availability selection and upload.

3.2.1.C. Pour point data availability and upload:

Accurate delineation of pour points constitutes a fundamental prerequisite for infrastructure geo-location, hydraulic capacity estimation, and vulnerability assessment. In hydrologic terms, pour points represent outlet nodes within a catchment or sub-catchment where accumulated flow converges and exits the drainage area. These locations function as critical reference points for downstream hydrologic modeling, hydraulic simulation, and risk evaluation workflows.

The data availability and upload functionality enable users to:

- Define custom pour point locations aligned with critical infrastructure assets or monitoring sites.
- Validate and adjust pour point placement against existing hydrographic datasets and infrastructure inventories.
- Provide the baseline for subsequent analyses, including capacity assessment and the specification of vulnerability assessment targets.

Within the **CULVERT v01 framework**, multiple conditions of pour point data availability are supported to maximize flexibility in user-defined inputs as demonstrated in the workflow in Figure 3.2.1.C. Specifically, users may:

- **'No Data Available':** Skip pour point data upload when such data are unavailable, allowing the system to proceed with default or automatically derived pour points.
- **'Both Culvert and Gauging Station Point Data Available'** Upload pour point shapefiles that include both road–stream crossing infrastructure (culverts, bridges, fords, etc.) and gauging stations.
- **'Only Culvert Point Data Available':** Provide shapefiles containing only road–stream crossing infrastructure locations.
- **'Only Gauging Station Point Data Available':** Supply datasets restricted solely to gauging station points when other pour point data are unavailable.

For culvert discharge capacity analysis, users can include detailed geometric and hydraulic parameters in their pour point datasets. These parameters enable precise hydraulic calculations using established engineering methods (inlet control, outlet control, and Manning's uniform flow) to determine infrastructure capacity and assess vulnerability under various flow conditions. The system applies intelligent defaults for missing parameters while accommodating comprehensive datasets when available.

This modular approach ensures that critical infrastructure and hydrologic monitoring locations can be consistently integrated into the modeling workflow, regardless of the completeness of the available dataset as demonstrated below along with the necessary data format required to be used in the CULVERT v01 application.

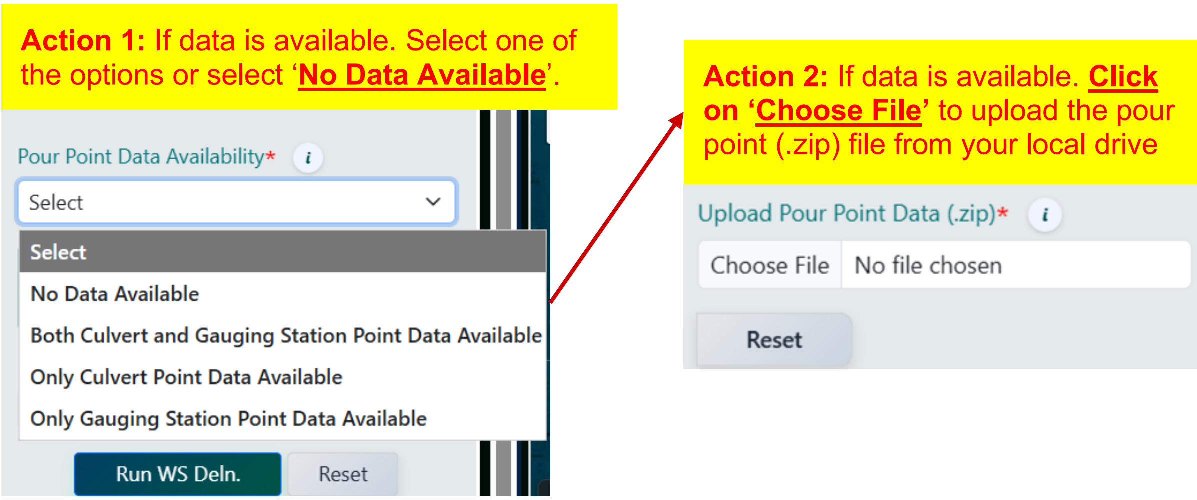

Figure 3.2.1.C. Schematic illustrating the steps for pour point data availability selection and upload.

Condition 1: 'No Data Available'

Users can delineate watersheds specific to road-stream intersections even when they do not have or provide pour-point data. In that case, instead of analyzing user-specified locations, the system automatically identifies ALL road-stream crossings within the study area. This shifts from targeted analysis to complete infrastructure vulnerability mapping. For more details refer to **Appendix 8.1.**

Condition 2: Acceptable format for 'Both Culvert and Gauging Station Point Data Available'

- Upload a ZIP file containing pour point files: `.shp`, `.shx`, `.dbf`, and `.prj`.
- Points located outside the region boundary will be excluded from the analysis.
- At least one pour point must be within the boundary, or watershed delineation will throw an error.
- A maximum of 300 pour points can be included in the analysis at a time.
- The point shapefile must have these headers (Note- user can have more columns like user may find in the sample dataset which was modified from the CATT's dataset, but the data and columns described in the table below are mandatory) as shown in Table 3.2.1.C.1.:

Table 3.2.1.C.1. Acceptable format for 'Both Culvert and Gauging Station Point Data Available'

Column Name	Description	Used in Culvert discharge capacity estimation method	Data Requirement
Point_ID	Unique Integer Identifier for each pour point.	All methods	Mandatory
Point_Name	Unique Name (alpha-numeric) Identifier for each pour point, e.g., culvert name and Gauging station name.	Not used	Optional
Width_ft	Width of the culvert in feet units. Must be set to NA for gauging stations.	All methods	Mandatory
Height_ft	Height of the culvert in feet units. Must be the same as the 'Width_ft' for Circular culverts. Must be set to NA for gauging stations.	All methods	Mandatory
Longitude	geographical X-coordinate in degrees.	All methods	Mandatory
Latitude	geographical Y-coordinate in degrees.	All methods	Mandatory
Pour_Sha	Present type or shape of the culverts and/or gauging stations. Currently only supports Pour_Sha = Circular, Box, Pipe arch, Elliptical, `'Round'`, and Bridge. If NA/missing then it defaults to "Circular". Note: Bridge, if mentioned, will be excluded from the hydrologic vulnerability analysis.	All methods	Optional
Flag_Gst	Must be set to 1 if the pour point is a gauging station, and must be set to 0 if it is not a gauging station.	Not used	Optional
Grp_ID	Identifier (alpha-numeric) for culverts belonging to the same group (pair, triple, or larger group). Rows indicating single	Not used	Optional

Column Name	Description	Used in Culvert discharge capacity estimation method	Data Requirement
	drainage structure, bridge, or gauging station must be set to NA.		
Grp_Size	The size (integer) of the group (2 for paired, 3 for triple, or a greater number for larger groups). Rows indicating single drainage structure, bridge, or gauging station must be set to NA.	All methods	Optional
GWS_ID	Unique identifier (alpha-numeric) for the gauged watershed drained by the gauging station. Must be set to NA if it's not a gauging station.	Not used	Optional
Culvert_Sl	Culvert slope as decimal (e.g., 0.01 = 1%). Defaults to 0.01 if missing	Inlet Control, Outlet Control, Manning Uniform	Optional
HW_ft	Headwater depth in feet. Defaults to 1.5 × culvert height if missing	Inlet Control, Outlet Control	Optional
TW_ft	Tailwater depth in feet. Defaults to 0.5 × culvert height if missing	Outlet Control	Optional
L_ft	Culvert length in feet. Defaults to 98.4 ft (30 m) if missing	Outlet Control	Optional
n_manning	Manning's roughness coefficient. Defaults to material-based values if missing	Outlet Control, Manning Uniform	Optional
Material	Culvert material: "Concrete", "Steel", "HDPE", "Aluminum", "Plastic", "CMP". Defaults to "Concrete" if missing	Outlet Control, Manning Uniform	Optional

Column Name	Description	Used in Culvert discharge capacity estimation method	Data Requirement
Condition	Culvert condition: "Good", "Fair", "Poor". Defaults to "Good" if missing	Manning Uniform	Optional
Ke	Entrance loss coefficient. Defaults to inlet-type based values if missing	Outlet Control	Optional
Inlet_Type	Inlet type: "Square_Edge", "Grooved_End", "Beveled", "Projecting", "Mitered". Defaults to "Square_Edge" if missing	Outlet Control	Optional
Y	Inlet geometry factor (FHWA HDS-5). Defaults to 0.6 if missing	Inlet Control	Optional
ks	Slope correction factor (FHWA HDS-5). Defaults to -0.5 if missing	Inlet Control	Optional
c	Inlet geometry constant (FHWA HDS-5). Defaults to 0.038 if missing	Inlet Control	Optional

Download Sample Data here

Condition 3: Acceptable format for 'Only Culvert Point Data Available'

- Upload a ZIP file containing pour point files: `.shp`, `.shx`, `.dbf`, and `.prj`.
- Points located outside the region boundary will be excluded from the analysis.
- At least one pour point must be within the boundary, or watershed delineation will throw an error.
- A maximum of 300 pour points can be included in the analysis at a time.
- The point shapefile must have these headers (Note- user can have more columns like user may find in the sample dataset which was modified from the CATT's dataset, but the data and columns described in the table below are mandatory) as shown in Table 3.2.1.C.2.:

Table 3.2.1.C.2. Acceptable format for 'Only Culvert Point Data Available'

Column Name	Description	Used in Culvert discharge capacity estimation method	Data Requirement
`Point_ID`	Unique `Integer` Identifier for each pour point.	All methods	Mandatory
`Point_Name`	Unique Name (`alpha-numeric`) Identifier for each pour point, e.g., culvert name in this case.	Not used	Optional
`Longitude`	geographical X-coordinate in degrees.	All methods	Mandatory
`Latitude`	geographical Y-coordinate in degrees.	All methods	Mandatory
`Pour_Sha`	Present type or shape of the culverts and/or gauging stations. Currently only supports Pour_Sha = Circular, Box, Pipe arch, Elliptical, `'Round'`, and Bridge. If NA/missing then it defaults to "Circular". Note: Bridge, if mentioned, will be excluded from the hydrologic vulnerability analysis.	All methods	Mandatory
`Width_ft`	Width of the culvert in feet units.	All methods	Mandatory
`Height_ft`	Height of the culvert in feet units, must be the same as 'Width_ft' for Circular culverts.	All methods	Optional
`Flag_Gst`	Must be set to `NA` because it is not applicable in this case.	Not used	Optional
`Grp_ID`	Identifier (`alpha-numeric`) for culverts belonging to the same group (pair, triple, or larger group). Rows indicating single	Not used	Optional

Column Name	Description	Used in Culvert discharge capacity estimation method	Data Requirement
	drainage structure, bridge, or gauging station must be set to NA.		
Grp_Size	The size (integer) of the group (2 for paired, 3 for triple, or a greater number for larger groups). Rows indicating single drainage structure, bridge, or gauging station must be set to NA.	All methods	Optional
GWS_ID	Unique identifier (alpha-numeric) for the gauged watershed drained by the gauging station. Must be set to NA if it's not a gauging station.	Not used	Optional
Culvert_Sl	Culvert slope as decimal (e.g., 0.01 = 1%). Defaults to 0.01 if missing	Inlet Control, Outlet Control, Manning Uniform	Optional
HW_ft	Headwater depth in feet. Defaults to 1.5 × culvert height if missing	Inlet Control, Outlet Control	Optional
TW_ft	Tailwater depth in feet. Defaults to 0.5 × culvert height if missing	Outlet Control	Optional
L_ft	Culvert length in feet. Defaults to 98.4 ft (30 m) if missing	Outlet Control	Optional
n_manning	Manning's roughness coefficient. Defaults to material-based values if missing	Outlet Control, Manning Uniform	Optional
Material	Culvert material: "Concrete", "Steel", "HDPE", "Aluminum", "Plastic", "CMP". Defaults to "Concrete" if missing	Outlet Control, Manning Uniform	Optional

Column Name	Description	Used in Culvert discharge capacity estimation method	Data Requirement
Condition	Culvert condition: "Good", "Fair", "Poor". Defaults to "Good" if missing	Manning Uniform	Optional
Ke	Entrance loss coefficient. Defaults to inlet-type based values if missing	Outlet Control	Optional
Inlet_Type	Inlet type: "Square_Edge", "Grooved_End", "Beveled", "Projecting", "Mitered". Defaults to "Square_Edge" if missing	Outlet Control	Optional
Y	Inlet geometry factor (FHWA HDS-5). Defaults to 0.6 if missing	Inlet Control	Optional
ks	Slope correction factor (FHWA HDS-5). Defaults to -0.5 if missing	Inlet Control	Optional
c	Inlet geometry constant (FHWA HDS-5). Defaults to 0.038 if missing	Inlet Control	Optional

Download Sample Data here

Condition 4: Acceptable format for 'Only Gauging Station Point Data Available'

- Upload a ZIP file containing pour point files: `.shp`, `.shx`, `.dbf`, and `.prj`.
- Gauging stations should be located inside the region boundary.
- Gauging stations outside the region boundary will be excluded from the analysis.
- A maximum of 300 gauging station points can be included in the analysis at a time.
- The point shapefile must have these headers (Note- user can have more columns like user may find in the sample dataset which was modified from the CATT's dataset, but the data and columns described in the table below are mandatory) as shown in Table 3.2.1.C.3.:

Table 3.2.1.C.3. Acceptable format for 'Only Gauging Station Point Data Available'

Column Name	Description	Used in Culvert discharge capacity estimation method	Data Requirement
Point_ID	Unique Integer Identifier for each Gauging station.	All methods	Mandatory
Point_Name	Unique Name (alpha-numeric) Identifier for each Gauging station.	Not used	Optional
Longitude	geographical X-coordinate in degrees.	All methods	Mandatory
Latitude	geographical Y-coordinate in degrees.	All methods	Mandatory
Pour_Sha	Must be set to NA because it is not applicable in this case.	All methods	Mandatory
Width_ft	Must be set to NA because it is not applicable in this case.	All methods	Mandatory
Height_ft	Must be set to NA because it is not applicable in this case.	All methods	Optional
Flag_Gst	Must be set to 1.	Not used	Optional
Grp_ID	Must be set to NA because it is not applicable in this case.	Not used	Optional
Grp_Size	Must be set to NA because it is not applicable in this case.	All methods	Optional
GWS_ID	Unique identifier (alpha-numeric) for the gauged watershed drained by the gauging station.	Not used	Optional
Culvert_Sl	Culvert slope as decimal (e.g., 0.01 = 1%). Defaults to 0.01 if missing	Inlet Control, Outlet Control, Manning Uniform	Optional

Column Name	Description	Used in Culvert discharge capacity estimation method	Data Requirement
HW_ft	Headwater depth in feet. Defaults to 1.5 × culvert height if missing	Inlet Control, Outlet Control	Optional
TW_ft	Tailwater depth in feet. Defaults to 0.5 × culvert height if missing	Outlet Control	Optional
L_ft	Culvert length in feet. Defaults to 98.4 ft (30 m) if missing	Outlet Control	Optional
n_manning	Manning's roughness coefficient. Defaults to material-based values if missing	Outlet Control, Manning Uniform	Optional
Material	Culvert material: "Concrete", "Steel", "HDPE", "Aluminum", "Plastic", "CMP". Defaults to "Concrete" if missing	Outlet Control, Manning Uniform	Optional
Condition	Culvert condition: "Good", "Fair", "Poor". Defaults to "Good" if missing	Manning Uniform	Optional
Ke	Entrance loss coefficient. Defaults to inlet-type based values if missing	Outlet Control	Optional
Inlet_Type	Inlet type: "Square_Edge", "Grooved_End", "Beveled", "Projecting", "Mitered". Defaults to "Square_Edge" if missing	Outlet Control	Optional
Y	Inlet geometry factor (FHWA HDS-5). Defaults to 0.6 if missing	Inlet Control	Optional
ks	Slope correction factor (FHWA HDS-5). Defaults to -0.5 if missing	Inlet Control	Optional
c	Inlet geometry constant (FHWA HDS-5). Defaults to 0.038 if missing	Inlet Control	Optional

Download Sample Data here

3.2.2. Step 2 - Hydro-enforcement

The hydro-enforcement component is optional and modifies elevation data to better represent how roads and culverts affect natural drainage patterns. Each parameter in the HTML form directly controls specific processing steps.

When hydro-enforcement is deemed necessary based on terrain characteristics, the system implements terrain modification procedures including breakline creation with segments perpendicular to roads at pour points, DEM burning along breaklines, and road elevation adjustment to prevent unrealistic flow patterns across transportation infrastructure such as culverts, bridges and fords. The final watershed delineation process traces upslopes contributing areas from each pour point, calculating critical watershed characteristics including drainage area, average slope, channel length, and overland flow paths that serve as fundamental inputs for subsequent hydrologic and hydro-geomorphological vulnerability assessments. All these geospatial operations are performed using open-source python and rust libraries and tools like the Whitebox Tool, geopandas, rasterio, and GDAL.

