



Michigan Hydrologic Calculation Procedures

Final Report, Project Number OR21-019

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16. Abstract This report describes analyses and recommended updates to methods for estimating flood discharges in ungaged watersheds. Tasks included updating rainfall frequency and storm distribution data, recalibrating the unit hydrograph model, and evaluating the time of concentration method. GIS-based tools were developed for hydro-enforcement, watershed delineation, and weighted Curve Number calculation. In addition, regional regression models were revised based on new geospatial datasets and advanced statistical methods. A final task investigated alternative hydrologic techniques, specifically methods for incorporating climate projections and the use of rain-on-grid modeling techniques.		
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List of Acronyms

3DEP – 3D Elevation Program of the United States Geological Survey
CDA - Contributing drainage area
CMIP – Coupled Model Intercomparison Project
CN - Curve number (also referred to as RCN, runoff curve number)
DEM - Digital elevation model
EGLE - Michigan Department of Environment, Great Lakes, and Energy
FHWA - Federal Highway Administration
GIS - Geographic information system
IDS – Inter-Disciplinary Science
KML – Keyhole Markup Language
LOCA – Localized Constructed Analogs
LP - Lower Peninsula of Michigan
LULC - Land use / land cover
MDOT - Michigan Department of Transportation
MTRI - Michigan Tech Research Institute
MTU - Michigan Technological University
NASA – National Aeronautics and Space Administration
NEH - National Engineering Handbook
NLCD - National Land Cover Database
NOAA - National Oceanic and Atmospheric Administration
NRCS - Natural Resource Conservation Service (formerly Soil Conservation Service)
PILF - Potentially influential low flow
PRF - Peak rate factor
RAP - Research Advisory Panel
RCN - Runoff curve number
RMSE - Root mean square error
SCS - Soil Conservation Service
SSURGO - Soil Survey Geographic Database
TDA - Total drainage area
TR - Township and range
UH - Unit hydrograph
USACE - United States Army Corps of Engineers
UP - Upper Peninsula of Michigan
USDA - United States Department of Agriculture
USGS - United States Geological Survey

1. Executive Summary

This report describes the methods, findings, and results of the “Michigan Hydrologic Calculation Procedures” research project, contract number 2019-0311, as funded by the US DOT Federal Highway Administration (FHWA) and Michigan Department of Transportation (MDOT). Professor David Watkins of the Department of Civil, Environmental, and Geospatial Engineering (CEGE) at Michigan Technological University (Michigan Tech/MTU) served as the Principal Investigator on the project, with a period of performance of November 1, 2021 to June 30, 2025. Senior Research Scientist Colin Brooks of the Michigan Tech Research Institute (MTRI), a research center of Michigan Tech, served as Co-Investigator on the project and the lead of the MTRI geospatial tool development team. The other Co-Investigators were Dr. Veronica Webster of the CEGE Department at Michigan Tech and Dr. Mary Ellen Miller of MTRI. A diverse and knowledgeable research project team of Michigan Tech researchers and students contributed to completing research tasks and documenting the project’s findings and recommendations.

This work has been shared regularly with the project’s research advisory panel (RAP), composed of the project manager, the research manager, MDOT and EGLE subject matter experts, and experts from other agencies and organizations, including the Natural Resources Conservation Service, Federal Highway Administration, US Geological Survey, Southeast Michigan Council of Governments, and Wade Trim Consulting. Preliminary project results were presented at the 2023 Transportation and Environment Conference.

This report describes analyses and recommended updates to methods for estimating flood discharges in ungaged watersheds. Tasks specific to the analysis of small watersheds (drainage areas generally less than 20 square miles) included updating rainfall frequency and storm distribution data from NOAA Atlas 14, Volume 8: Midwestern States (Perica et al., 2013). Rainfall and stream gage data for individual storm events were also compiled for recalibrating the unit hydrograph model used in Michigan. In addition, automated GIS-based tools were developed for hydro-enforcement and watershed delineation, and the current manual method for estimating time of concentration was evaluated for possible automation.

For watersheds of all sizes, a major research task was to analyze GIS data for developing SCS (NRCS) Curve Numbers. Land use/land cover datasets were evaluated for their potential to improve hydrologic calculations, and updated land use/land cover data sets were evaluated or developed and recommended for use. Automated GIS-based tools for desktop ArcGIS Pro were developed for deriving weighted CN values and making watershed delineation more practical for everyday use.

Another major research task was to update regional regression models typically used for flood discharge calculations in larger watersheds. Updated geospatial datasets representing basin physiographic and climatic characteristics were compiled, and advanced statistical methods that have been developed since the previous study were applied.

A final research task was to investigate alternative hydrologic techniques for calculating peak discharges at ungaged sites and provide recommendations for future research. Methods for incorporating climate projections in peak discharge calculations and the use of rain-on-grid modeling techniques were specifically reviewed.

2. Background

2.1 Objectives

Michigan has experienced a number of severe floods in recent years, and there is evidence that extreme weather events are becoming more frequent. In 2018, the Houghton Father's Day Flood, in which 7 inches of rain fell in 6 hours (NWS, 2018), caused an estimated \$30 million in damage to local area roads (Houghton Co. Road Comm., 2018; see Fig. 2.1a). In May 2020, two privately owned dams near Midland broke following 5-8 inches of rainfall over two days, causing an estimated \$175 million in damage (WJRT, 2021; Fig. 2.1b). In June 2021, the Metro Detroit area experienced heavy rainfall and flooding that closed many local roads, as well as I-94 when power outages made pumping stations inoperable (WDIV, 2021). A study for MDOT by Michigan Tech found an increasing trend in the frequency of heavy rainfall events (greater than 2 in/day) during the 20th century (Trefry et al., 2005). Other studies have found similar regional trends (Bonnin et al., 2011; Papalexiou and Montanari, 2019; Wright et al., 2019). In addition, Kunkel et al. (2013) pointed to increases in probable maximum precipitation over the 21st century. Wright et al. (2019) concluded that current U.S. hydrologic design standards are insufficient due to large increases in the frequency of extreme rainfall events, although more research is needed on possible offsetting effects on flooding, such as increased evapotranspiration and reduced soil moisture.



Figure 2.1. a) Houghton 2018 Father's Day Flood (image courtesy of the National Weather Service). b) Michigan Tech UAV photo of the former location of the Edenville Dam, taken two weeks after the historic May 2020 flood event that also caused the failure of the Sanford Dam and the collapse of the M-30 bridge over Wixom Lake.

The Michigan Department of Transportation (MDOT) and Michigan Department of Environment, Great Lakes, and Energy (EGLE) use widely accepted methods for calculating design discharges, and many older conceptual approaches to hydrologic modeling (e.g., the SCS Curve Number method) are still widely used by state and federal agencies. However, significant advances have been made with respect to geospatial databases, analysis and mapping software,

and tools that enable automated workflows. In addition, a number of relevant hydrologic studies have been performed by other states and by federal agencies such as the U.S. Geological Survey (USGS), and there is potential to adopt and adapt best practices for use in Michigan.

Furthermore, updating discharge estimation methods and relying on best available datasets facilitate compliance with federal directives such as Federal Highway Administration Order 5520 -Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events (FHWA, 2014) and Executive Order 14008 - Tackling the Climate Crisis at Home and Abroad (Federal Register, 86(19), February 1, 2021).

To ensure accurate design discharge estimation, reliability of drainage and flood conveyance systems, and optimal allocation of infrastructure funding, it is important to update frequently the data sets used in hydrologic calculation procedures, as well as to review new procedures for potential operational use. As of the writing of this report, NOAA Atlas 14, Volume 8 (Perica et al., 2013) provides the most recent rainfall depth-duration-frequency estimates for Michigan, serving as an update to the Rainfall Atlas of the Midwest (“Bulletin 71”) (Huff and Angel, 1992). Compared to Bulletin 71, Atlas 14 is based on approximately 30 years of additional rainfall data. Further, Atlas 14 provides location-specific rainfall distributions, replacing the SCS Type II distribution that has typically been used statewide.

For consistency in risk and reliability assessment, updating the rainfall data used in design should be accompanied by updated calibration and validation of rainfall-runoff models. Since parameters in the current Michigan SCS Method (Sorrell, 2010) were derived for use with Bulletin 71 rainfall data, substituting Atlas 14 rainfall could result in unrealistically high discharge estimates, at least in some parts of the state. Along with more recent rainfall data, approximately 10 years of additional streamflow data is available since EGLE’s SCS Method was last updated, and approximately 40 years of additional observations are available since the USGS regression model for discharges from large watersheds in Michigan was developed. EGLE has already made significant revisions to the SCS Method to customize it for Michigan watersheds, including deriving a state-specific dimensionless unit hydrograph (Sorrell, 2010). Other updates and revisions have been proposed for the SCS Method (e.g., ASCE, 2009), which is typically recommended for watersheds less than 10-20 mi² due to the assumption of spatially uniform rainfall.

For larger watersheds, peak discharge regression equations are often used, and these have been updated for numerous states in the region, including Minnesota (Lorenz et al., 2010; Sanocki and Levin, 2023), Wisconsin (Walker et al., 2017; Levin and Sanocki, 2023), and Ohio (Koltun, 2019). In addition, public-domain software such as HEC-HMS (USACE, 2020), WinTR-20 (USDA, 2004), and EPA-SWMM (Rossman, 2015) are readily available for developing more complex models, as may be appropriate when reservoir storage is significant, hydrographs from sub-basins are to be combined, or watersheds are highly urbanized.

Along with more recent hydroclimatic data and advances in rainfall-runoff modeling, updated geospatial data sets and new software tools are available to facilitate and standardize calculations. Revised data sets include the 2021 National Land Cover Database (NLCD) (USGS, 2021) and the 2020 Gridded Soil Survey Geographic (SSURGO) Database, which is accompanied by an ArcGIS toolbox (Soil Survey Staff, 2021). Airborne LiDAR surveys over Michigan collected from 2010-2020 as part of the Michigan Statewide Authoritative Imagery & LiDAR (MiSAIL) program have improved Digital Elevation Model (DEM) data for most of the state to meter or sub-meter resolution, with additional aerial surveys planned through 2024 (EGLE, 2019). Ten-meter DEM data are also available statewide through the USGS 3D Elevation Program (3DEP), and 1- to 3-meter resolution data are available for the majority of Michigan.

Numerous GIS-based software tools have been developed for processing DEM, soils, and land use data for hydrology applications. In early work, Olivera and Maidment (1999) developed an ArcView extension for calculating peak discharges based on the Texas Statewide Regional Rural Regression Equations (Asquith and Slade, 1997), which later helped led to the ArcHydro extension usable in ArcMap. More recently, several states in collaboration with the USGS have developed GIS-based web applications for computing streamflow statistics and peak discharges based on regional regression equations (e.g., Kolton et al., 2006). The widely used software HEC-GeoHMS (USACE, 2013) has tools for merging land use with soils data to generate a SCS Curve Number (CN) grid. Zhan and Huang (2004) developed a similar ArcGIS extension for processing vector (polygon) data and reducing processing time. Similar methods were used to generate CN values with a semi-automated method within ArcGIS (Jabri and Hessane, 2020). Use of these data and tools can greatly reduce the time and effort required for determining design discharges, as well as increase the transparency and reproducibility of the calculations.

The goal of this study was to update Michigan's hydrologic calculation procedures for flood discharge estimation in ungaged watersheds. Specific objectives were as follows:

1. Incorporate modern data sets into existing methodologies to improve computed flood discharges in small ungaged basins (Sorrell, 2010).
2. Analyze and update GIS data for developing NRCS (SCS) Runoff Curve Numbers.
3. Update statistical models for estimating peak discharges in Michigan watersheds (Holtzschlag and Crosky, 1984).
4. Explore and develop alternative methods to calculate recurrence interval peak discharges at ungaged sites.

2.2 Research Tasks

The specific tasks of this research project needed to achieve the objectives were as follows:

Task 1. Administration Setup: This included initial correspondence with MDOT and EGLE staff, discussion of potential members of the Research Advisory Panel (RAP), and scheduling initial meetings and interviews to ensure the project team's understanding of current methodologies.

Task 2. Update and Validate Existing Method for Small Ungaged Basins: This task involved updating the rainfall frequency and storm distribution data used in the analysis of small watersheds, along with the collection of rain and stream gage data for recalibrating the unit hydrograph method. In addition, automated GIS-based tools for use in ArcGIS Pro were developed for watershed delineation, and the time of concentration method was evaluated for possible automation.

Task 3. Analyze GIS data for developing SCS Curve Numbers: Land use/land cover datasets were evaluated for their potential to improve hydrologic calculations, and other geospatial datasets (e.g., soils, wetlands) were evaluated for SCS Curve Number (CN) development. Automated GIS-based tools for use in ArcGIS Pro were developed for deriving weighted CN values.

Task 4. Update the 1984 MI Regression Equations: This task was to update regional regression models for flood discharges in larger watersheds using updated data sets and newer methods that have been developed since the previous study.

Task 5. Investigate Alternative Hydrologic Techniques: The final research task was to investigate alternative hydrologic techniques for calculating recurrence interval peak discharges at ungaged sites and provide recommendations for future research to the RAP.

Document updates based on the results of Tasks 2 and 4, along with the development of training materials, an implementation action plan, and this final report were the focus of Task 6.

3. Task Descriptions and Results

3.1 Administration Setup and Interviews

Initial project administration included organizing a project kick-off meeting with MDOT and EGLE staff and scheduling quarterly meetings with the Research Advisory Panel (RAP). RAP members included not only MDOT and EGLE staff, but also subject matter experts from other agencies and organizations, including the FHWA, USGS, Michigan NRCS, and the Southeast Michigan Council of Governments (SEMCOG), and Wade Trim Consulting.