The system balances automation with practical usability, providing both automated processing and user control over key parameters that affect watershed delineation.The parameters of watershed delineation with and without hydro-enforcement along with their purpose, rationale, consideration, and impact are illustrated below in Figure 3.2.2.

Figure 3.2.2. Schematic showing the steps to perform select the watershed delineation parameters with or without hydro-enforcement.

3.2.3. Step 3 - Run Watershed Delineation and Exclude or Include Flagged Watershed in Risk Analysis

Include (keep) or exclude (remove) watersheds that are flagged for extending beyond the defined boundary by more than the specified threshold area. This helps ensure accurate flood peak discharge calculations at culvert inlets. Consider excluding non-critical watersheds if flagged or expanding the boundary of the region of interest and start a new watershed delineation for important ones to keep. Figure 3.2.3. Illustrates the steps to achieve that.

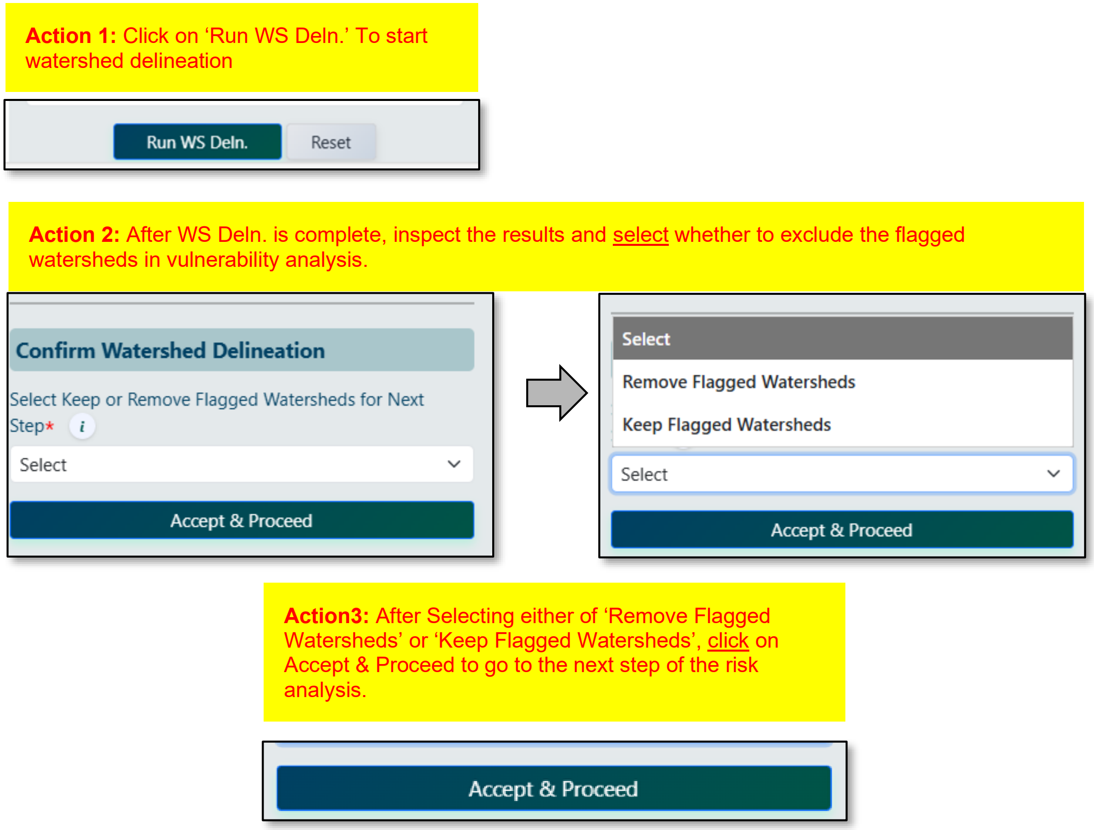

Figure 3.2.3. Schematic showing the steps to run watershed delineation and include (keep) or exclude (remove) watersheds that are flagged for extending beyond the defined boundary by more than the specified threshold area.

3.3. Visualize Analysis Results

3.3.1. Accessing Detailed Point Information

Users can access comprehensive analysis results and infrastructure data by clicking on individual circular markers displayed on the interactive map. Each click opens a detailed popup window containing multiple information sections organized in an intuitive card-based layout. The popup interface provides immediate access to infrastructure specifications, watershed characteristics, and vulnerability assessment results without requiring navigation to separate pages or external applications as shown in Figure 3.3.3.

3.3.2. Infrastructure Details

The infrastructure details section provides comprehensive culvert characterization data including point identification (Point Name and Gauging ID), structural specifications (type or shape, material composition, condition assessment), and dimensional parameters (width and height measurements in feet). Additional technical information encompasses hydraulic discharge capacity estimates in cubic meters per second and precise geographic coordinates for spatial reference, though hydraulic discharge capacity values initially display as "N/A" until hydrologic vulnerability assessment is completed. This foundational data supports engineering assessments by establishing baseline infrastructure conditions and geometric constraints that directly influence hydraulic performance under varying flow conditions.

3.3.3. Watershed Characteristics

The watershed characteristics component presents critical hydrologic and geomorphologic parameters essential for understanding catchment behavior and runoff generation processes. Key metrics include drainage area in hectares, average watershed slope percentage, hydrologic soil group classification, and time of concentration in minutes. Additional parameters encompass composite runoff coefficients, main channel length measurements, and maximum overland flow path lengths in meters. These watershed attributes provide the fundamental inputs for hydrologic modeling and vulnerability assessment, enabling accurate representation of precipitation-runoff relationships and flow routing characteristics that determine peak discharge magnitudes and timing at culvert locations.

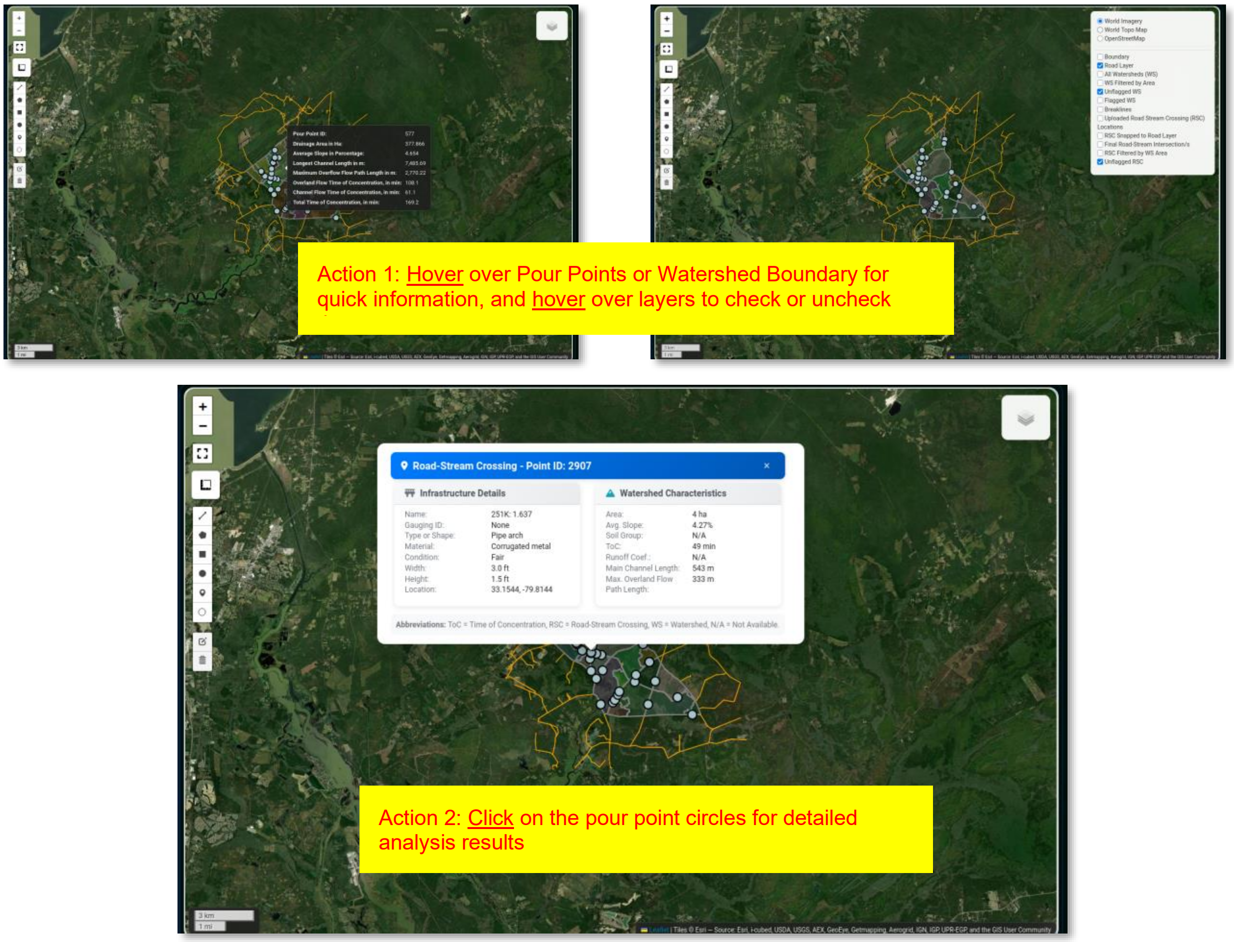

Figure 3.3.3. Schematic showing the visualization of watershed delineation analysis results.

4. Hydrologic Vulnerability Assessment

4.1. Step 1: Upload Instantaneous Streamflow and Precipitation Intensity Data

The hydrologic vulnerability assessment module automatically identifies gauging stations from the watershed boundaries that were created around user's specified pour points. When users select **Conditions 2 or 4** (as described in **Section 3.2.1.C**), the system will prompt users to specify what streamflow and precipitation data users have available for each watershed outlet.

The system determines which pour points are actual gauging stations based on a Flag_Gst parameter in user's pour point data:

- Flag_Gst = 1 means the pour point is an active gauging station
- Flag_Gst = 0 means the pour point is not a gauging station

Users can select from three data availability scenarios for both instantaneous streamflow and precipitation intensity datasets (as shown in Figure 4.1.):

Instantaneous Streamflow Data: (1) 'Only AMS of Inst. Streamflow Data Available' (2) 'Full Series of Inst. Streamflow Data Available' (3) 'No Data Available' (default option)

Precipitation Intensity Data: (1) 'Only AMS of PI Data Available' (2) 'Full Series of PI Data Available' (3) 'No Data Available' (default option)

All data uploads must be in CSV format only.

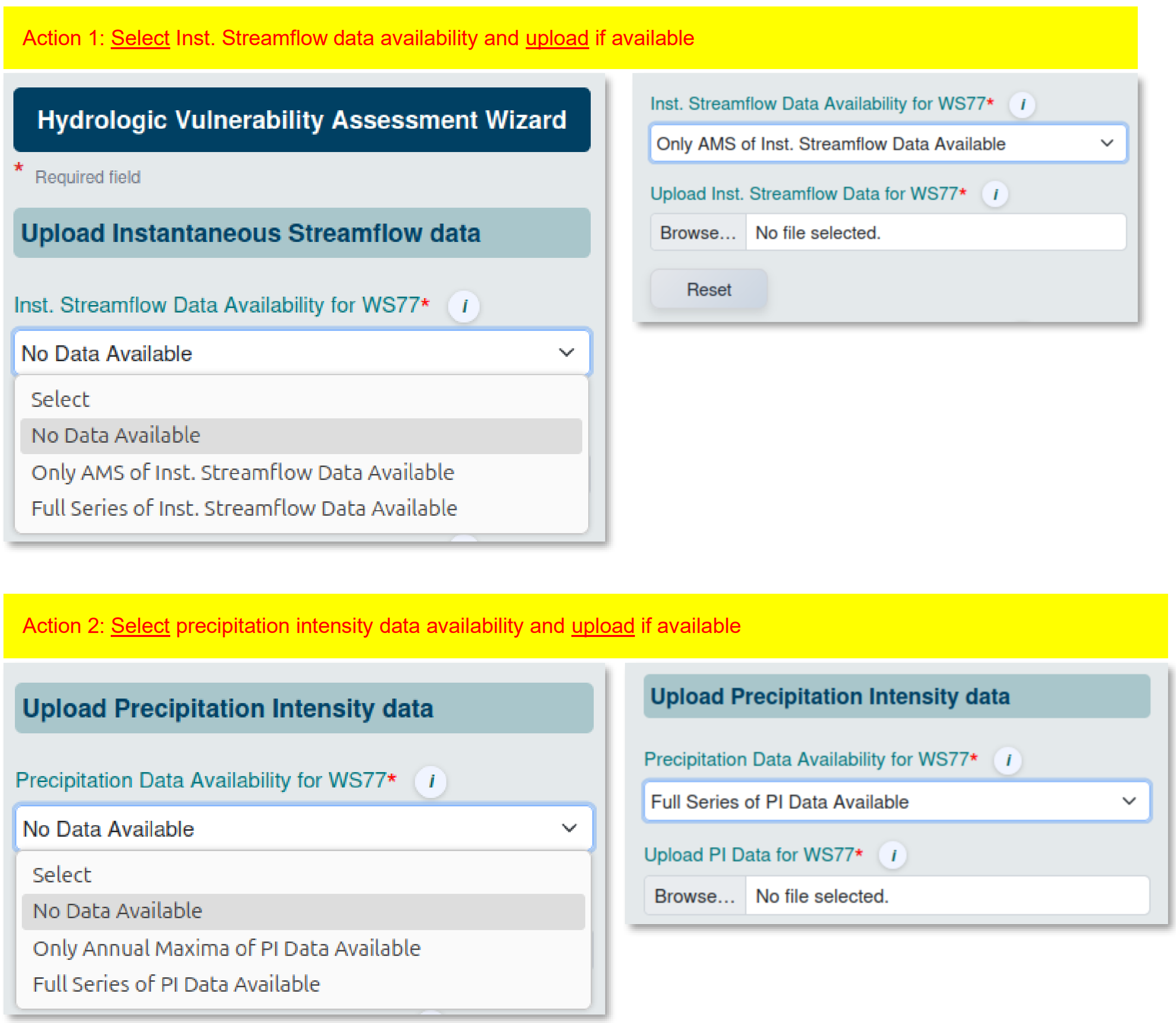

Figure 4.1. Snapshots showing the available options and steps to upload Instantaneous Streamflow and Precipitation Intensity Data

Important: The data upload interface for streamflow and precipitation will not appear if users have selected **Condition 1**, **Condition 3**, or if user chose **Conditions 2 and 4** but set Flag_Gst = 0 for all pour points during the watershed delineation step (see **Section 3.2.1.C** for pour point data requirements).

The following sections describe the required CSV file format and data structure specifications for uploading instantaneous streamflow and precipitation intensity datasets under different data availability scenarios.

4.1.1. Upload Instantaneous Streamflow Data

Condition 1: Only AMS of Instantaneous Streamflow Data Available (AMS: Annual Maxima Series) as shown in Table 4.1.1.1.

Table 4.1.1.1. Mandatory column headers for annual maxima streamflow series (CSV Files) - one file required per gauging station

Column Name	Description
GWS_ID	Unique identifier (alpha-numeric) for the gauged watershed drained by the gauging station. Must be exactly the same ID as declared under the header GWS_ID in the Pour Point shapefile for the gauging station.
Point_Name	Unique identifier (alpha-numeric) for the gauging station draining the WS. Must be the same ID as declared under the header Point_Name in the Pour Point shapefile for the gauging station.
Year	Year of peak flow. Must be at least 15 years with valid peak flow data. Missing data rows, if present, must be set to NA.
Month	Month when peak flow occurred. Must be set to NA for missing data rows.
Day	Day when peak flow occurred. Must be set to NA for missing data rows.
Flow	Peak flow in m^3/s for each year. Must have valid peak flow data length of at least 15 years. Missing data rows, if present, must be set to NA.
Covar	(Optional) data for chosen covariate to perform non-stationary frequency analysis. Missing data rows, if present, must be set to NA. Note: Users can

Column Name	Description
	perform non-stationary analysis even without this data-column. The covariate in that case will be set to time. But if present, then peak flows with missing Covar, will be excluded from the non-stationary analysis.
Area_km2	Drainage area (in square km) of the officially gauged watershed upstream of the gauging station. This represents the station's original design catchment area, not the computationally delineated watershed area, and is used for specific discharge calculations.

Condition 2: Full Series of instantaneous streamflow data available as shown in Table 4.1.1.2.