To understand current hydrologic methods and their application, several small group meetings were held with MDOT and EGLE staff who attended the kickoff meeting, as well as other staff identified by MDOT with relevant expertise. These meetings occurred in January through October of 2022 and covered geospatial data available for the project, unit hydrograph calculations, spatial aggregation of NOAA Atlas 14 rainfall frequency grids, and potential automation methods. The MDOT Drainage Manual, Chapter 3 Hydrology (specifically 3.3.8 Hydrologic Analysis Procedure Flow Chart) was discussed with MDOT and EGLE staff to get a better understanding of the use of the different methods for peak discharge and hydrograph analysis. Meetings to review progress on the ArcGIS tools for RCN calculation and watershed delineation were also held regularly from 2022 to 2025 to enable periodic in-person review of tool progress. Through these in-depth meetings, the project team gained a better understanding of the recent use of these methods for the classes of watershed sizes listed in the manual, as well as systematic inaccuracies known to MDOT and EGLE, such as unrealistically high peak discharges resulting from the replacement of Bulletin 71 rainfall values with Atlas 14 rainfall values in some parts of the state, and the high variability of regression model estimates of peak discharges in small basins.

3.2 Update and Validate Method for Small Ungaged Basins

3.2.1 Methodology

3.2.1.1 Demonstrate Understanding of Existing Methodology

To demonstrate understanding of the existing small watersheds methodology and ensure consistency of results, the project team coordinated with MDOT and EGLE to select a set of test watersheds for which peak discharges were calculated using the EGLE Peak Discharge Spreadsheet with Bulletin 71 rainfall depths and the SCS Type II rainfall distribution. For each of these watersheds, the time of concentration and ponded area were estimated from 2023 USGS topographical maps, following procedures described by EGLE staff. The time of concentration estimation required finding the longest hydraulic flow path to the watershed outlet, dividing the flow path into segments, calculating the slope of each segment, and determining the velocity

along each segment based on the flow type (sheet flow, waterway, or small tributary). Per EGLE procedures, known waterbodies were removed from the flow path. Figure 3.1 shows an example of the watershed delineation, ponded areas, and flow paths evaluated for time of concentration (Tc) estimation for one of these watersheds. Table 3.1 shows the findings for all the watersheds selected for this test, following adjustments made based on comments received from MDOT and EGLE staff. Also shown are the time of concentration values developed by MDOT and EGLE staff (for 7 of the 11 watersheds), which show a close match with those estimated by the project team. Discrepancies can arise by not considering all possible flow paths in determining the longest travel time. Also, using elevation data with different resolutions will cause discrepancies, with higher resolution data (either gridded data or contours) generally leading to longer time of concentration estimates.

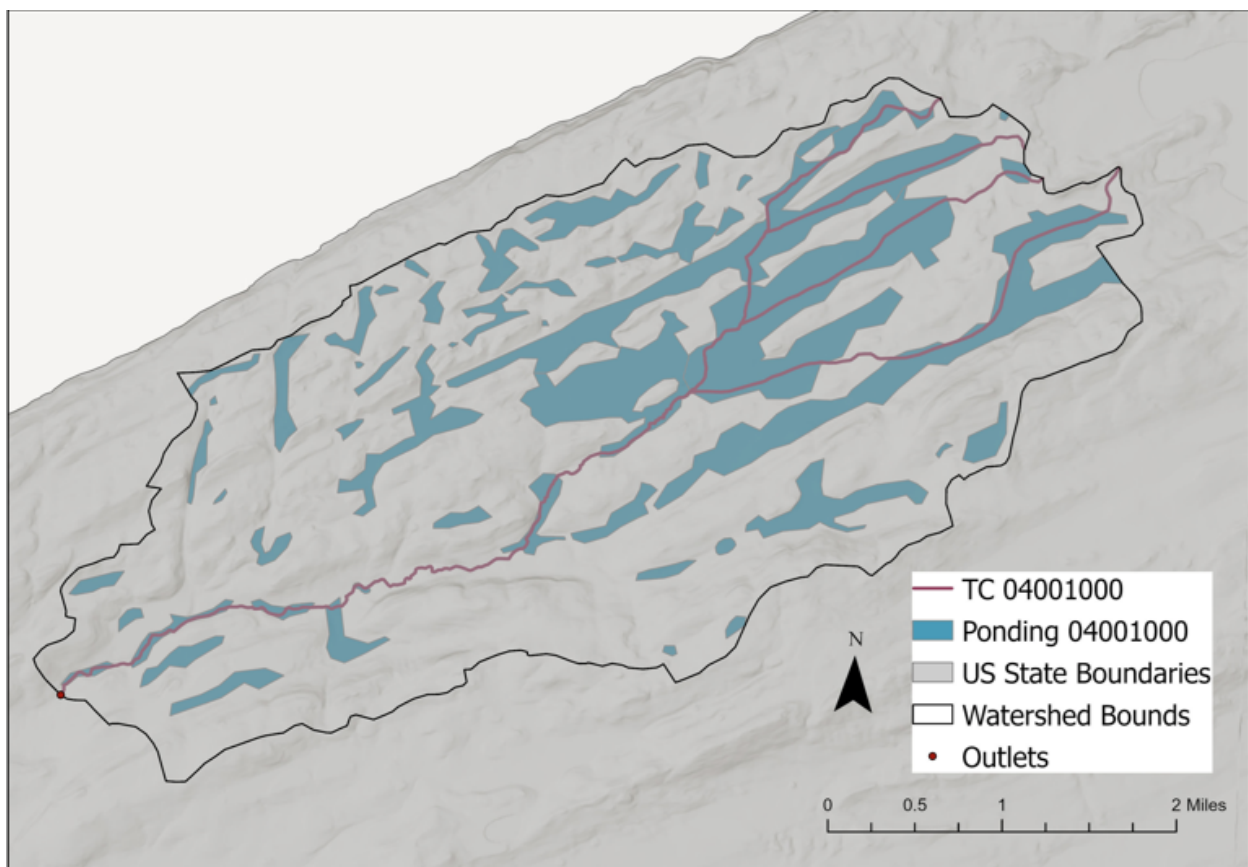


Figure 3.1. Watershed delineation, flow paths evaluated to determine time of concentration, and ponded areas for the Washington Creek watershed in Keweenaw County (USGS Gauge 04001000).

Table 3.1. Initial set of small watersheds selected for review of current methodology. Listed are the total drainage area (TDA), contributing drainage area (CDA), pond/swamp area, and estimated times of concentration (Tc) by MTU and MDOT.