Table 4.1.1.2. Mandatory column headers for full instantaneous streamflow series (CSV Files) - one file required per gauging station

Column Name	Description
GWS_ID	Unique identifier (alpha-numeric) for the gauged watershed drained by the gauging station. Must be the same ID as declared under the header GWS_ID in the Pour Point shapefile for the gauging station.
Point_Name	Unique identifier (alpha-numeric) for the gauging station draining the WS. Must be the same ID as declared under the header Point_Name in the Pour Point shapefile for the gauging station.
Year	Year values. It must be at least 15 years with valid inst. streamflow data. Missing data rows, if present, must be set to NA.
Month	Month when inst. streamflow data recorded. Must be set to NA for missing data rows.
Day	Day when peak flow occurred. Must be set to NA for missing data rows.
Flow	inst. streamflow records in m3/s. Must have valid data length of at least 15 years. Missing data rows, if present, must be set to NA.
Covar	(Optional) data for chosen covariate to perform non-stationary frequency analysis. Missing data rows, if present, must be set to NA. Note: Users can perform non-stationary analysis even without this data-column. The covariate

Column Name	Description
	in that case will be set to time. But if present, then peak flows with missing Covar, will be excluded from the non-stationary analysis.
Area_km2	Drainage area (in square km) of the officially gauged watershed upstream of the gauging station. This represents the station's original design catchment area, not the computationally delineated watershed area, and is used for specific discharge calculations.

4.1.2. Upload Precipitation Intensity Data

Condition 1: Only AMS of precipitation intensity data available (AMS: Annual Maxima Series) as shown in Table 4.1.2.1.

Table 4.1.2.1. Mandatory column headers for annual maxima precipitation series (CSV Files) - one file required per gauging station

Column Name	Description
GWS_ID	Unique identifier (alpha-numeric) of the gauged watershed associated to the rain gauge for the analysis. Must be the same ID as declared under the header GWS_ID in the Pour Point shapefile. Note: Data from one rain gauge can be used for multiple WSs in data scarcity/limited conditions.
Rg_ID	Unique identifier (alpha-numeric) of the rain gauge.
Year	Year of maximum PI. It must be at least 15 years with valid data. Missing data rows, if present, must be set to NA.
Month	Month when maximum PI was observed. Must be set to NA for missing data rows.
Day	Day when maximum PI was observed. Must be set to NA for missing data rows.
Hr	Day when maximum PI was observed. Must be set to NA for missing data rows.
Min	Day when maximum PI was observed. Must be set to NA for missing data rows.

Column Name	Description
PI	Maximum PI in cm/hr for each year. Must have valid data length of at least 15 years. Missing data rows, if present, must be set to NA.
Covar	(Optional) data for chosen covariate to perform non-stationary frequency analysis. Missing data rows, if present, must be set to NA. Note: Users can perform non-stationary analysis even without this data-column. The covariate in that case will be set to time. But if present, then the annual maximum PIs with missing Covar, will be excluded from the non-stationary analysis.

Condition 2: Full Series of precipitation intensity) as shown in Table 4.1.2.2.

Note: CULVERT V1 currently only supports hourly or sub-hourly PI series data upload which is relevant for hydrologic analysis for small head-water catchments.

Table 4.1.2.2. Mandatory column headers for full precipitation series (CSV Files) - one file required per gauging station

Column Name	Description
GWS_ID	Unique identifier (alpha-numeric) of the gauged watershed associated with the rain gauge for the analysis. Must be the same ID as declared under the header GWS_ID in the Pour Point shapefile. Note: Data from one rain gauge can be used for multiple WSs in data scarcity/limited conditions.
Rg_ID	Unique identifier (alpha-numeric) of the rain gauge.
Year	Year values. It must be at least 15 years with valid data. Missing data rows, if present, must be set to NA.
Month	Month when PI was observed. Must be set to NA for missing data rows.
Day	Day when PI was observed. Must be set to NA for missing data rows.
Hr	Day when maximum PI was observed. Must be set to NA for missing data rows.
Min	Day when maximum PI was observed. Must be set to NA for missing data rows.
PI	PI values in cm/hr. Must have a valid data length of at least 15 years. Missing data rows, if present, must be set to NA.

Column Name	Description
Covar	(Optional) data for chosen covariate to perform non-stationary frequency analysis. Missing data rows, if present, must be set to NA. Note: Users can perform non-stationary analysis even without this data-column. The covariate in that case will be selected as the time (*1, 2, …., T*). But if this column exists but has Covar = NA for all rows, then this series will be excluded from the non-stationary analysis.

4.2. Step 2: Select Methods and Parameters for Peak Discharge and Culvert Capacity Estimation

Hydrologic vulnerability assessment uses three hydrologic analysis methods—nonstationary regional frequency analysis, rational method, and graphical peak discharge method, respectively. Three methods are available for users to choose from for the discharge capacity estimation of culverts - Inlet control (FHWA-HDS-5), Outlet control (FHWA-HDS-5), and Manning's Uniform Flow as shown in Figure 4.2.

These methods have gained widespread acceptance in engineering practice due to their complementary strengths in data efficiency, computational scalability, and methodological flexibility, particularly for applications in small headwater catchments where data availability is often limited. Furthermore, these methods demonstrate strength in their application to both gauged and ungauged catchments, with results that can be directed to individual culverts for site-specific infrastructure vulnerability assessment.

Together, these methods provide a comprehensive analytical framework that balances methodological rigor with practical implementation constraints, enabling effective hydrologic vulnerability assessment across diverse headwater catchment conditions while maintaining the scalability and automation potential necessary for regional-scale infrastructure planning applications.

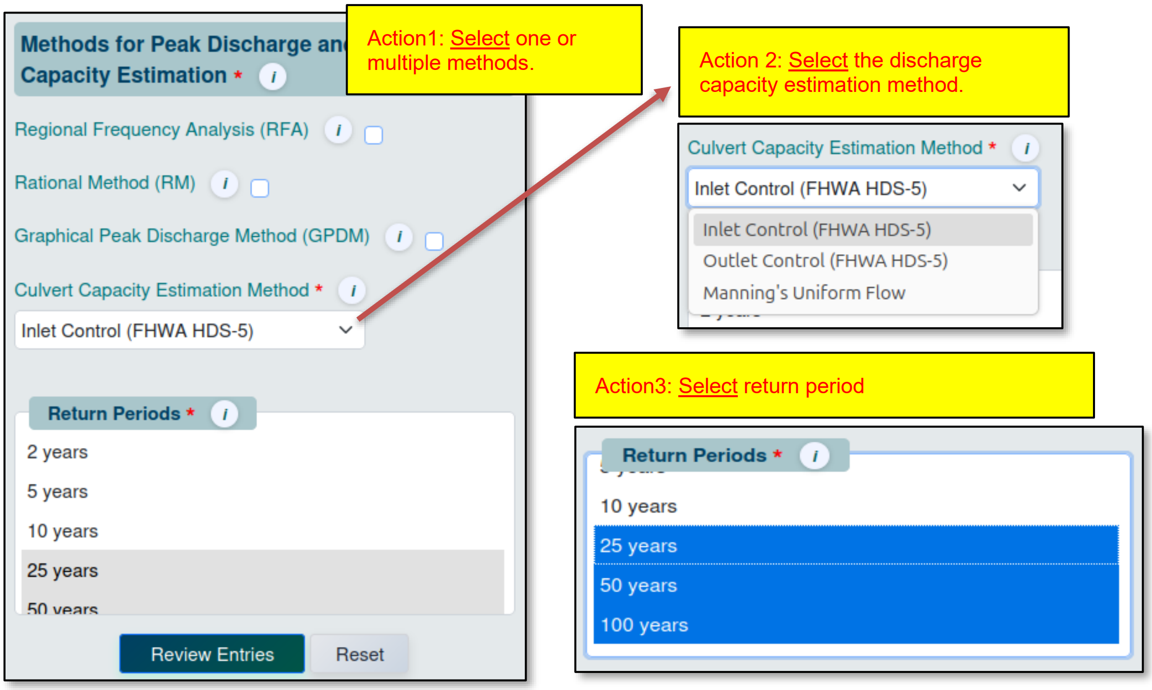

Figure 4.2. Schematic showing the steps to select the methods for hydrologic vulnerability assessment.

4.2.1. Regional Frequency Analysis

The steps to select the parameters of the regional frequency analysis are demonstrated in Figure 4.2.1. Note that to perform regional frequency analysis users should upload instantaneous streamflow data for at least one of the watersheds flagged as drained by a gauging station in their pour point data (refer to section 3.2.1.(C) and section 4.1.1. For reference).

Action: Select the parameters of Regional Frequency Analysis

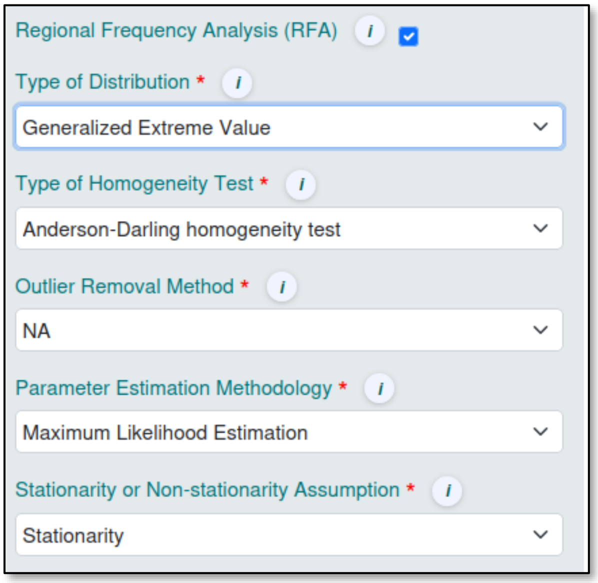

Figure 4.2.1. Schematic showing the steps to select the parameters of regional frequency analysis.

4.2.2. Rational Method

The steps to select the parameters of the rational method analysis are demonstrated in Figure 4.2.2. Note that to perform rational method analysis using runoff coefficient back-calculated using streamflow and precipitation data, users should upload streamflow and precipitation intensity for at least one of the gauged watersheds flagged in their pour point data (refer to section 3.2.1.(C) and section 4.1.2. For reference). The rational method also takes a single event-based precipitation intensity as input allowing users to assess the hydrologic risk of road-stream crossings to hurricane induced or isolated historic flood events.

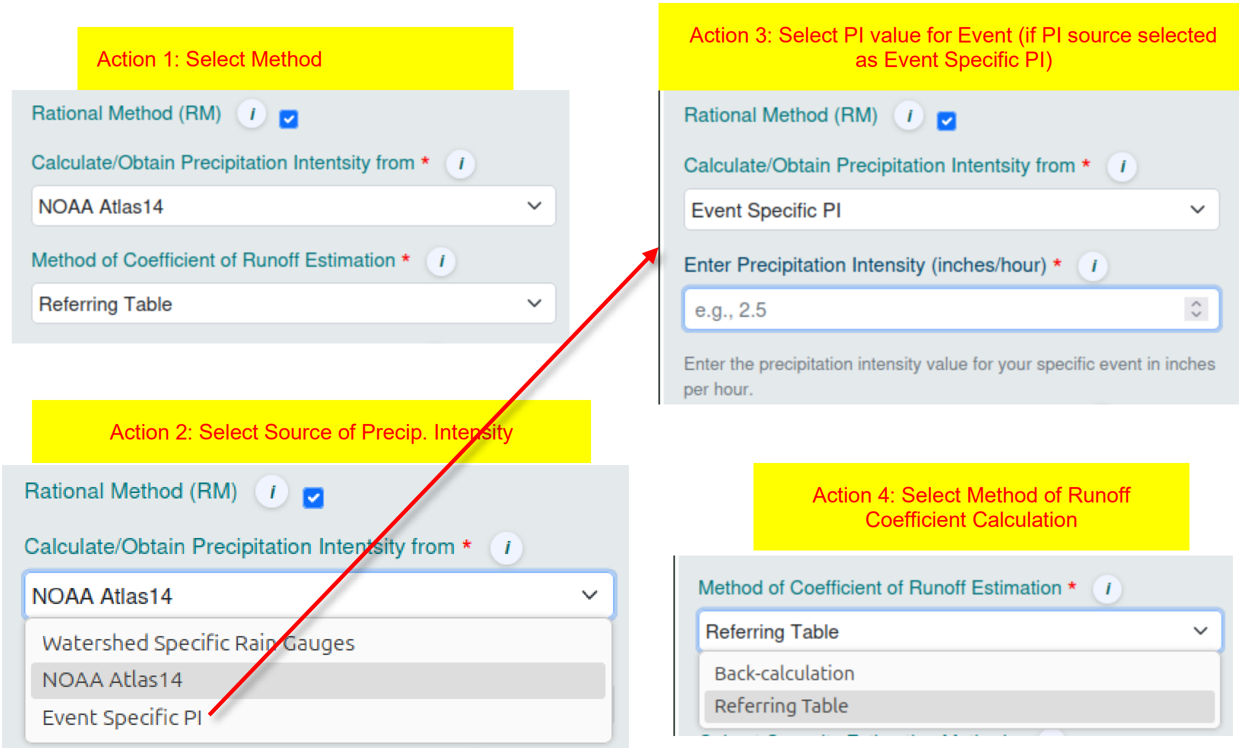

Figure 4.2.2. Schematic showing the steps to select the parameters of rational method.

4.2.3. Graphical Peak Discharge Method

The graphical peak discharge methodology incorporates automated data acquisition from NOAA Atlas 14 precipitation depth raster datasets. The system also accommodates single-event precipitation depth inputs, facilitating vulnerability analysis of road-stream crossing infrastructure subjected to hurricane-induced or exceptional historic flood events. The workflow is depicted in Figure 4.2.3.

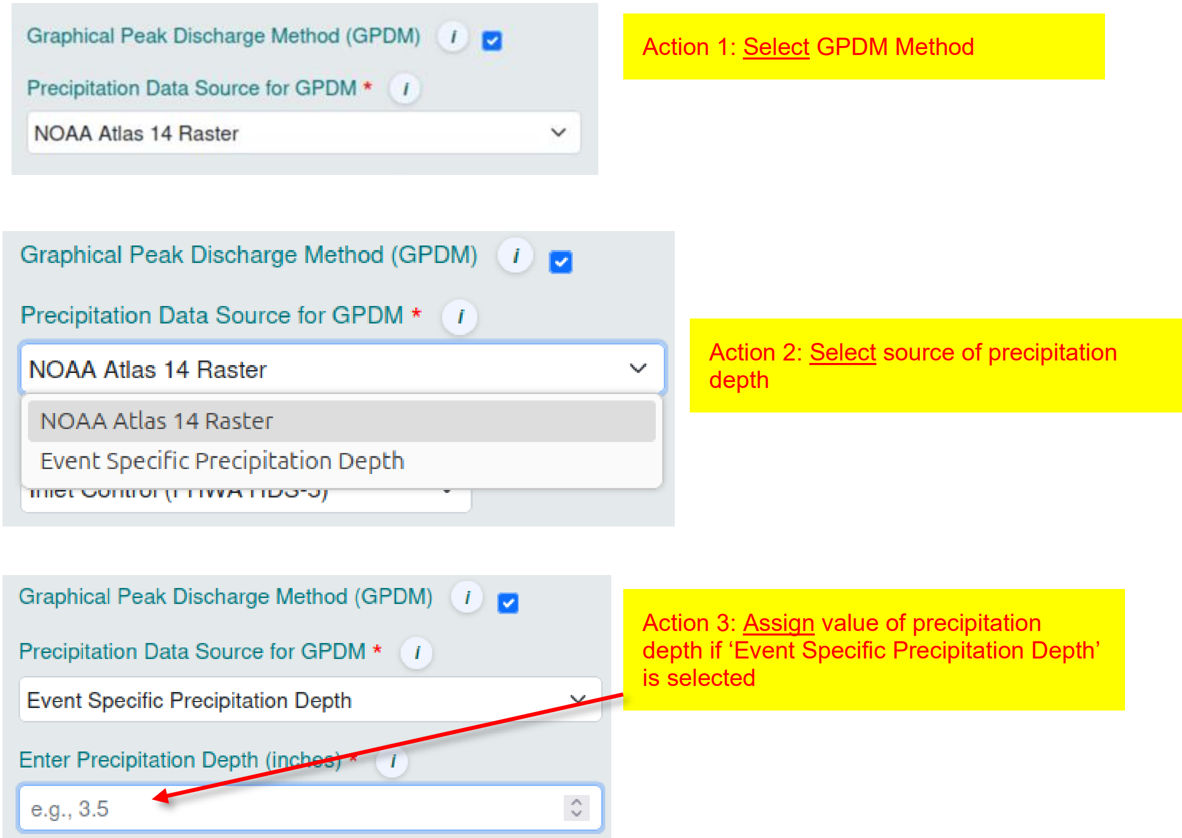

Figure 4.2.3. Schematic showing the steps to perform Graphical Peak Discharge Method.

4.2.4. Culvert Capacity Estimation

The CULVERT v01 framework incorporates three established hydraulic methods for culvert discharge capacity estimation: inlet control, outlet control, and Manning's uniform flow. These methods enable comprehensive assessment of culvert performance under varying flow conditions and infrastructure configurations. All geometric and hydraulic parameters required for implementing these calculation methods are accommodated within the pour point data upload specification detailed in the comprehensive data requirements table (see **Section 3.2.1.C** for pour point data requirements). The workflow is depicted in Figure 4.2.4.

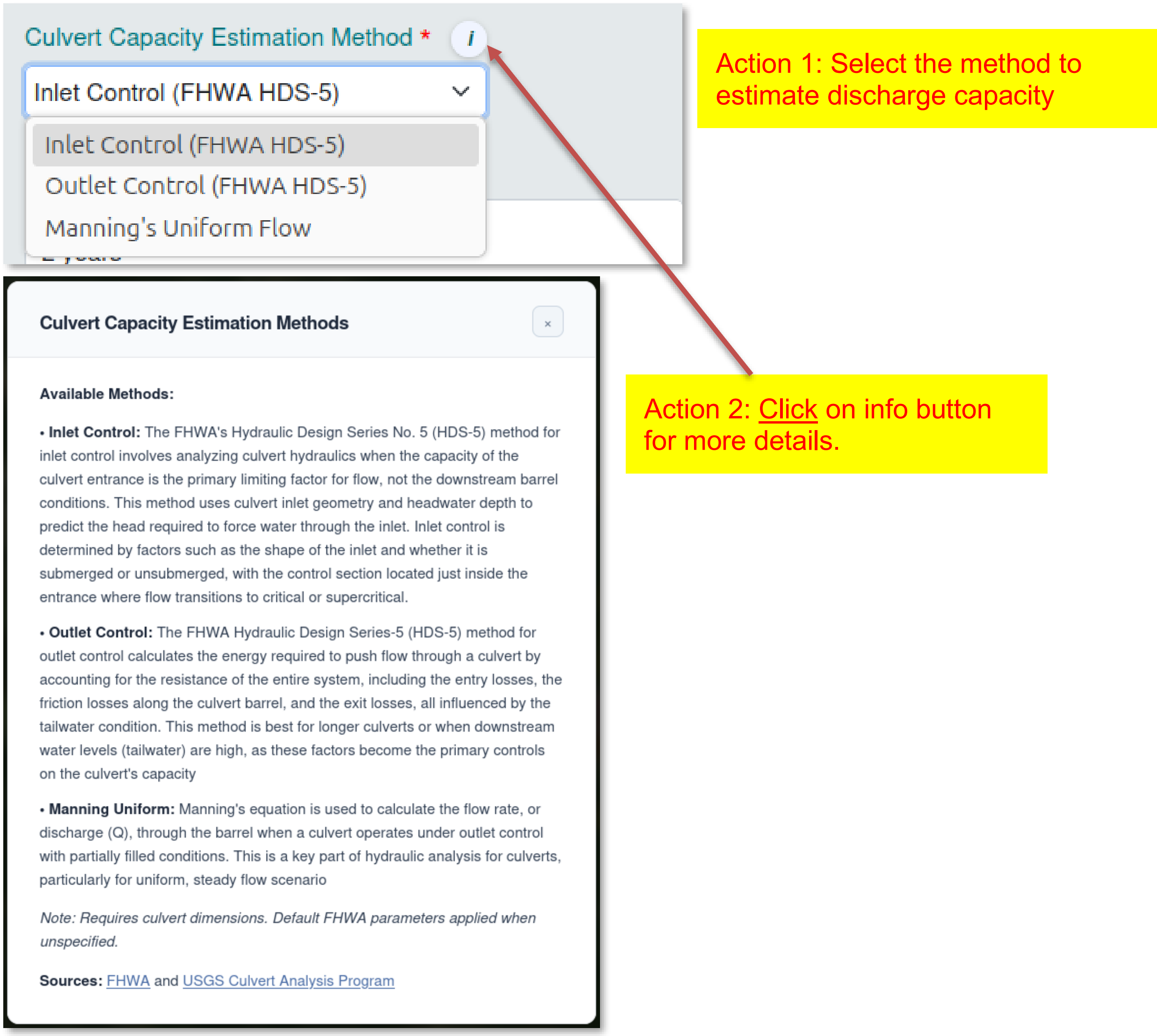

Figure 4.2.4. Schematic showing the steps to perform culvert capacity estimation methodology.

4.3. Step 3: Review Entries and Run Hydrologic Vulnerability Assessment

This step integrates all user-defined parameters and executes the comprehensive hydrologic vulnerability assessment workflow. This phase combines the selected peak discharge estimation method (rational method, regional frequency analysis, or graphical peak discharge method) with the chosen culvert capacity calculation approach (inlet control, outlet control, or Manning's uniform flow) to evaluate infrastructure performance under specified hydrologic conditions. The assessment process systematically compares estimated peak discharges against culvert capacities to identify vulnerable infrastructure and quantify risk levels across the study area. Users can review all input parameters, verify methodology selections, and initiate the integrated analysis that produces spatially explicit vulnerability maps and infrastructure-specific risk assessments. The complete analytical workflow and decision tree for this step are illustrated in Figure 4.3.

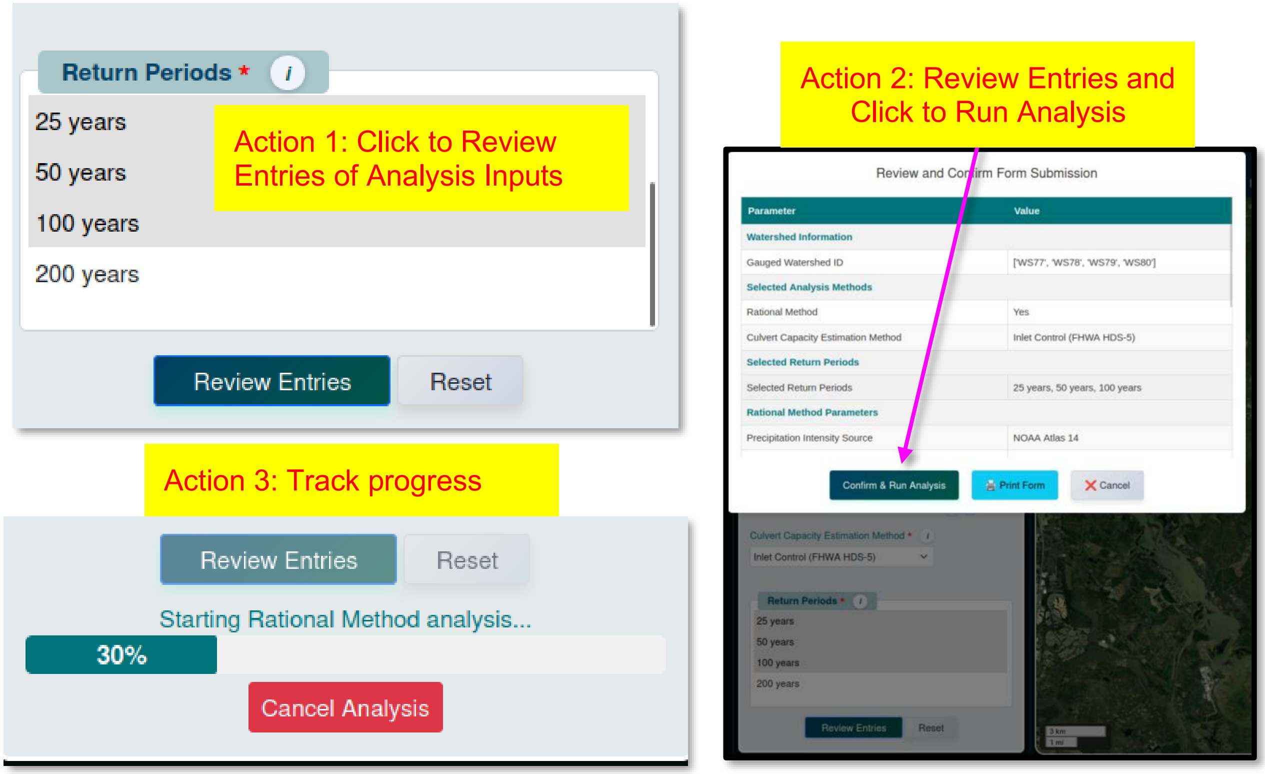

Figure 4.3. Schematic showing the steps to review entries and run hydrologic vulnerability assessment.

4.4. Step 4: Visualize Analysis Results

The hydrologic analysis component generates distinct selectable layers including "RF Hydrologic Vulnerability" (Regional Frequency Analysis), "RM Hydrologic Vulnerability" (Rational Method), and "GPDM Hydrologic Vulnerability" (Graphical Peak Discharge Method), each accessible through the layer control panel. Users can interactively explore results by clicking on individual culvert points to access detailed popup windows containing complete analysis results, including geometric parameters, hydraulic calculations, capacity estimates, peak discharge values, and vulnerability classifications for each return period analyzed. These comprehensive displays reveal method-specific discharge calculations, confidence intervals, and vulnerability classifications for multiple return periods, supporting decision-making processes for infrastructure management and flood risk mitigation planning.

The hydrologic vulnerability assessment employs a binary classification system using red markers to indicate "Vulnerable" culverts where peak discharge exceeds capacity, green markers for "Not

Vulnerable" infrastructure with adequate capacity, and grey markers for locations with insufficient data. Each popup presents detailed tabular results showing lower confidence intervals, expected values, and upper confidence intervals for discharge estimates across different return periods (typically 2, 5, 10, 25, 50, 100, and 200-year events), alongside corresponding vulnerability status determinations. For event-based analyses (Rational Method and GPDM with specific precipitation inputs), the interface displays single peak discharge values with associated vulnerability classifications rather than return period tables. The workflow is depicted in Figure 4.4.

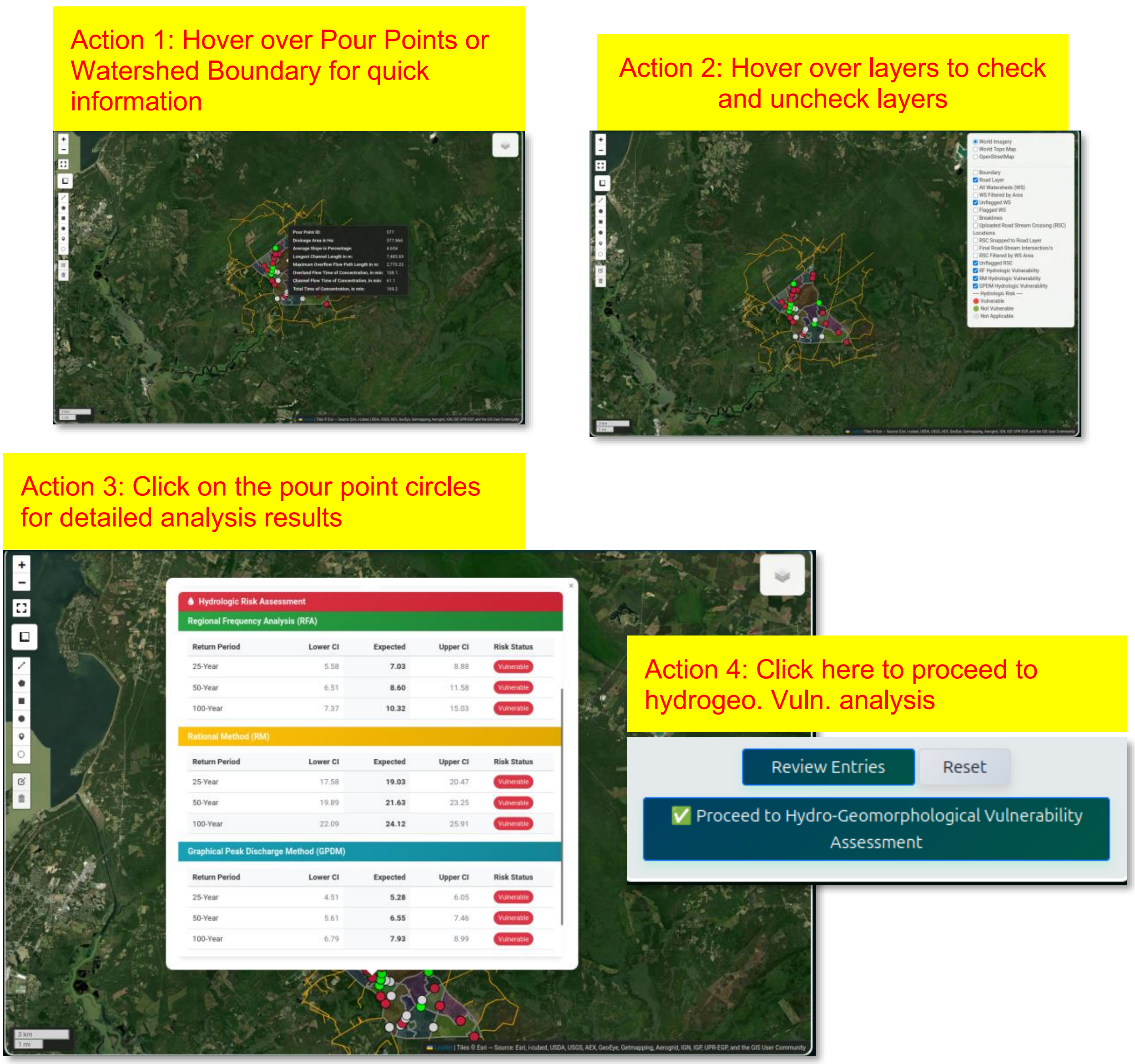

Figure 4.4. Schematic showing the steps to visualize the hydrologic vulnerability assessment results.

5. Hydro-geomorphologic Vulnerability Assessment

5.1. Step 1: Generate Stream Networks for SBEVA and WDFM Analysis

The stream generation process utilizes flow accumulation raster to delineate stream networks based on a user-defined threshold value. This is only needed for SBEVA and WDFM analysis. Users must enter a 'Flow Accumulation Threshold' to verify and confirm the generated stream network, with typical values of 10,000 recommended for small headwater catchments for 1-m spatial resolution. Users can fine tune it based on their elevation raster spatial resolution. Lower threshold values produce more detailed and extensive stream networks, while higher values create simplified networks with fewer tributaries. This threshold selection is critical as it determines the stream-bank area used in the Slope-Based Erosion Vulnerability Assessment (SBEVA) method and establishes the foundation for creating stream buffers in the Weighted Distance from Main-stem (WDFM) analysis. The proximity to generated streams significantly influences debris flow vulnerability, as the WDFM analysis assigns higher vulnerability scores to pixels located within smaller stream buffers. This relationship reflects the increased hazard potential near watercourses, where channel erosion and stream undercutting destabilize adjacent slopes, saturated conditions enhance failure potential, and established drainage pathways provide ready transport corridors for debris flow material. The workflow is depicted in Figure 5.1.

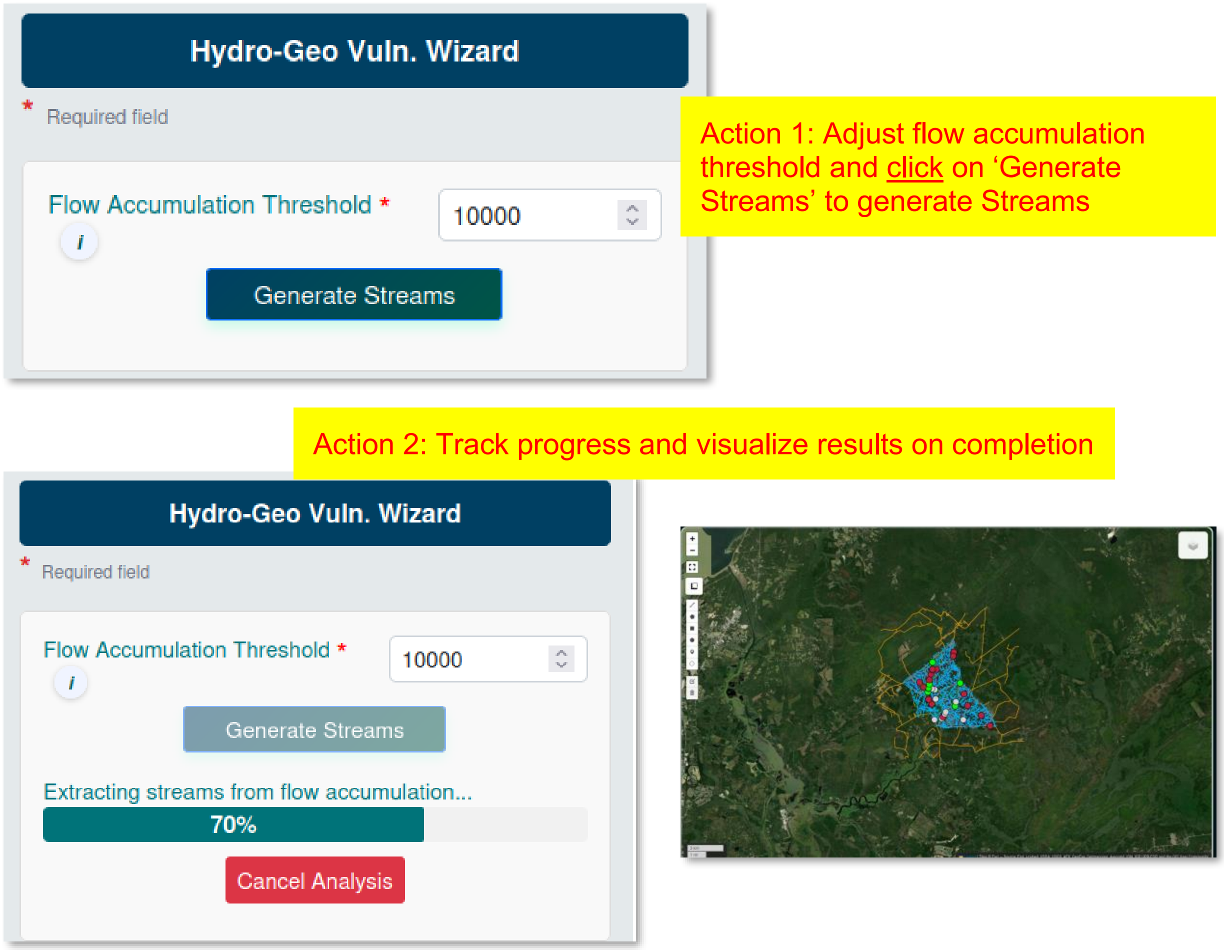

Figure 5.1. Schematic showing the steps to generate stream networks for SBEVA and WDFM analysis.