USGS #	SITE NAME	TDA (sq.mi.)	CDA (sq.mi.)	Ponded (%)	Estimated Tc (hr)	MDOT/EGLE Est. Tc (hr)
04001000	WASHINGTON CR. AT WINDIGO	13.66	–	25.0	8.41	8.68
04043238	SALMON TROUT R. NR BIG BAY	7.47	–	2.7	10.22	10.44
04043244	E. BR. SALMON TROUT RIVER	10.17	–	5.2	5.6	5.72
04044200	CARP CR. AT ISHPEMING	16.68	–	16.8	16	15.12
04058300	WARNER CREEK NR PALMER	15.77	13.95	5.6	25.42	N/A
04138600	GAMBLE CREEK AT LUPTON	9.62	9.57	18.29	5.8	N/A
04138700	BIXBY CREEK NR ROSE CITY	2.62	–	1.91	1.71	2.2
04138900	WILKINS CREEK NR ROSE CITY	9.69	–	2.86	6.74	7.6
04139900	AMMOND CREEK NR SELKIRK	3.12	–	1.96	2.8	N/A
04140200	KLACKING CREEK NR SELKIRK	7.10	7.10	7.36	4.9	4.22
04141000	S. BR. SHEPARDS CR. NR SELKIRK	1.14	–	3.78	2.065	N/A

3.2.1.2 Update Rainfall Frequency Data and Storm Distributions

A primary objective of this study was to update the rainfall data used by EGLE and MDOT in their flood discharge analyses based on results from NOAA Atlas 14 Volume 8. NOAA Atlas 14 provides precipitation frequency estimates at a spatial scale of 30-arc seconds (approximately 1 km² grid cells) for durations ranging from 5 minutes through 60 days, and for return periods of 1 year through 1000 years. The data are provided in GIS-compatible format, along with upper and lower bounds of the 90% confidence intervals.

EGLE staff had previously determined that averaging the 30-arc second precipitation frequency estimates at the county level resulted in some estimates being outside of the 90% confidence interval for some locations. The project team evaluated spatial averaging at the township and range (TR) scale, with 1873 TR zones delineated, each containing up to 165 gridded NOAA Atlas 14 rainfall values. The TR areas were intersected with the 30 arc-second grid centroids to obtain spatial average rainfall values for each zone. The project team confirmed for both the 2-year and 500-year rainfall frequency values that the TR area averages were within the 90% confidence intervals at all locations throughout the state (see Figure 3.2).

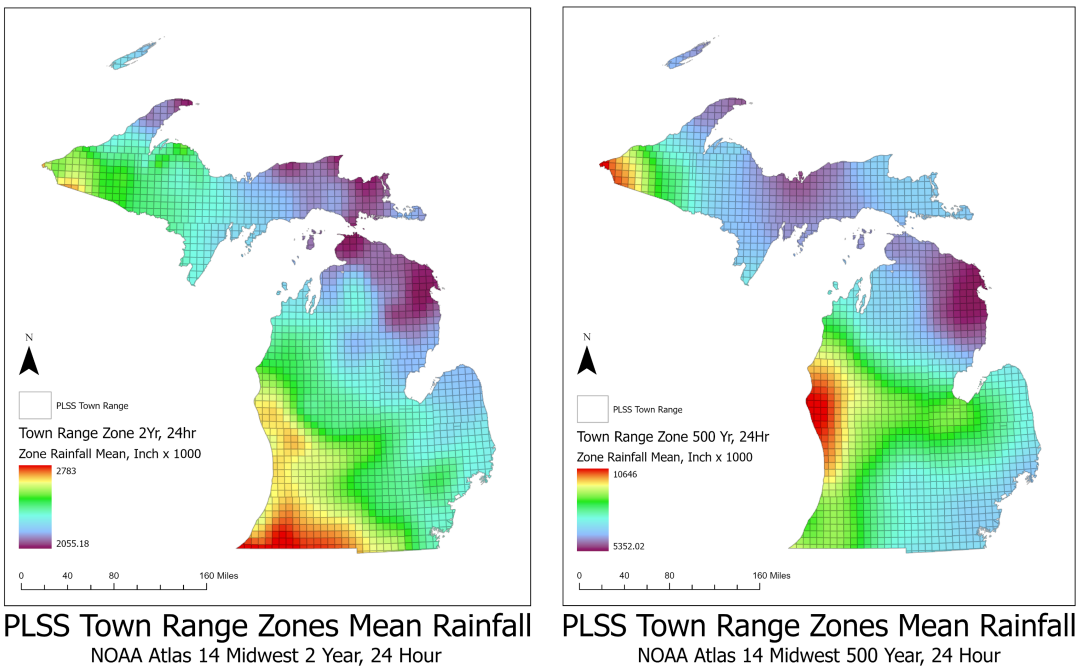


Figure 3.2. Michigan PLSS Town Range zones overlaid with 2-year and 500-year 24-hour rainfall values.

In addition to updated rainfall frequency estimates, NOAA Atlas 14 results have led to the development of new rainfall (design storm) distributions for many parts of the U.S. For the Midwest, the NRCS has developed six new rainfall distribution types (MSE1 through MSE6) to replace the standard NRCS Type II distribution. As implemented in NRCS software (EFH-2, WinTR-20, and WinTR-55), the MSE3 and MSE4 distributions are recommended for Michigan on a county-by-county basis based on the primary distribution in each county (see Figure 3.3). A comparison of the distributions is shown in Figure 3.4, indicating that the short-duration rainfall intensities of the MSE3 and MSE4 storm distributions are greater than the Type II distribution. The complete list of Michigan county assignments, as implemented in NRCS software, is provided in Table 6.1 in Appendix A.

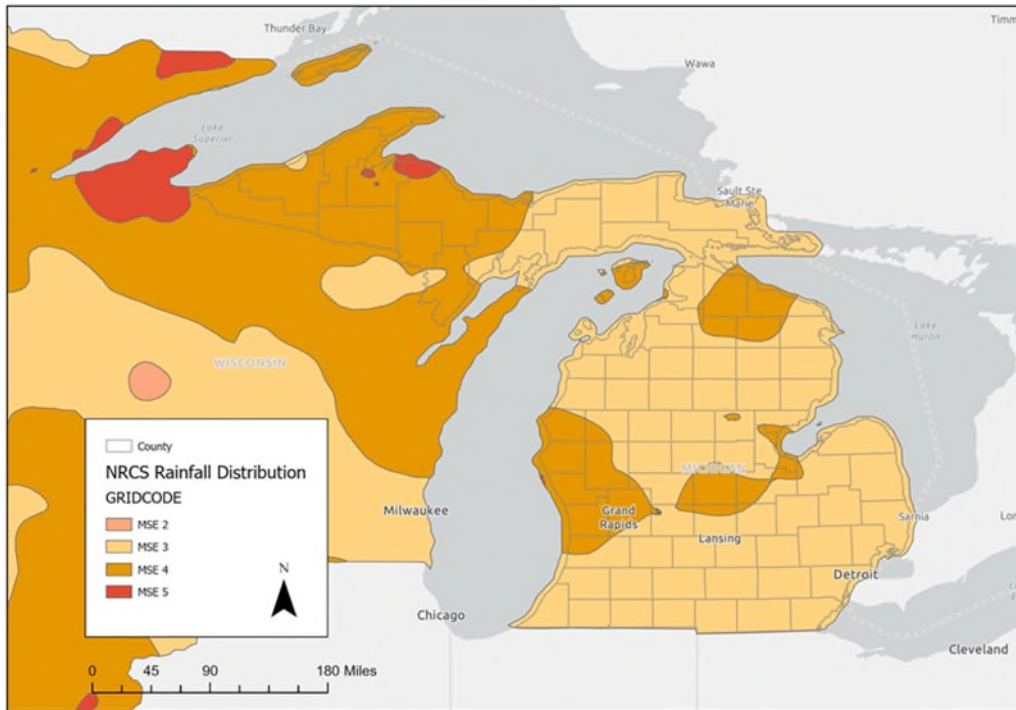


Figure 3.3. Rainfall distribution zones in Michigan (NRCS).