5.2. Step 2: Select Methods

Select the appropriate analysis method based on your study objectives and available data. Choose RUSLE (Revised Universal Soil Loss Equation) for quantitative soil erosion assessment using rainfall, soil, topographic, cover, and management factors. Select SBEVA Stream-bank Erosion Vulnerability Assessment) for climate and terrain-focused vulnerability analysis emphasizing slope, soil, and other morphological characteristics. Choose WDFM (Watershed Debris Flow Model) to evaluate debris flow vulnerability based on terrain-focused vulnerability analysis like vegetation, climate, slope, soil, geology and other morphological characteristics proximity to stream networks and roads. Each method addresses different aspects of erosion and mass movement processes, allowing users to tailor their analysis to specific research requirements and data availability as shown in Figure 5.2.

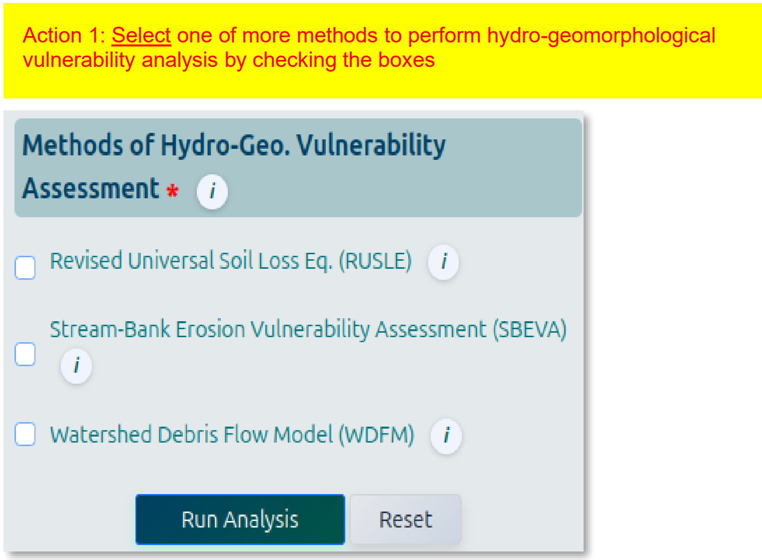

Figure 5.2. Schematic showing the step to select the methods for hydro-geomorphologic vulnerability assessment.

5.3. Step 3: Assign SBEVA stream-bank buffer distance and variable weights

The SBEVA method requires users to configure analysis parameters and assign weights to multiple environmental variables that influence stream-bank erosion vulnerability. Begin by setting the Stream Buffer Distance (minimum 5 meters, default 10 meters), which defines the area around stream networks where erosion vulnerability will be assessed. Next, assign relative importance weights to each of the ten contributing variables, ensuring the total weight equals exactly 1.0. The system includes ten key variables: 24-hr 100-year Precipitation Intensity (default weight: 0.25), 30-year Precipitation Normal (0.05), 30-year Mean Temperature Normal (0.01), 30-year Mean Solar Radiation Normal (0.01), Root-zone Available Water Storage (0.10), Runoff Class (0.10), Drainage Class (0.10), Hydrologic Soil Group (0.15), Slope (0.05), and Land Cover (0.18). Users can adjust these weights based on local conditions and expert knowledge, with higher weights assigned to variables deemed more critical for erosion processes in their study area. The interface displays the running total of assigned weights and provides warnings if the total deviates from the required 1.0 value, ensuring proper model calibration before analysis execution as shown in Figure 5.3.

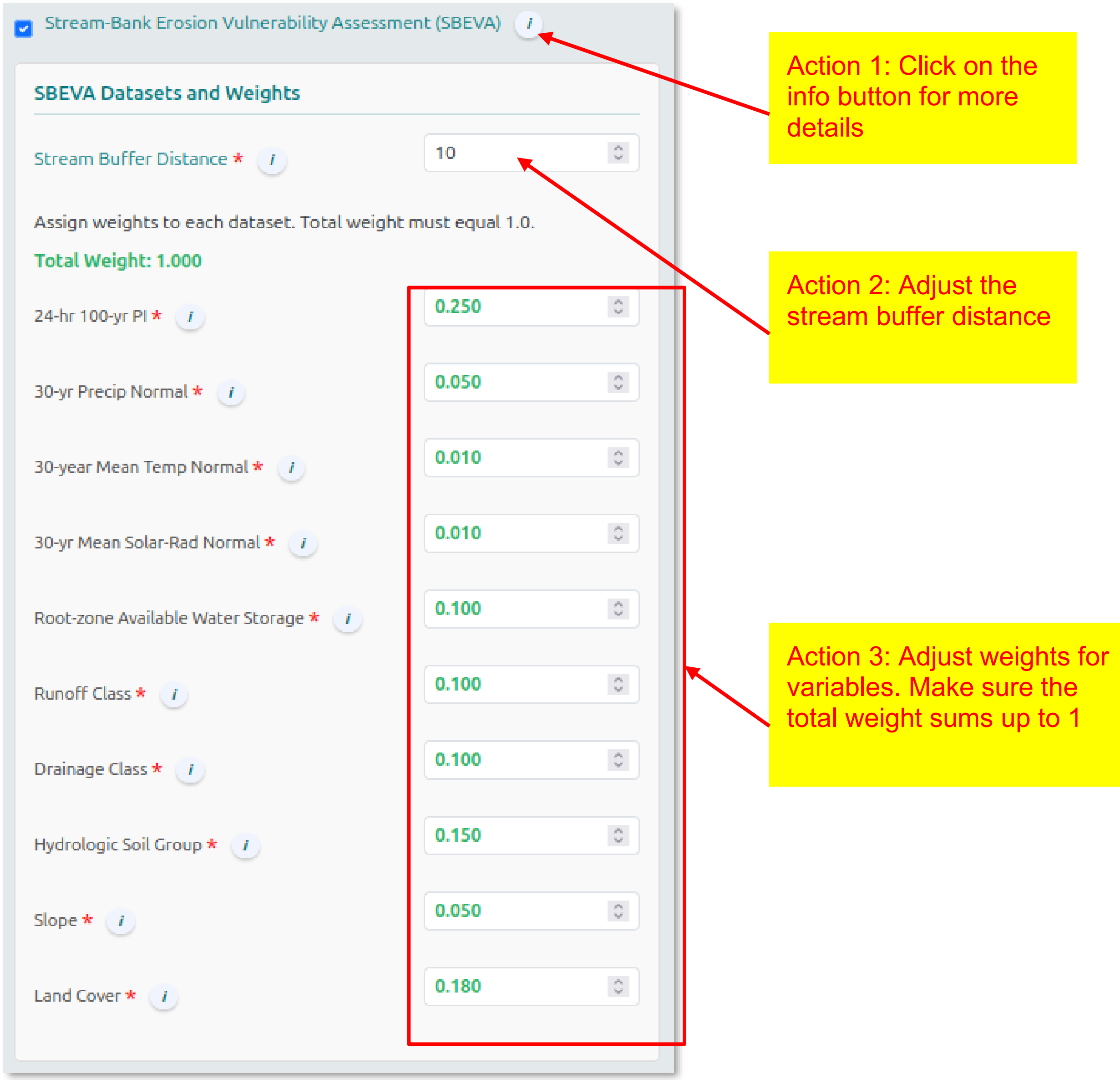

Figure 5.3. Schematic showing the step to select the weights for performing SBEVA.

Table 5.3. Default weights for variables used in SBEVA

Variable	Default Weight	Description
24-hr 100-yr PI	0.25	Extreme precipitation intensity driving erosive forces
30-yr Precip Normal	0.05	Long-term precipitation patterns
30-yr Mean Temp Normal	0.01	Temperature effects on weathering processes
30-yr Solar Radiation Normal	0.01	Solar energy influence on evapotranspiration
Root-zone Available Water Storage	0.10	Soil water holding capacity
Runoff Class	0.10	Surface water flow characteristics
Drainage Class	0.10	Soil drainage properties
Hydrologic Soil Group	0.15	Soil infiltration and runoff potential
Slope	0.05	Terrain steepness affecting erosion
Land Cover	0.18	Vegetation protection and surface characteristics
Total	**1.00**	**Required sum of all weights**

5.4. Step 4: Assign WDFM variable weights

The WDFM method evaluates debris flow vulnerability through a comprehensive multi-criteria analysis incorporating fifteen environmental and anthropogenic variables. Users must assign relative importance weights to each variable, ensuring the total weight equals exactly 1.0. The model integrates hydrological factors (Available Water Storage 0-150 cm, Drainage Class, Saturated Hydraulic Conductivity), soil properties (K-Factor Rock Free, Runoff Class, Soil Slip Potential, Soil Bottom Depth, Soil Taxonomic Order, T-Factor), geological characteristics (Geology Rock Type 1), vegetation conditions (NDVI), climatic drivers (24-hr 100-year Precipitation Intensity), topographic factors (Slope), and infrastructure influences (Road Buffer, Stream Buffer). The default weight distribution emphasizes soil taxonomic classification, runoff characteristics, and T-factor soil tolerance, while maintaining balanced contributions from hydrological, geological, and anthropogenic factors. Users can modify these weights based on local expertise, field observations, and regional debris flow susceptibility patterns. The interface continuously monitors the weight total and alerts users when adjustments are needed to maintain the required 1.0 sum before model execution as shown in Figure 5.4. Please refer to the info (‘*i*’) icon beside each of the variables provided in the web-application to know more.

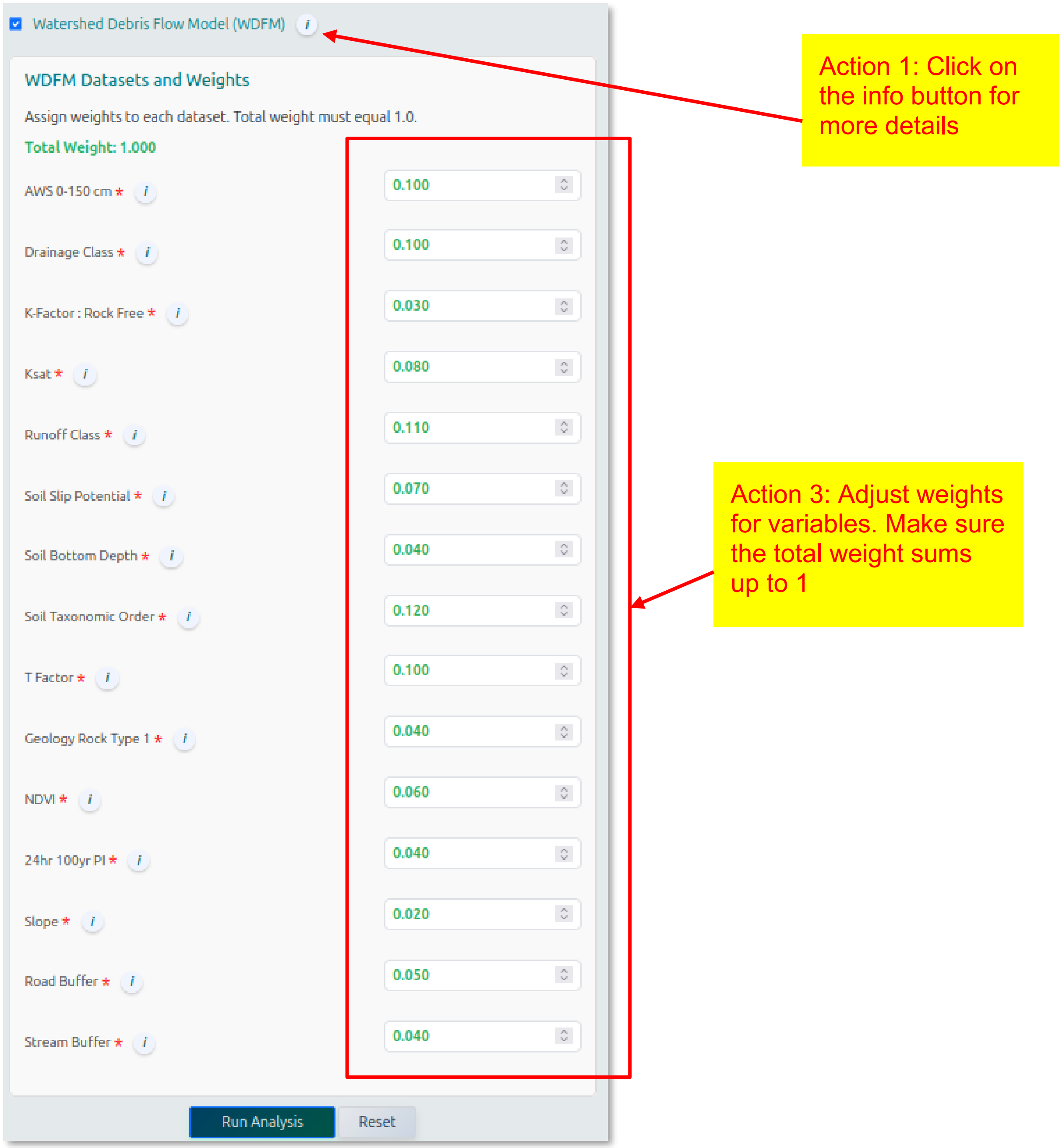

Figure 5.4. Schematic showing the step to select the weights for performing WDFM analysis.

Table 5.4. Default weights for variables used in WDFM

Variable	Default Weight	Description
AWS 0-150 cm	0.10	Available water storage capacity in soil profile
Drainage Class	0.10	Natural soil drainage characteristics
K-Factor Rock Free	0.03	Soil erodibility factor excluding rock fragments
Ksat	0.08	Saturated hydraulic conductivity
Runoff Class	0.11	Surface water flow classification
Soil Slip Potential	0.07	Inherent slope stability characteristics
Soil Bottom Depth	0.04	Depth to restrictive soil layer
Soil Taxonomic Order	0.12	Soil classification system grouping
T Factor	0.10	Soil loss tolerance threshold
Geology Rock Type 1	0.04	Primary bedrock geological formation

Variable	Default Weight	Description
NDVI	0.06	Normalized Difference Vegetation Index
24hr 100yr PI	0.04	Extreme precipitation intensity
Slope	0.02	Terrain gradient steepness
Road Buffer	0.05	Proximity to transportation infrastructure
Stream Buffer	0.04	Distance from drainage networks
Total	**1.00**	**Required sum of all weights**

5.5. Step 5: Run Analysis

Execute the configured analysis by clicking the "Run Analysis" button to initiate the computational process. The system displays a real-time progress bar indicating the completion status of each selected method, allowing users to monitor the analysis advancement through different stages of computation. During execution, a "Cancel Task" button becomes available, enabling users to terminate the process if needed due to time constraints or requirement changes. Additionally, a "Reset" button provides the capability to restore all form inputs to their default values, facilitating quick reconfiguration without manual adjustment of individual parameters. The analysis duration varies depending on the selected methods, study area size, and computational complexity of the chosen vulnerability assessment approaches.

5.6. Step 6: Visualize Analysis Results

Interactive visualization presents analysis results through an integrated mapping interface displaying point-based vulnerability assessments with color-coded risk classifications. The system generates multiple selectable layers including "SBEVA Hydro-geomorphologic Vulnerability," "RUSLE Hydro-geomorphologic Vulnerability," "WDFM Hydro-geomorphologic Vulnerability," "WEPP Hydro-geomorphologic Vulnerability," and "EHVI Hydro-geomorphologic Vulnerability," along with an optional "Stream Network" layer for contextual reference. Users can click on individual points of interest to access comprehensive popup windows containing detailed information for all selected methods including RUSLE, SBEVA, WDFM, WEPP, and EHVI results when multiple approaches are employed simultaneously. The hydro-geomorphologic vulnerability classification system utilizes a standardized five-tier color scheme representing Very Low vulnerability (0 to <1, blue), Low vulnerability (1 to <2, green), Moderate vulnerability (2 to <3, yellow), High vulnerability (3 to <4, orange), and Very High vulnerability (4-5, red). Each popup provides method-specific numerical scores for all assessment approaches, categorical classifications, and relevant environmental parameters. RUSLE results additionally display quantitative erosion values in kilograms per year, while all methods including EHVI present standardized vulnerability scores for comparative analysis. The interactive interface supports layer toggling through the layer control panel, allowing selective visualization of individual methods or combined multi-criteria assessments for comprehensive spatial risk evaluation and cross-method comparison of vulnerability patterns as demonstrated in Figure 5.6.

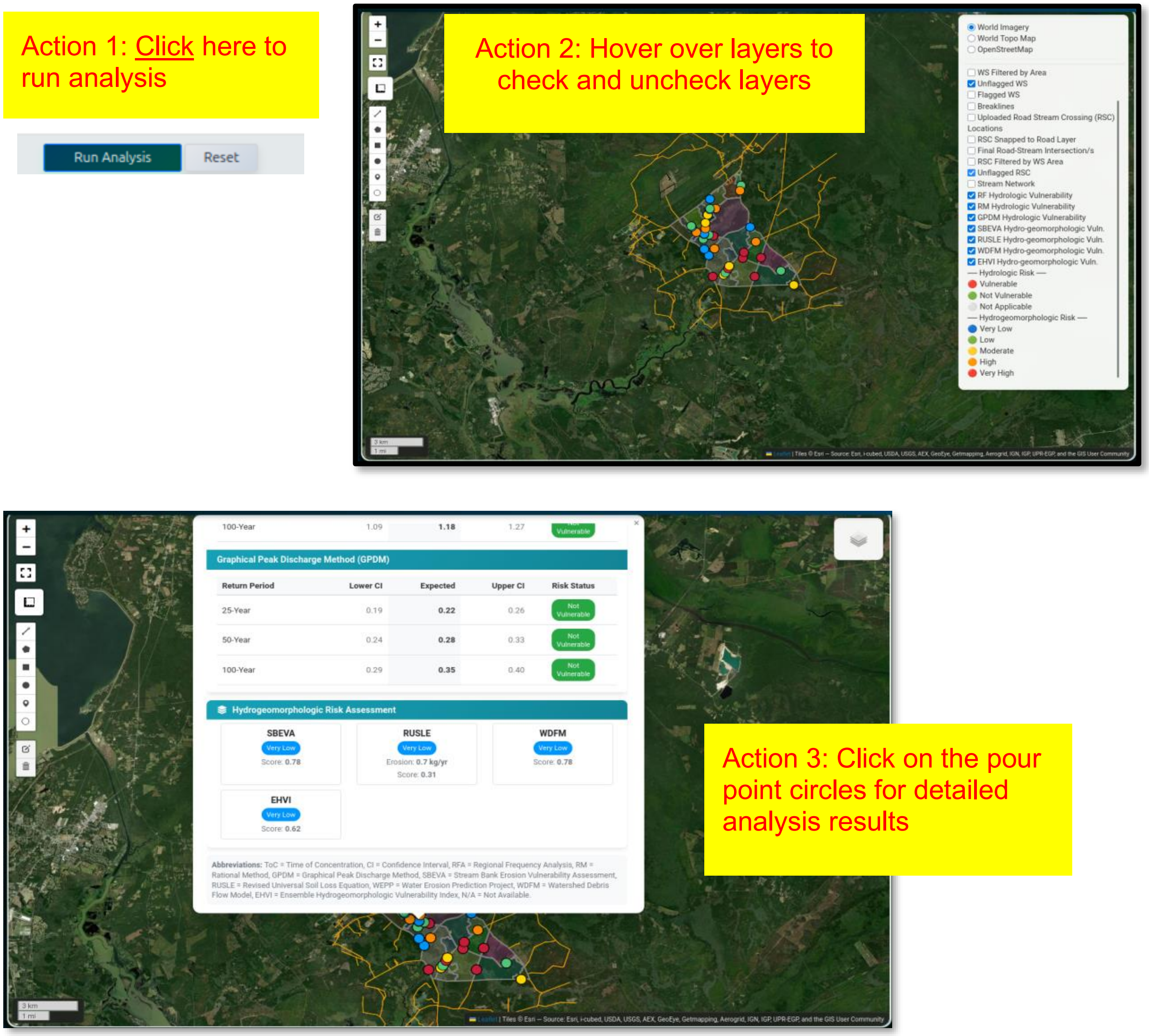

Figure 4.4. Schematic showing the steps to visualize the hydro-geomorphologic vulnerability assessment results.

6. Miscellaneous Features

6.1. 'Menu' Option

The application header provides a comprehensive "Menu" option offering streamlined navigation and essential functionality access throughout the CULVERT platform as demonstarte din Figure 6.1.

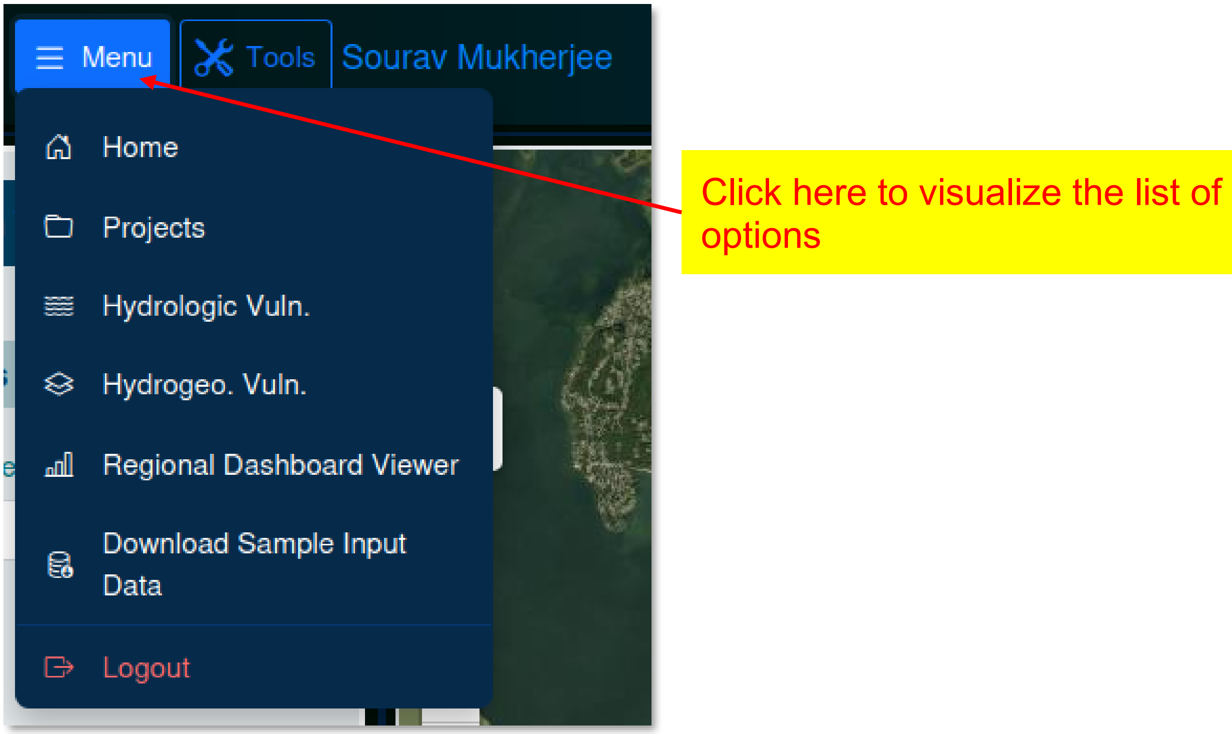

Figure 6.1. Schematic showing additional features aiding in page navigation.

6.1.1. Navigation to and from Analysis Interface

- Home - Direct navigation to the main landing page
- Projects - Switch between existing projects or create new ones directly from the analysis interface without returning to the project dashboard
- WS Deln. - Navigate to Watershed Delineation module
- Hydrologic Vuln. - Access Hydrologic Vulnerability Assessment page (only allowed if watershed delineation is complete and accepted)
- Hydrogeo. Vuln. - Switch to Hydro-geomorphologic Vulnerability Assessment interface (only allowed if watershed delineation is complete and accepted)
- Logout - Securely exit session ensuring proper session termination and data security

6.1.2. Additional Features

- Regional Dashboard Viewer - Examine preprocessed analysis results from specific areas or projects of interest uploaded to the static dashboard viewer
- Download Sample Input Data - Access Santee Experimental Forest test datasets for application evaluation (also available through footer on home page and project dashboard)

This centralized menu system enhances user experience by providing quick access to all major platform functions without interrupting active analysis workflows as shown in Figure 6.1.2.

6.2. Available 'Tools'

6.2.1. View Data Dashboard

Upon completion of any analysis, users can access the comprehensive data dashboard by clicking the 'Tools' option in the application header, which reveals a dropdown menu containing the 'View Dashboard' selection as shown in Figure 6.2.1. The dashboard modal opens to display an integrated three-component interface featuring an interactive map, linked data tables, and statistical visualization charts. The map-table link provides bidirectional interactivity such that clicking on specific table rows corresponding to pour points causes those locations to appear as magnified red circles on the map, while conversely, clicking on map pour points highlights the corresponding rows in the data tables. Users can seamlessly switch between chart and table views by selecting their layer of interest from available options, with layer availability dependent on completed analyses. For charts, the available layers dynamically populate based on executed assessments and may include Watershed Characteristics, Hydrologic Vulnerability, Hydro-geomorphologic, and Summary statistics when corresponding analyses have been completed, each accessible through dropdown selection for customized data exploration. Table views offer detailed datasets that appear only when relevant analyses have been performed, potentially including Watershed Analysis, RF - Hydrologic Vulnerability, RM - Hydrologic Vulnerability, GPDM - Hydrologic Vulnerability, RUSLE - Erosion Analysis, SBEVA – Hydro-geomorphologic Vulnerability, and WDFM – Hydro-geomorphologic Vulnerability based on user-selected assessment methods. This conditional layer presentation ensures users only see relevant data options while enabling comprehensive data exploration, comparative analysis across different assessment methods, and detailed examination of results through multiple visualization approaches, supporting both rapid overview assessment and detailed technical review of vulnerability analysis outcomes.

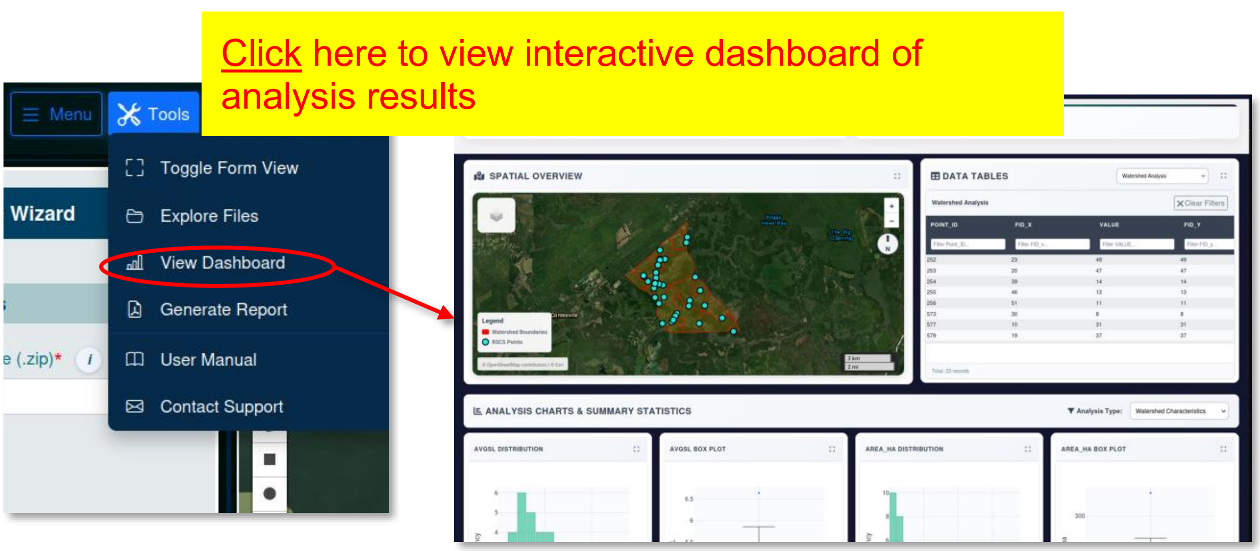

Figure 6.2.1. Schematic showing step to view interactive dashboard of analysis results.

6.2.2. Explore Output Data

Upon completion of any analysis, users can access comprehensive output data by clicking the 'Tools' option in the application header and selecting "Explore Files" to access and download all generated analysis outputs through a dedicated file management interface. This is depicted in Figure 6.2.2. This opens a modal window displaying a comprehensive list of available files produced during the completed analyses, with file availability corresponding to the specific assessment methods that were executed. Users can selectively choose individual files of interest or utilize the "Select All Files" functionality to mark all generated output files for batch download. The interface streamlines the download process by packaging selected files into a single compressed ZIP archive when the "Download Selected Files" button is activated, eliminating the need for multiple individual downloads. This file management system ensures users can efficiently identify and retrieve spatial datasets, statistical reports, vulnerability maps, and other analytical products for external use, further analysis in specialized software, or archival purposes. The table and figure referenced provides visual documentation of this file exploration and download procedures, illustrating the complete workflow from file selection through download completion.

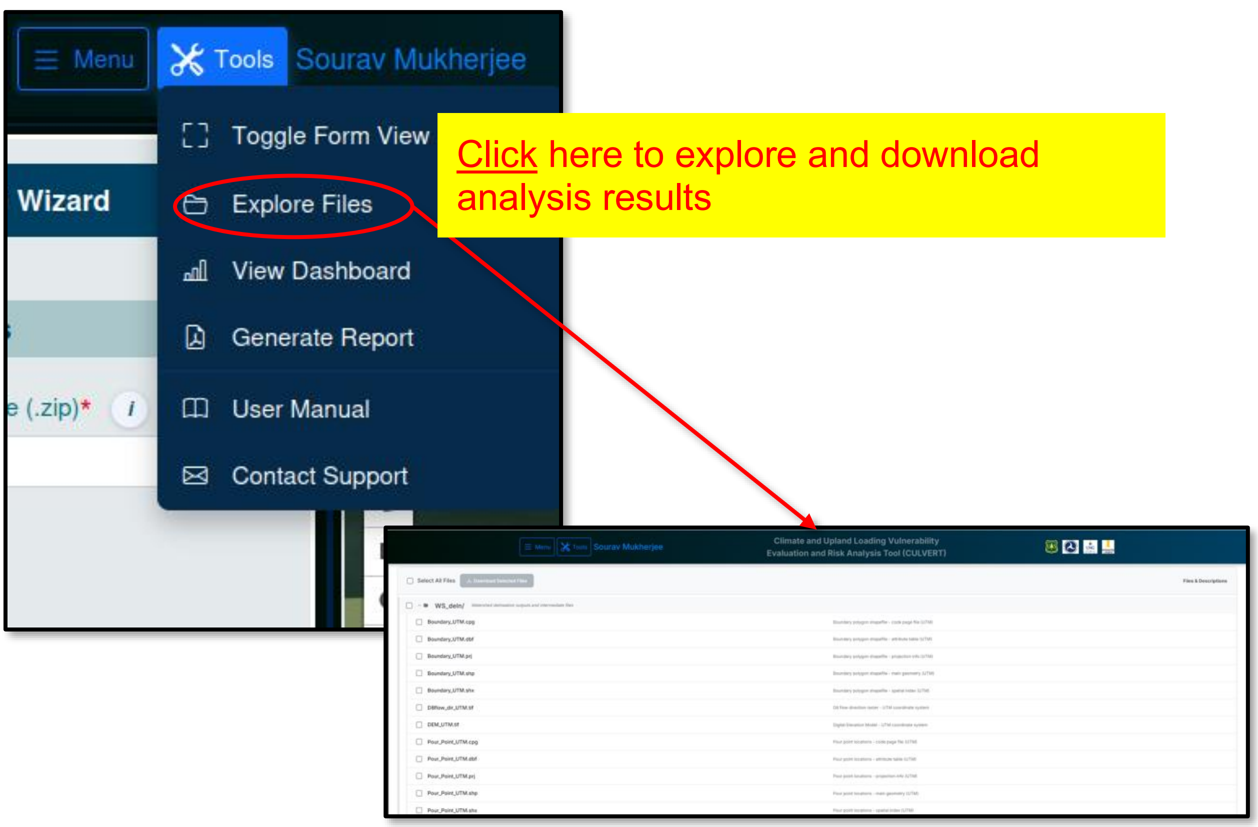

Figure 6.2.2. Schematic showing the step to explore data outputs for exploration and download.