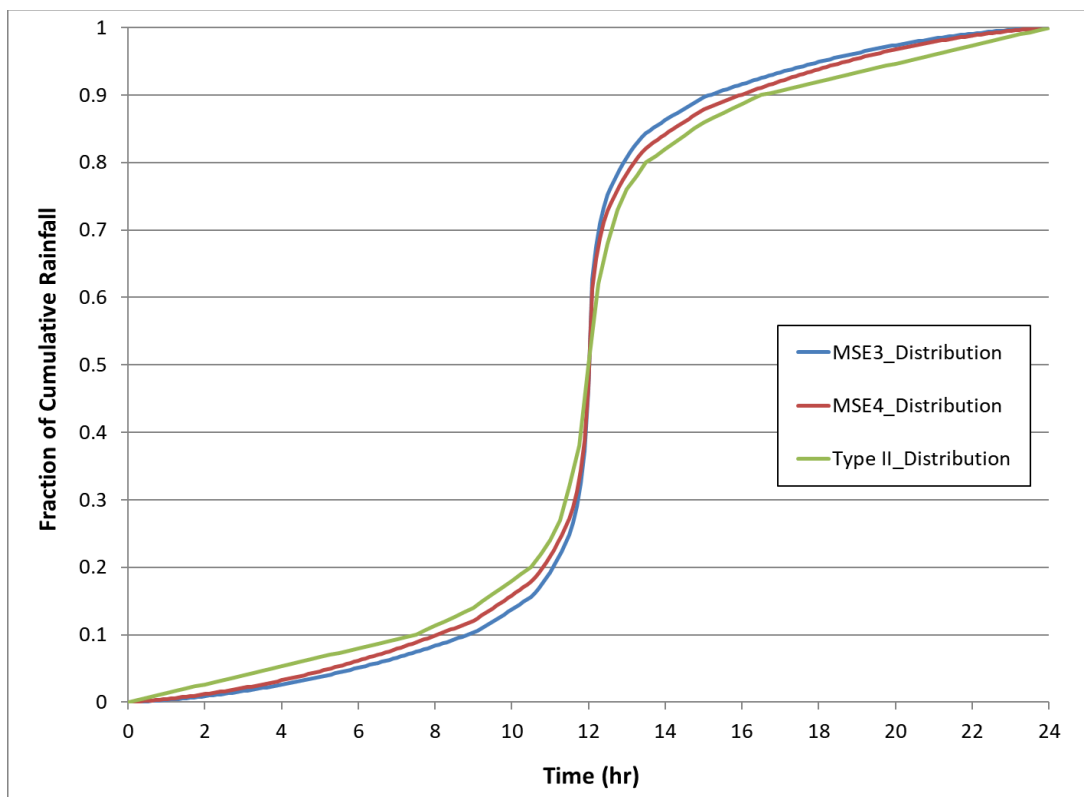


Figure 3.4. NRCS MSE3 and MSE4 distributions, derived from NOAA Atlas 14 rainfall frequency values, compared to the NRCS Type II distribution currently used in Michigan.

3.2.1.3 Develop Updated Unit Hydrograph Model

Sorrel (2010) reported on a study to revise the shape of the standard SCS dimensionless unit hydrograph (UH) to be more applicable to Michigan streams. That study used 74 flood events from 24 gaged streams with drainage areas less than 50 mi², and the results indicated that observed hydrographs could best be matched if the standard SCS UH is revised to have 28.5% of the volume under the rising limb, which is within the SCS-acknowledged range for this parameter. The UH peak, q_u , used in the current EGLE SCS Method is based on TR-20 simulations using a triangular UH with 28.5% of the volume under the rising limb, which corresponds to a peak rate factor of 368.

To update the unit hydrograph model, concurrent rainfall and flood discharge data were compiled for 21 watersheds with drainage areas less than 50 mi². Initially, the team attempted to implement the procedure for unit hydrograph estimation outlined in Chapter 16 Hydrographs of NEH Part 630. However, the procedure was difficult to apply without a large set of storm events that closely meet the assumptions of unit hydrograph theory, including a constant rainfall intensity and spatially uniform rainfall over the watershed. The vast majority of the flood discharge events corresponded to complex storms, with significant variations of precipitation intensity during the event. Thus, the procedure was adapted for application in HEC-HMS (USACE, 2020) as follows:

- 1) Identify high flow events in basins with both measured rainfall and streamflow. High flow events were selected based on USGS 15-minute or hourly streamflow observations. To avoid events influenced by snowfall and spring runoff, selection was limited to the months of April through November for the Lower Peninsula watersheds and between May and October for the Upper Peninsula watersheds. For each water year, a 90% threshold was set to screen for streamflow peaks. One to two peaks per year were selected from this subset as long as the peak was not influenced by a preceding event and the event duration was under 24 hours.
- 2) Calculate the runoff volume by separating baseflow from the observed flood hydrograph. Baseflow separation was performed using a Lyne-Hollick digital filter (Lyne and Hollick, 1979).
- 3) Compile rainfall data corresponding to these events. Hourly or 15-minute rainfall data was compiled from the National Climatic Data Center's (NCDC) Climate Data Online and the Michigan Automated Weather Network (MAWN). Rain gages were required to be located either in the watershed or within 2 miles of the watershed boundary. In addition, for four watersheds in the Metro Detroit area, gridded data were obtained from the Great Lakes Water Authority from their gage-adjusted radar rainfall data product.
- 4) Input rainfall and runoff time series in HEC-HMS and calibrate a basin model by adjusting the UH peak rate factor (PRF) and optimizing RCN and basin lag time to match the observed and computed hydrographs. In the analysis, the PRF was set to the following values: 250,

300, 350, 400, and 484 (standard NRCS UH). Using the peak-weighted RMSE as the objective function (to be minimized), the RCN and basin lag were optimized using the differential evolution algorithm with a population size of 30 and a maximum number of iterations of 100. The algorithm typically converged to a solution in less than 30 iterations. Figure 3.5 shows an example of calibration results in HEC-HMS.