6.2.3. Generate Technical Report

The Tools menu includes a "Generate Report" option that automatically creates comprehensive technical documentation using the analysis outputs generated by users as shown in Figure 6.2.3. This feature produces professionally formatted reports in DOCX format containing integrated plots, data tables, and descriptive text that summarize the completed vulnerability assessments and their findings. The report generation process draws from all available analysis results, incorporating relevant charts, statistical summaries, spatial visualizations, and methodological explanations into a cohesive document structure. Users can download the generated report for immediate use or further customization, enabling them to edit content, add project-specific information, modify formatting, or integrate findings into larger technical documents or presentations. This automated report generation capability streamlines the documentation process for engineering assessments, regulatory submissions, or stakeholder communications by providing a standardized yet editable foundation that captures the essential elements of the vulnerability analysis workflow and results.

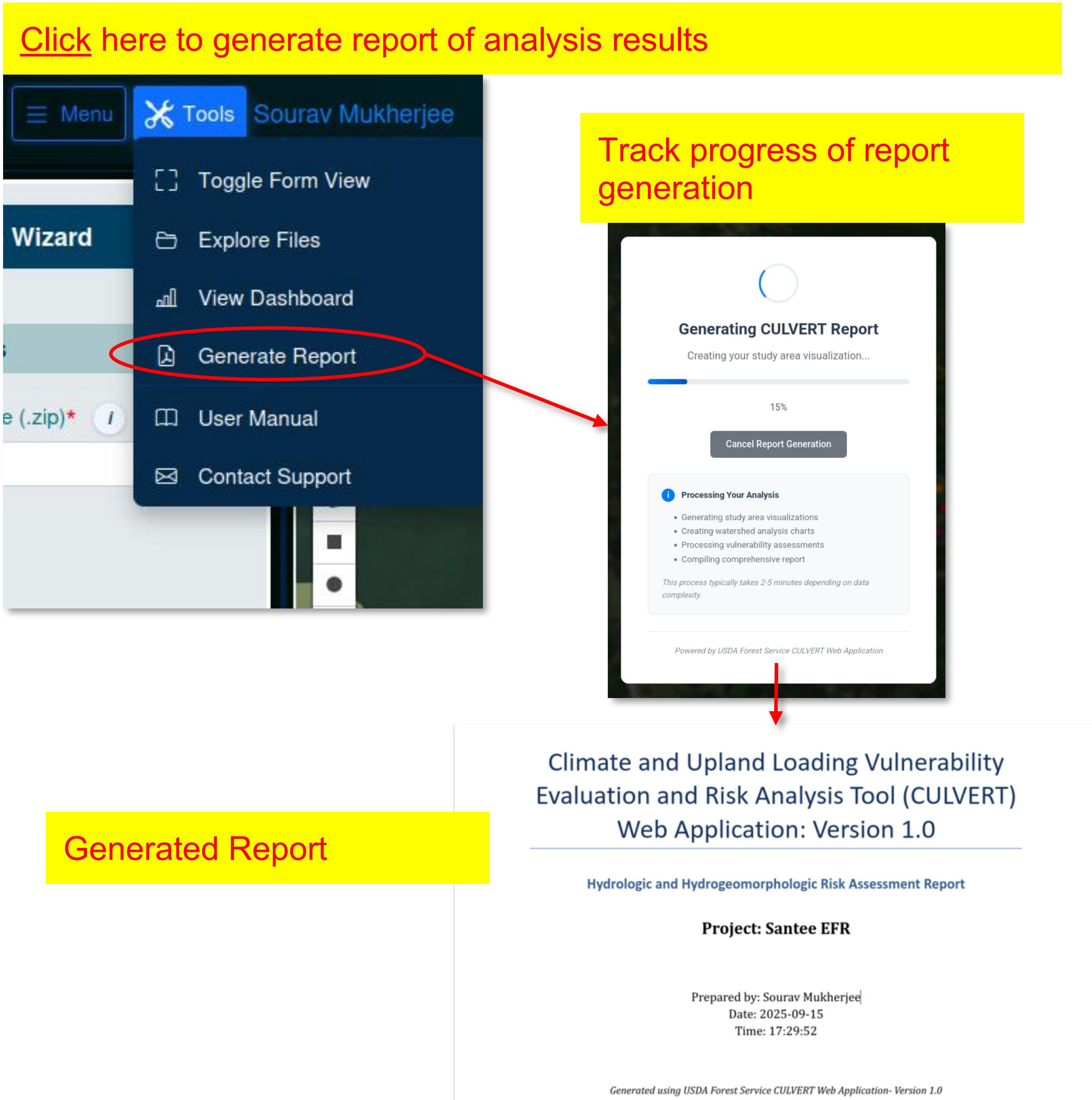

Figure 6.2.3. Schematic illustrating the step to generate an editable technical report using the analysis results.

6.2.4. Additional Features

The Tools option in the header additionally provides:

- **User Manual -** Opens the comprehensive user manual as a PDF in a new browser tab for detailed guidance and reference (Figure 6.2.4).
- **Contact Support** - Opens a modal window with auto-filled sections and user input fields to email the technical support team for assistance (Figure 6.2.4).

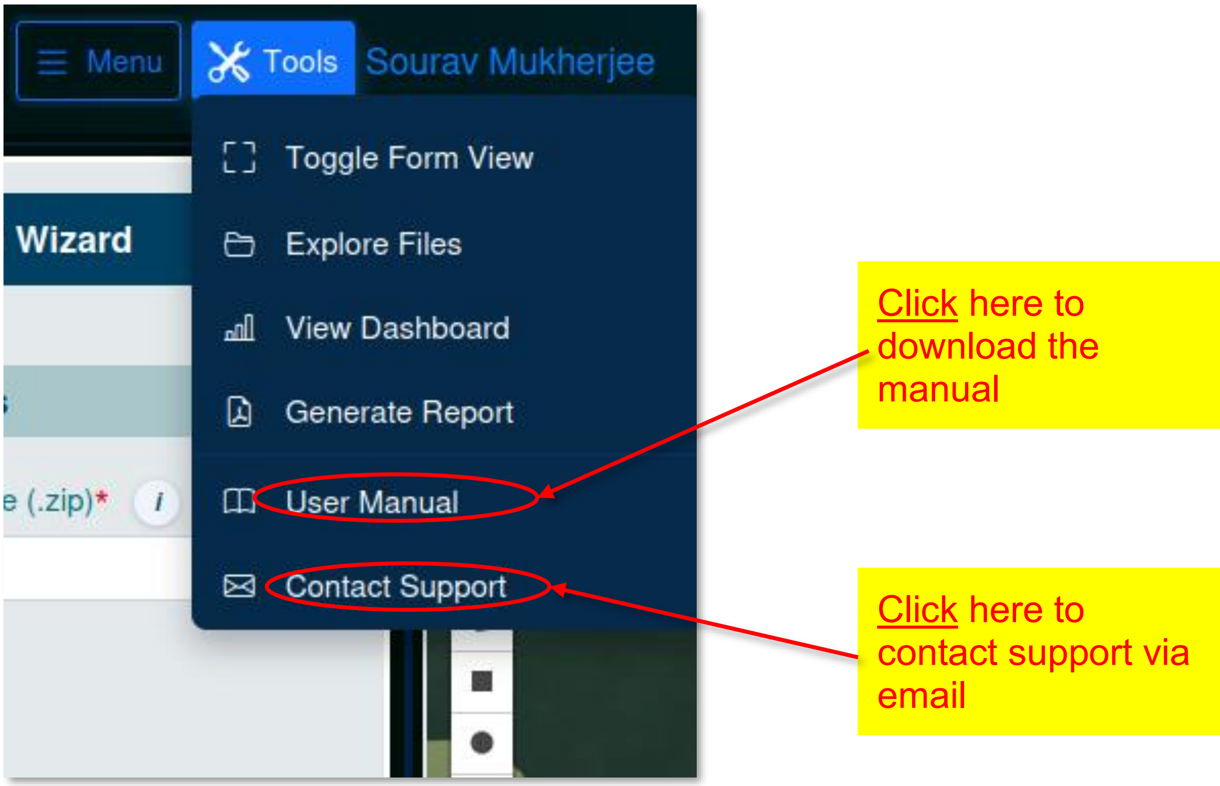

Figure 6.2.4. Schematic illustrating the step to download user manual and contact technical support.

7. Acknowledgement

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8. Appendix

8.1. Watershed Delineation with no culvert/pour point data available

The analysis skips the hydro-enforcement phase entirely since there are no user-provided points to enhance flow routing around. The system proceeds directly from DEM conditioning to stream extraction, then automatically generates intersection points where roads cross the computed stream network.

The current implementation dramatically simplifies when no culvert data is detected, removing all hydro-enforcement parameters (road fill heights, breakline offsets, burning depths) and pour point snapping distances. Only three core parameters remain: flow accumulation threshold (controlling stream density), minimum watershed area (filtering insignificant basins), and the boundary extension flag threshold.

This approach typically generates far more analysis points than user-provided data would - potentially hundreds of road-stream crossings requiring individual watershed delineation. While computationally intensive, this provides comprehensive coverage that manual point selection might miss.

The no-culvert-data workflow transforms data limitation into a systematic vulnerability assessment tool. Rather than analyzing known problem locations, it identifies ALL potential infrastructure risk points, supporting regional planning, investment prioritization, and comprehensive climate adaptation strategies.

Since the system generates points automatically, additional validation becomes crucial. The workflow includes enhanced boundary compliance checking and area-based filtering to ensure generated watersheds represent meaningful drainage areas rather than computational artifacts.

This approach essentially converts the watershed delineation tool from a diagnostic instrument (analyzing known locations) into a discovery instrument (identifying potential problems), making it valuable for preliminary risk assessment and infrastructure planning even without detailed culvert or other road-stream crossing infrastructure inventory data.

8.3. Regional Frequency Analysis

The Regional Frequency Analysis (RFA) workflow implements a comprehensive statistical framework for flood frequency estimation that accommodates both stationary and non-stationary hydrological conditions across gauged and ungauged watersheds.

The methodology begins with data preprocessing where time series data from precipitation or streamflow sources are loaded, with annual maxima extracted and normalized by catchment area, followed by optional outlier detection and removal using either Z-score or interquartile range (IQR) methods based on user-defined thresholds.

For trend analysis, the system applies the Mann-Kendall test to identify significant temporal trends in the data, and when trends are detected and non-stationary analysis is requested, three generalized extreme value distribution models are fitted: a baseline stationary model (M0) with constant parameters (μ_0, σ_0, ξ_0), and two non-stationary models incorporating time as a covariate affecting either the location parameter only (M1) or both location and scale parameters (M2). Model selection is performed through likelihood ratio tests and information criteria (AIC/DIC) comparison to identify the optimal model structure for each site.

The regional analysis component processes multiple stream gauges within homogeneous regions, calculating regional growth curves through weighted parameter averaging and bootstrap confidence interval estimation, while ungauged sites are assigned to appropriate homogeneous regions for parameter transfer.

The workflow concludes by applying regional growth curves to calculate return period estimates, generating flood peak volumes through the combination of index floods, growth curve quantiles, and catchment areas, and producing comprehensive outputs including shapefiles with return values, site-specific statistics, and regional growth curve estimates with associated confidence intervals for integration into the broader culvert vulnerability assessment framework.

8.4. Rational Method

The Rational Method (RM) implementation workflow (Figure 4) establishes a comprehensive framework for peak discharge estimation that integrates multiple data sources and adapts to varying data availability scenarios across watersheds of different scales. The peak discharge estimates with associated confidence intervals (for Coefficient of Runoff and PI) through the fundamental rational equation is given as,

$$Q = C \times PI \times A \times Correction\,Factor$$

The methodology initiates with a systematic data ingestion phase where essential geospatial datasets are acquired and processed, including National Land Cover Database (NLCD) for land use classification, Digital Elevation Models (DEM) for topographic analysis, gridded Soil Survey Geographic (gSSURGO) database for hydrologic soil group determination, and watershed boundary delineations, with optional integration of local precipitation and streamflow time series data when available. Spatial processing operations include coordinate system standardization, data clipping to watershed boundaries, resampling for consistent resolution, and extraction of key watershed characteristics including dominant hydrologic soil groups, slope categories (classified as 0-2%, 2-6%, and >6%), and area-weighted runoff coefficients derived from lookup tables based on the intersection of land cover types, soil groups, and slope classifications. The system implements a hierarchical approach for parameter estimation that accommodates four distinct data availability scenarios:

- Case 1 utilizes tabulated runoff coefficients with NOAA Atlas-14 precipitation intensities for ungauged watersheds,
- Case 2 combines tabulated coefficients with local rain gauge data,
- Case 3 employs back-calculated runoff coefficients from observed flow-precipitation relationships using the top 10,000 wet events with local precipitation intensity data, and
- Case 4 applies back-calculated runoff coefficients with NOAA Atlas-14 intensities for enhanced regional consistency.
- Case 5 enables event-based analysis where users can input specific precipitation intensity values for targeted storm event assessments and real-time vulnerability evaluation.

For watersheds exceeding 400 hectares, area reduction factors based on Technical Paper 29 (TP-29) guidelines are applied to account for spatial variability in precipitation, while time of concentration calculations guide the selection of appropriate precipitation intensity durations from NOAA Atlas-14.

8.5. Graphical Peak Discharge Method

The Graphical Peak Discharge Method (GPDM) workflow (Figure 5) implements the TR-55 graphical approach combined with the SCS Curve Number method to estimate peak discharge through a systematic integration of watershed characteristics, rainfall distributions, and hydrologic parameters. The methodology begins with comprehensive data ingestion including watershed characteristic shapefiles containing essential parameters such as Point_ID, wetland area (WetAHa), total watershed area (area_ha), time of concentration (TCmin), and curve number values (CN_val), along with state boundary data and rainfall distribution type lookup tables that classify regions into SCS rainfall distribution types (I, IA, II, III) based on geographic location. Spatial preprocessing operations reproject watershed boundaries to EPSG:4326 coordinate system, extract centroid coordinates for each watershed, and determine the appropriate state and corresponding rainfall distribution type through spatial intersection analysis. The system automatically downloads 24-hour precipitation depths from NOAA Atlas-14 for user-specified return periods (typically 2, 5, 10, 25, 50, 100, and 200 years) based on watershed centroid coordinates, with additional capability for event-based analysis where users can input specific precipitation depth values for targeted storm event assessments. Initial abstraction (Ia) is calculated as a function of curve number, followed by runoff depth estimation (R) using the SCS Curve Number method relationship between precipitation depth and curve number. Unit peak discharge (qu) is computed using the TR-55 graphical method as a function of initial abstraction, precipitation depth, time of concentration, and rainfall distribution type, while wetland adjustment factors (Fp) are calculated to account for flood peak reduction effects of wetland areas within the watershed. The final peak discharge estimation follows the equation,

$$Qp = qu \times R \times Area \times Fp$$

This produces comprehensive outputs including shapefiles with peak discharge values and precipitation depths with associated confidence intervals (lower bounds, estimates, and upper bounds) for each return period, enabling robust flood frequency analysis for culvert design and vulnerability assessment applications.

8.6. Culvert Discharge Capacity Methods

8.6.1. Inlet Control Method

Description

Inlet control occurs when the culvert entrance restricts flow capacity. The discharge is controlled by the inlet geometry, headwater depth, and inlet configuration. This condition typically occurs when the culvert has sufficient downstream capacity, but the inlet acts as a bottleneck.

Governing Equations

The FHWA HDS-5 inlet control equations are based on the relationship between headwater depth and discharge:

Unsubmerged Orifice Flow (HW/D ≤ 1.2):

$$Q_i = A \times D^{0.5} \times \sqrt{\left(\frac{HW}{D} - Y + k_s \times S\right) \div c}$$

Submerged Orifice Flow (HW/D > 1.2):

$$Q_i = A \times D^{0.5} \times \sqrt{\left(\frac{HW}{D} - Y\right) \div c}$$

$$Q = Q_i \times N$$

Where:

- $Q = Total\ discharge\ capacity\ (cfs)$
- $Q_i =$ Discharge (cfs) for single culvert
- $N = Group\ size\ (or\ number\ of\ culverts\ in\ a\ group)$
- $A = \text{Cross} - \text{sectional area (ft}^2)$
- $D =$ Culvert diameter (for circular/round) or height (ft)
- $HW =$ Headwater depth (ft)
- $Y =$ Inlet geometry factor (dimensionless)
- $k_s =$ Slope correction factor (dimensionless)
- $S = Culvert$ slope (ft/ft)
- $c = Inlet\ geometry\ constant$ (dimensionless)

Key Parameters

- Y, c, k_s: Empirical coefficients from FHWA HDS-5 tables based on culvert shape and inlet type
- HW: Critical parameter determining flow regime (submerged vs. unsubmerged)

8.6.2. Outlet Control Method

Description

Outlet control occurs when flow is restricted by friction losses through the culvert barrel, exit losses, or downstream conditions. The entire culvert system (inlet, barrel, and outlet) affects the flow capacity. This condition is common in longer culverts or when tailwater levels are high.