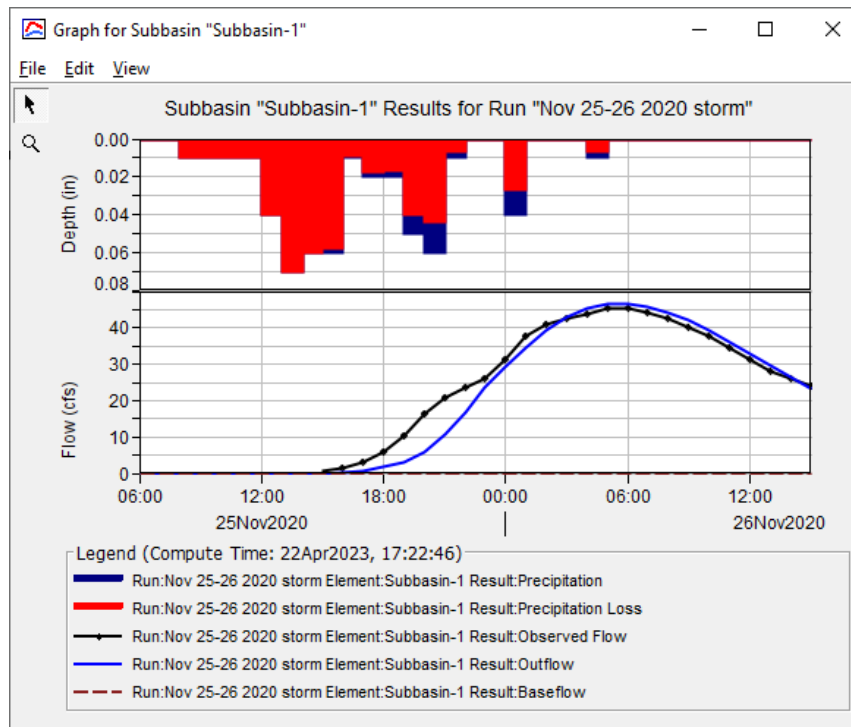


Figure 3.5. Example results from the calibration procedure in HEC-HMS.

3.2.1.4 Evaluate Time of Concentration Method

Both the velocity method, as currently specified by EGLE, and the watershed lag method for computing the time of concentration are outlined in Chapter 15 of NEH Part 630. The velocity method involves computing the travel times for flow segments along the most hydraulically distant flow path, with velocities based on slope and land cover. In contrast, the watershed lag method is based on parameters computed at the watershed scale, including the longest flow length, average watershed slope, and a flow retardance factor, which in practice is often taken to be the same as the CN. The velocity method is recommended for urbanizing watersheds or in cases where hydraulic modifications are being considered along the flow path. However, the watershed lag method also has wide applicability (Folmar and Miller, 2000) and may be easier to automate.

In discussions with the RAP, the project team learned that the watershed lag method is not preferred by EGLE, and various automated methods have been found to be unreliable. To evaluate the potential for an automated (or semi-automated) method, the team selected 30 small watersheds for comparison of the currently used velocity method with the watershed lag method and a novel regression analysis to evaluate relationships between the velocity method time of concentration and spatial watershed parameters. Both the watershed lag method and regression analysis used a GIS-based approach to calculate the longest flow path in ArcGIS Pro using the Flow Length tool with a Spatial Analyst license.

3.2.1.5 Review Pond and Swamp Adjustment Factor

The EGLE Peak Discharge Method applies a pond and swamp adjustment factor (POND) to account for temporary storage areas in the watershed (as defined by the USGS map symbol for “marsh”) that may retain runoff. The origin and application of this adjustment factor, which reduces peak discharge estimates, was reviewed. However, updates to the adjustment factor values were not considered in the watershed analyses.

As given by Sorrel (2010), the EGLE SCS Method is summarized with the following equation:

$$Q_p = q_u * SRO * CDA * POND \quad (\text{Eq. 1})$$

where Q_p is the peak discharge in cubic feet per second (cfs); q_u is the unit hydrograph peak factor in cfs per inch of runoff per square mile of drainage area, which is a function of time of concentration (T_c) and the peak rate factor (PRF); SRO is surface runoff depth in inches, given by the Curve Number method; CDA is contributing drainage area in square miles; and POND is the pond and swamp adjustment factor, which is unitless.

3.2.1.6 Automated Processes

Automation of Hydro-enforcement Tool

Hydro-enforcement can be used on digital elevation models (DEMs), such as current generations of LiDAR-derived DEMs available from USGS and MSU, to modify the elevation of impediments (i.e., culverts or bridge decks) to simulate continuous downslope flow (Poppenga 2014). This allows for a base layer for complex modeling of surface water flow. This tool artificially lowers the surface elevation of the waterways within a watershed to better represent water flow. This is done through: 1) dropping the elevation of the cells corresponding to the stream feature class by a certain amount, 2) buffering the streamline, and 3) assigning elevations to the cells inside the buffer. Parameters relevant to the creation of the stream burn-in that are editable by the user in this tool include:

- **Inwall Buffer distance:** Assigns elevation to the cells inside the buffer so that there is a straight-line path from the vector line to the original elevation outside the buffer.

- **Inwall Height:** Builds the height of the wall created around the buffer - prevents outside watersheds from interfering with the result. Wall is two pixels thick–inside.
- **Outwall Height:** Builds the height of the wall created around the buffer - prevents outside watersheds from interfering with the result. Wall is two pixels thick–outside.
- **Agree Buffer:** Buffer distance around Agree function (stream dropping function).
- **Agree Smooth:** Used to build a smooth modified elevation grid.
- **Agree Sharp:** Controls how much the cells corresponding to the stream feature class are dropped/raised after the smooth modified elevation grid is completed. ‘Digs a trench’ if negative, ‘builds a wall’ if positive.
- **Bowling Depth:** Generates the input datasets from hydrography features for enforcing a gradient.

This tool was based on code originally developed by F. Hellweger, in collaboration with TXDOT, which was incorporated into the USGS StreamStats coding package (Barnhart 2020). While the user can alter the values of these parameters, these values were determined based on recommendations of these two studies.

Development on the Hydro-enforcement Tool began in July 2022. MTRI incorporated algorithms developed by Hellweger (1997) and Barnhart (2020) into ArcPy and Python to be used within an ArcGIS Pro toolbox. This tool was built as a replacement for ArcHydro’s ‘Burn Stream Slope’ tool in ArcMap, which allowed “burning in” streams with slopes built based on elevation features in the stream feature class, and was not available in the ArcGIS version of ArcHydro at the time of the task start. The tool uses a 200-meter elevation dropping value to “burn” hydrology lines into the DEM. This tool is meant to be implemented onto a DEM before running the watershed delineation tool, so it can be used as an input in said tool. The DEM produced by this tool should not be used in analysis post-watershed delineation, due to the artificial depth change created within the product. The main parameter entry pane for the Hydro-enforcement tool is shown in Figure 3.6.

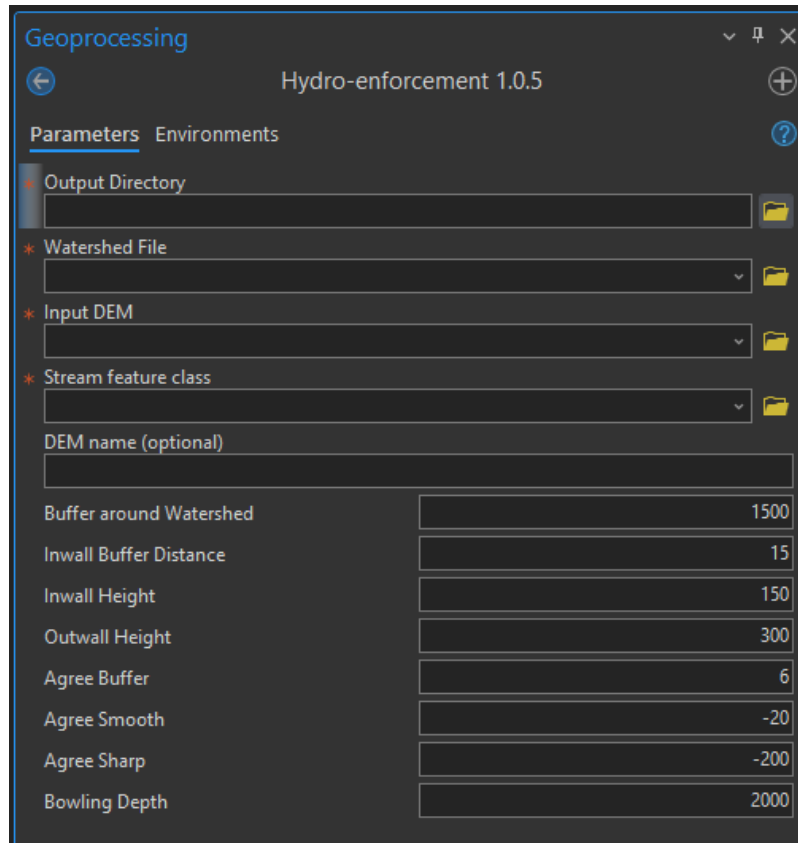


Figure 3.6. Screen grab of Hydro-enforcement tool as seen in "MTU_Hydro_Tool_1.0.5"

Process of incorporating this tool into MDOT/EGLE workflows

Multiple iterations of this tool have been delivered to MDOT/EGLE. The first iteration of this tool was delivered prior to an in-person meeting at the MDOT Van Wagoner Building on February 28, 2023. The tool was provided within a toolbox titled "MDOT_tool Beta Version 0.9.2", and was titled "Hydroenforce" (see Figure 3.7). It had the capacity to burn in flowlines for a single watershed in multiple counties. Recommendations from MDOT/EGLE on this version of the tool included:

- Allowing for the ability of running the tool on multiple watersheds at a time.
- Allowing for the ability to run one selected watershed in a shapefile with multiple watersheds for enhanced ease of use.
- Adding the ability to name the hydroenforced DEM output

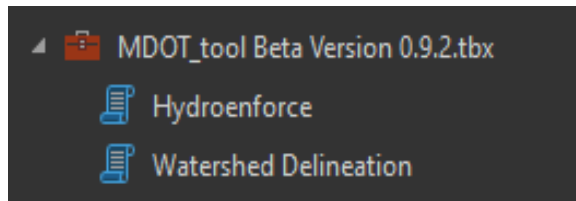


Figure 3.7. Screen-grab of MDOT_tool Beta Version 0.9.2.tbx. This version of the tool only contained the Hydro-enforcement and Watershed Delineation Tools.

The next version of this tool was delivered prior to an in-person meeting at the MDOT Van Wagoner Building on June 7, 2023. This tool was delivered in a toolbox titled “MDOT_Tool Beta Version 0.9.3”, and was called “Hydro-enforcement”. This tool had the ability to enforce DEMs for more than one area at a time, and it allowed the user to name the hydroenforced DEM output. It was also clarified that it was necessary to have Spatial Analyst licensed through ArcGIS Pro to run this tool; this extension is available to MDOT and EGLE staff under the State of Michigan ESRI site license. Improvements to the tool from this point on were primarily in updating workflow and in assisting in implementation. No major changes were made to this algorithm after this meeting, with just minor changes to syntax to support both ArcGIS Pro 2.9.x and 3.1 (and later versions). The “Hydroenforcement” Tool was included in the final version of the toolbox, then titled “MTU_Hydro_Tool_1.0.4”, and was delivered prior to a final in-person tool review meeting at the MDOT Earl Center with MDOT and EGLE staff on April 9, 2025. The final version of the tool, titled MTU Hydro Tool 1.0.5, with some requested improvements was then delivered via email and uploaded onto Projectwise on May 15, 2025.

Automation of Watershed Delineation Tool

Watershed delineation is the process of creating a boundary around the upslope area that contributes flow to a common outlet. This tool uses a (potentially hydro-enforced) DEM and pour points to automatically delineate a watershed. It works by computing the flow direction, flow accumulation, and snapped pour point in order to determine the contributing area of the watershed. This tool (see Figure 3.8) was originally developed by Dr. M.E. Miller through a previous MTRI project to gather inputs for Curve Number hydrology models in ESRI’s Desktop ArcMap. It was then converted to ArcPy/Python to be utilized in ArcGIS Pro through this project.

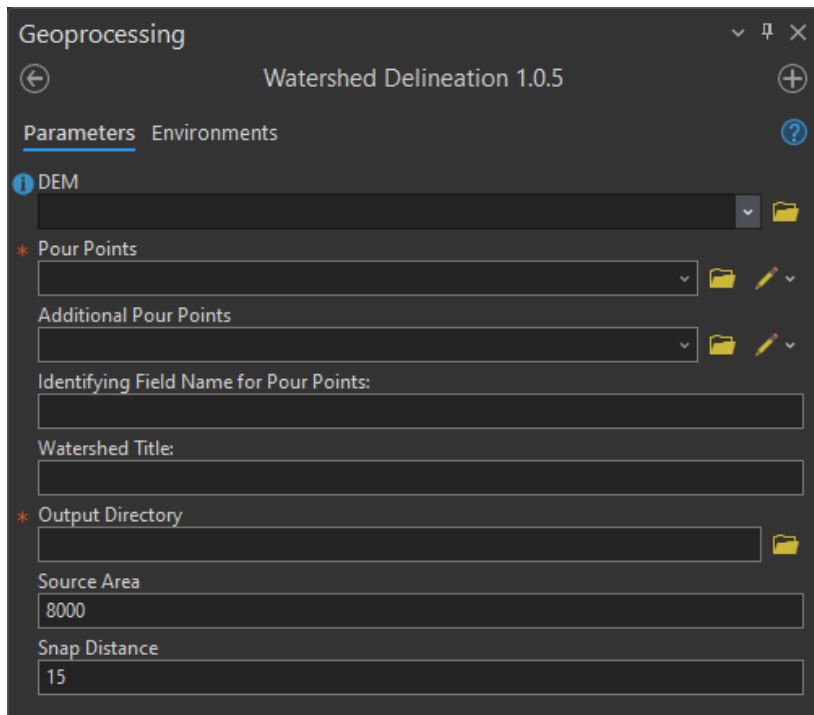


Figure 3.8. Screen grab of Watershed Delineation tool as seen in "MTU_Hydro_Tool_1.0.5"