Governing Equations

The outlet control equation accounts for all energy losses through the culvert system:

Headwater Depth Calculation:

$$HW = TW + H - S_o \times L$$

Total Head Loss Equation:

$$H = \left[1 + K_e + \left(\frac{29.2 \times n^2 \times L}{R^{4/3}}\right)\right] \times \frac{V^2}{2g}$$

Discharge Capacity Calculation:

$$Q = Q_i \times N$$

where,

$$Q_i = A \times \sqrt{\frac{2g \times H_a}{C_h}}$$

$$H_a = HW - h_o + S_o \times L$$

$$C_h = 1 + Ke + \left(\frac{29.2 \times n^2 \times L}{R^{4/3}}\right)$$

- $Q = Total\ discharge\ capacity\ (cfs)$
- $HW =$ Headwater depth (ft), defaults to $1.5 \times$ D when $S_o\ and\ L\ are\ missing$, where D = culvert diameter in ft
- $TW =$ Tailwater depth (ft), defaults to $0.5 \times$ D when $missing$, where D = culvert diameter in ft
- $S_o =$ Culvert slope (ft/ft)
- $L =$ Culvert length (ft)
- $K_e = Entrance\ loss\ coefficient$
- $n = Manning's\ roughness\ coefficient$

- $R = Hydraulic\ radius\ (ft)$
- $V = Velocity\ (\frac{ft}{s})$
- $g = Gravitational\ acceleration\ (32.2\ ft/s^2$
- $Q_i = Discharge\ capcity\ of\ a\ single\ culvert\ (\frac{ft^3}{s})$
- $A = Cross - sectional\ area\ (ft^2)$
- $h_o = control\ depth\ at\ outlet\ (ft) = \max(TW, H_t)$, where $H_t =$ culvert height (ft),
- $C_h = Headloss\ coefficient,$
- $N = Group\ size\ (or\ number\ of\ culverts\ in\ a\ group)$

Key Parameters

- Ke: Entrance loss coefficient based on inlet type
- n: Manning's roughness coefficient based on culvert material and condition
- L: Culvert length significantly affects friction losses

8.6.3. Manning Uniform Flow Method

Description

Manning's uniform flow method assumes steady, uniform flow conditions throughout the culvert. This simplified approach treats the culvert as an open channel flowing full, neglecting entrance and exit losses. It provides a theoretical maximum capacity under ideal conditions.

Governing Equations

Manning's Equation (English Units):

$$Q_i = \frac{1.49}{n} \times \frac{R^{2/3}}{\sqrt{S}} \times A$$

Hydraulic Radius:

$$R = A/P$$

Where:

- $Q = Total\ discharge\ capacity\ (cfs)$
- $Q_i = Discharge\ capcity\ of\ a\ single\ culvert\ (\frac{ft^3}{s})$
- $n = Manning's\ roughness\ coefficient$
- $A = Cross - sectional\ area\ (ft^2)$
- $R = Hydraulic\ radius\ (ft)$
- $S = Culvert$ slope (ft/ft)

- $P = Wetted\ perimeter$ (ft)
- 1.49 = Unit conversion factor for English units

Hydraulic Radius by Shape

- **Circular (full flow):** $R = D/4$
- **Box:** $R = \frac{W \times H}{2 \times (W + H)}$
- **Elliptical:** $R = A/P$ (using Ramanujan's approximation)

Key Parameters

- n: Manning's roughness coefficient varies by material and condition
- S: Culvert slope directly affects flow capacity
- $Slope$: Geometric efficiency varies by culvert cross-section

Limitations

- Assumes uniform flow (no acceleration or deceleration)
- Ignores entrance and exit losses
- May overestimate capacity compared to inlet/outlet control methods
- Best suited for preliminary estimates or comparison purposes

8.7. Revised Universal Soil Loss Equation

A spatially-distributed erosion modeling approach forms the foundation of the Revised Universal Soil Loss Equation (RUSLE) workflow, which quantifies soil erosion potential through the integration of climatic, topographic, soil, and vegetation factors across watershed landscapes. The computational framework initiates with comprehensive data acquisition including Digital Elevation Models and flow accumulation rasters for topographic analysis, NOAA Atlas-14 30-minute 100-year precipitation intensity data for rainfall erosivity calculations, gridded Soil Survey Geographic (gSSURGO) K-factor datasets for soil erodibility assessment, and NDVI vegetation indices for ground cover evaluation, with all datasets undergoing spatial preprocessing to ensure consistent projection, resolution, and watershed boundary alignment.

Topographic erosion factors are computed through sequential calculations beginning with flow length estimation ($\lambda = Flow\ Accumulation \times cell\ size$), followed by L-factor determination using the relationship $L = (\lambda/22.13)^m$, slope angle and category derivation, and S-factor calculation through the equation:

$$S = 65.41 Sin^2(\theta) + 4.56 Sin(\theta) + 0.065,$$

which are subsequently combined into the composite LS-factor representing topographic influence on erosion processes.

Climatic erosivity is quantified through kinetic energy calculations as a function of 30-minute precipitation intensity ($KE = f(PI30)$), followed by R-factor estimation ($R = KE \times PI30$), while vegetation cover effects are incorporated through C-factor computation using the exponential relationship as,

$$C = exp(-\alpha \times NDVI)/(\beta - NDVI)$$

that accounts for protective ground cover density. The final erosion rate estimation follows the classical USLE structure with P-factor set to unity, calculating pixel-level soil loss as the product of all factors as,

$$Erosion\ Rate = C - Factor \times R - Factor \times K - Factor \times LS - Factor)$$

This is followed by watershed-scale averaging and rank-based scaling to produce normalized vulnerability scores ranging from 0-5, ultimately providing infrastructure-specific erosion vulnerability classifications from very low to very high for culvert, bridge, and ford locations to support targeted maintenance and replacement prioritization strategies.

8.8. Stream-bank Erosion Vulnerability Assessment

The Streambank Erosion Vulnerability Assessment (SBEVA) workflow implements a comprehensive multi-criteria analysis framework that integrates diverse environmental datasets to evaluate erosion susceptibility across stream networks and their associated infrastructure. The methodology begins with systematic data ingestion and preprocessing operations, including acquisition of NOAA Atlas-14 24-hour 100-year precipitation data, Digital Elevation Models (DEM), stream network polyline shapefiles, PRISM climate normals (30-year precipitation, temperature, and solar radiation), gridded Soil Survey Geographic (gSSURGO) soil properties encompassing root-zone available water storage, runoff classification, drainage characteristics, and hydrologic soil groups, and National Land Cover Database (NLCD) land use data retrieved via API from the Multi-Resolution Land Characteristics Consortium. All datasets undergo rigorous spatial preprocessing including reprojection and resampling to match DEM resolution and ensure spatial alignment, followed by clipping operations to watershed boundaries and stream buffer zones to focus analysis on hydrologically relevant areas. The vulnerability assessment employs a weighted overlay approach where each environmental variable is categorized using softmax normalization for numerical variables and scaled to a standardized 1-5 range, with slope calculations performed for each pixel and open water areas excluded from analysis. User-defined variable weights are applied through a weighted sum operation, $\sum_{i=1}^{N} (layer_i \times weight_i)$ to generate composite vulnerability scores, which are subsequently normalized using rank-based scaling to produce final SBEVA scores ranging from 0-5 representing vulnerability categories from very low to very high. The workflow culminates in the extraction of location-specific SBEVA scores for each culvert, bridge, and ford infrastructure point, providing critical information for prioritizing maintenance, replacement, and adaptive management strategies based on streambank erosion vulnerability potential.

8.9. Watershed Debris Flow Vulnerability Assessment

The CULVERT-v01 web application integrates the Watershed Debris Flow Model (WDFM) as a critical component for assessing mass wasting hazards that pose significant threats to transportation infrastructure, particularly in mountainous and steep terrain environments where culverts, bridges, and fords are susceptible to blockage and structural damage from debris flow events. This comprehensive geomorphological assessment framework synthesizes multiple environmental datasets including Digital Elevation Models for slope analysis, soil properties from gridded databases encompassing available water storage (0-150 cm), saturated hydraulic conductivity (Ksat), drainage classification, runoff characteristics, soil slip potential, soil bottom depth, taxonomic orders, and T-factors, along with geologic rock type classifications, K-factor rock-free estimations, and remotely sensed vegetation indices (NDVI) and water indices (NDWI) for surface condition characterization. The modeling workflow incorporates infrastructure-specific spatial buffers around road networks and stream channels to focus analysis on areas of direct relevance to transportation systems, while wind velocity and precipitation intensity data provide climatic forcing parameters that trigger debris flow initiation processes. All input datasets undergo rigorous spatial preprocessing including reprojection and resampling to match DEM resolution and spatial alignment, followed by watershed-scale clipping operations and expert-defined categorical scaling to standardize diverse environmental variables into comparable ranges for multi-criteria analysis. The WDFM employs a weighted overlay approach where user-defined variable weights are applied through summation operations, $\sum_{i=1}^{N}(layer_i \times weight_i)$ to generate composite vulnerability scores for each pixel, followed by rank-based normalization scaling to produce standardized WDBFM scores ranging from 0-5 representing debris flow vulnerability categories from very low to very high. The assessment culminates in the extraction of location-specific vulnerability scores for each culvert, bridge, and ford infrastructure point, enabling transportation agencies to prioritize maintenance schedules, implement protective measures, and develop adaptive management strategies based on quantified debris flow hazard potential.

8.10. Ensemble Hydro-geomorphologic Vulnerability Index

The Ensemble Hydro-geomorphological Vulnerability Index (EHVI) represents the culminating analytical component of the CULVERT-v01 web application, providing a comprehensive risk synthesis approach that integrates multiple erosion and mass wasting vulnerability assessments into a unified decision-support metric for infrastructure management. This ensemble methodology combines the normalized vulnerability scales from three distinct hydro-geomorphological models: the Streambank Erosion Vulnerability Assessment (SBEVA) representing lateral channel erosion processes, the Modified Revised Universal Soil Loss Equation (MRUSLE) quantifying sheet and rill erosion potential, and the Watershed Debris Flow Model (WDBFM) assessing mass wasting hazards, each contributing standardized vulnerability scores ranging from 0-5 across very low to very high risk categories. The EHVI calculation employs a linear combination approach to each component model based on local environmental conditions, infrastructure priorities, and expert knowledge of dominant geomorphological processes affecting transportation systems in the study region. The integration follows the equation

$$EHVI = \frac{\sum_{n=1}^{N}(Score_n)}{N}$$

where N indicates the total number of methods selected and $Score_n$ indicates the score (ranging from 0 to 5) obtained for the nth method. This allows practitioners to emphasize specific hazard types based on regional geomorphological characteristics, such as prioritizing debris flow vulnerability in steep mountainous terrain or streambank erosion in meandering river systems. The resulting EHVI provides a holistic vulnerability assessment that captures the complex interactions between multiple erosion processes, enabling transportation agencies to develop comprehensive risk management strategies that address the full spectrum of hydro-geomorphological threats to culvert, bridge, and ford infrastructure while supporting evidence-based prioritization of maintenance, replacement, and adaptive management investments across diverse landscape settings.

9. Glossary

Annual Maxima Series (AMS) - A time series dataset containing the maximum value (peak discharge or precipitation intensity) recorded for each year of observation, used in frequency analysis to estimate return period events.

Available Water Storage (AWS) - The amount of water that soil can store and release for plant use, typically measured in centimeters depth over specified soil profile depths (0-150 cm).

Breakline - A linear feature used in hydrologic modeling to represent abrupt changes in terrain elevation, such as road embankments or drainage channels, used in hydro-enforcement procedures.

C-Factor - Cover-management factor in RUSLE represents the ratio of soil loss from land under specific cover and management conditions to that from clean-tilled, continuous fallow conditions.

Culvert Capacity - The maximum discharge that a culvert can convey under specific hydraulic conditions, typically calculated using inlet control, outlet control, or Manning's uniform flow methods.

D8 Flow Direction Algorithm - A single-direction flow routing method that assigns flow from each grid cell to one of eight neighboring cells based on the steepest descent gradient.

DEM (Digital Elevation Model) - A raster dataset representing ground surface elevations, used as the foundational input for watershed delineation and topographic analysis.

Drainage Class - A soil property classification indicating the natural drainage characteristics of soil, ranging from excessively drained to very poorly drained.

EHVI (Ensemble Hydro-geomorphological Vulnerability Index) - A composite vulnerability metric that integrates multiple erosion and mass wasting assessment methods into a unified risk score for infrastructure management.

Flow Accumulation - A raster dataset where each cell value represents the upslope contributing area that would flow through that cell, used for stream network extraction.

GPDM (Graphical Peak Discharge Method) - A TR-55 based hydrologic method that combines SCS Curve Number methodology with graphical techniques to estimate peak discharge from watershed characteristics.

Headwater Depth (HW) - The depth of water upstream of a culvert inlet, measured from the culvert invert to the water surface, critical for culvert hydraulic calculations.

Hydro-enforcement - DEM modification procedures that ensure proper representation of hydrologic flow patterns around infrastructure features like roads and culverts.

Hydrologic Soil Group (HSG) - A soil classification system (Groups A, B, C, D) based on infiltration rates and runoff potential, with Group A having the highest infiltration and Group D the lowest.

Hydraulic Radius - The ratio of cross-sectional area to wetted perimeter, used in Manning's equation and other hydraulic calculations (R = A/P).

Inlet Control - A culvert flow condition where the inlet geometry restricts discharge capacity, typically occurring when HW/D ratios are relatively low.

K-Factor - Soil erodibility factor in RUSLE represents the inherent susceptibility of soil to erosion, measured in units that facilitate erosion rate calculations.

L-Factor - Slope length factor in RUSLE that accounts for the effect of slope length on soil erosion rates, calculated from flow accumulation data.

Manning's n - Roughness coefficient representing flow resistance in open channels and conduits, varying by material type and surface conditions.

NDVI (Normalized Difference Vegetation Index) - A remote sensing index calculated from red and near-infrared reflectance values, indicating vegetation density and health.

NOAA Atlas-14 - A comprehensive precipitation frequency atlas providing statistical precipitation data for various durations and return periods across the United States.

Outlet Control - A culvert flow condition where friction losses through the culvert barrel, tailwater conditions, or exit losses restrict discharge capacity.

Pour Point - An outlet location in a watershed where accumulated surface water flow exits the drainage area, used as the starting point for watershed delineation.

Precipitation Intensity (PI) - The rate of precipitation, typically measured in centimeters per hour, used in hydrologic analyses and rational method calculations.

Rational Method - A simplified hydrologic technique for estimating peak discharge using the equation $Q = C \times I \times A$, where C is runoff coefficient, I is rainfall intensity, and A is drainage area.

Regional Frequency Analysis (RFA) - A statistical method for estimating flood frequencies at gauged and ungauged sites by pooling data from hydrologically similar watersheds.

Return Period - The average time interval between occurrences of a hydrologic event of given magnitude, commonly expressed in years (e.g., 100-year flood).

RUSLE (Revised Universal Soil Loss Equation) - An empirical erosion model that estimates average annual soil loss using rainfall, soil, topographic, cover, and management factors.

Runoff Coefficient - A dimensionless parameter representing the fraction of rainfall that becomes surface runoff, varying by land use, soil type, and slope.

S-Factor - Slope steepness factor in RUSLE that accounts for the effect of slope gradient on soil erosion rates.

SBEVA (Streambank Erosion Vulnerability Assessment) - A multi-criteria analysis method for evaluating erosion susceptibility along stream networks using environmental variables.

SCS Curve Number - A dimensionless parameter used in the SCS method to estimate direct runoff from precipitation, based on land use, soil type, and antecedent moisture conditions.

Tailwater Depth (TW) - The depth of water downstream of a culvert outlet, influencing outlet control calculations and overall culvert performance.

Time of Concentration - The time required for runoff to travel from the most remote point in a watershed to the outlet, used in hydrologic modeling.

T-Factor - Soil loss tolerance representing the maximum rate of annual soil erosion that can occur without degrading long-term soil productivity.

Vulnerability Assessment - A systematic evaluation process that identifies and quantifies the susceptibility of infrastructure to specific hazards or failure mechanisms.

WDFM (Watershed Debris Flow Model) - A geomorphological assessment framework that evaluates debris flow vulnerability based on terrain, soil, geological, and climatic factors.

Watershed Delineation - The process of identifying and mapping drainage area boundaries that contribute surface water flow to a specific outlet point using topographic analysis.

Wetted Perimeter - The length of the boundary between flowing water and the channel bottom and sides, used in hydraulic radius calculations.