Process of incorporating this tool into MDOT/EGLE workflows

Several iterations of this tool have been delivered to MDOT/EGLE. The first iteration of this tool was delivered prior to an in-person meeting at the MDOT Van Wagoner Building with MDOT and EGLE staff on February 28, 2023. The tool was provided within a toolbox titled "MDOT_tool Beta Version 0.9.2", and was titled "Watershed Delineation". This tool had the capability to delineate a watershed based on a DEM, but it could only delineate a single watershed at a time. Recommendations coming MDOT/EGLE on this version of the tool included:

- Adding a 'point and click' capability for selecting pour points
- Adding the ability of running the tool on multiple watersheds at a time

The next version of this tool was delivered prior to an in-person meeting at the MDOT Van Wagoner Building on June 7, 2023. This tool was delivered in a toolbox titled "MDOT_tool Beta Version 0.9.3", and continued to be called "Watershed Delineation". This tool had the ability to delineate multiple watersheds at a time, and it had point-and-click functionality for pour point generation. It was also discovered and clarified that it was necessary to Spatial Analyst was a requirement to run this tool. Recommendations from MDOT/EGLE on this version of the tool included:

- To consider adding KML Export Functionality

- To consider adding stream editing functionality in order to ensure higher flowline accuracy

The next version of this tool was delivered prior to an in-person meeting at the MDOT Earle building on October 10, 2023. It was provided in two toolboxes: “MDOT_Tool 0.9.4_Arcpro3.1”, and “MDOT_Tool 0.9.4_Arcpro2.9.5”, due to versioning issues in the RCN Tool discussed in section 3.3.1.2. In both versions of this toolbox, this tool was labeled “Watershed Delineation”. This version of the tool included KML export functionality, and the Stream Editor tool was introduced in the toolbox. No additional recommendations were reported at this meeting.

The next version of this tool was delivered prior to an in-person meeting at the MDOT Earle building on April 11, 2024, at the MDOT Earle Center. This version of the toolbox was titled “MDOT_tool_0.9.5_AllArcproversions”, and the tool was titled “Watershed Delineation”. The tool was marked as completed barring other recommendations from MDOT or EGLE at this meeting. The “Watershed Delineation” Tool was included in the then-final version of the toolbox, titled “MTU_Hydro_Tool_1.0.4”, and was delivered prior to an in-person meeting at the MDOT Earle Center on April 9, 2025. It is also part of the final version (1.0.5) of the toolset.

Creation of Stream Editor Tool

Based on feedback received at the June 7, 2023 in-person team meeting, the Stream Editor tool (Figure 3.9) was developed. This tool allows the user to either: a) quickly create a new stream layer for a watershed, or b) quickly add to a previously existing stream layer for a watershed. This stream layer can then be used to more accurately hydro-enforce a DEM. This suggestion from MDOT allows for greater control over the flowlines that are incorporated into the hydro-enforced DEM. This tool was introduced prior to the April 11, 2024 in-person meeting, and has been approved in its original format for use based on MDOT and EGLE feedback. MDOT and EGLE staff provided feedback that they have found the tool useful.

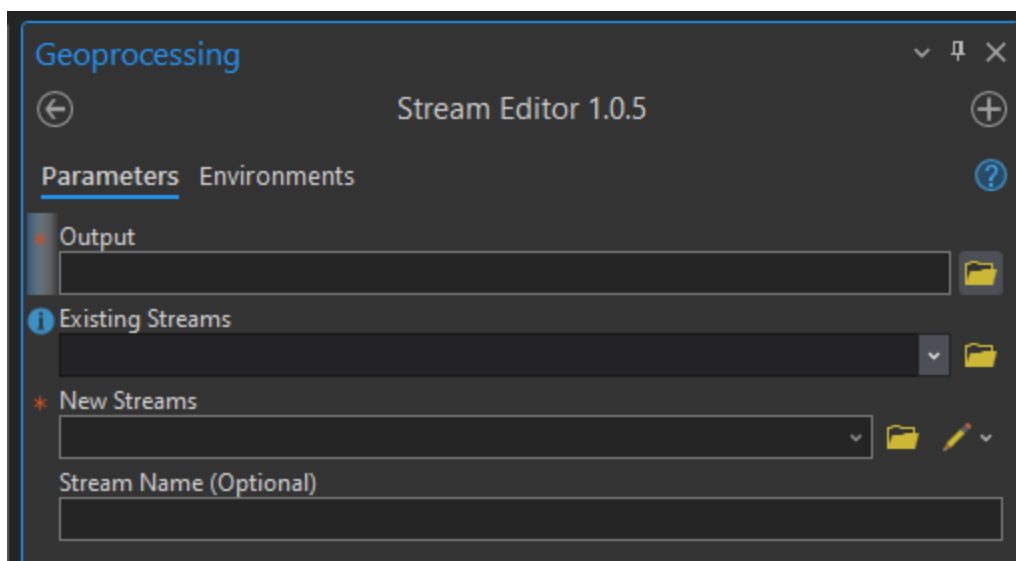


Figure 3.9. Screen-grab of Stream Editor Tool as seen in “MTU_Hydro_Tool_1.0.5.tbx”

3.2.2 Results

3.2.2.1 Updated Method for Small Ungauged Basins

Unit Hydrograph Peak Rate Factor

Table 3.2 provides a summary of the results from the unit hydrograph (UH) analysis. Runoff hydrographs were calibrated for a total of 66 events in 13 watersheds in the Lower Peninsula (LP) and 8 watersheds in the Upper Peninsula (UP). Results for each of the watersheds are shown in Table 6.2 in Appendix A. The lowest average absolute error in the peak discharge was found using a UH peak rate factor (PRF) of 300 in the LP watersheds and 350 in the UP watersheds. Considering all watersheds, the average absolute error was nearly the same for PRF values of 300 and 350. This is in line with several other state studies in areas with flatland and rolling hill landscapes, including Illinois (Melching and Marquadt, 1997), Indiana (Huang and Merwade, 2024), North Dakota (North Dakota NRCS, 2017), Texas (Lasco et al., 2022), North Carolina, and Georgia (Sheridan et al., 2002).

Table 3.2. Summary results of unit hydrograph analysis.

<i>Region</i>	<i>N_events</i>	<i>PRF</i>	<i>ABS(%Err Vol)</i>	<i>ABS(%Err Qp)</i>	<i>ABS(%Err Tr)</i>
Lower Peninsula	45	250	12.6	9.5	25.0
		300	14.2	9.0	25.8
		350	16.3	9.5	25.1
		400	18.6	10.3	26.4
		484	21.6	12.8	26.2
Upper Peninsula	21	250	10.1	9.4	12.0
		300	10.0	8.0	14.0
		350	10.6	7.3	12.6
		400	12.1	7.9	12.6
		484	15.4	10.1	14.0
Statewide Average	66	250	11.8	9.5	20.9
		300	12.9	8.72	22.1
		350	14.5	8.79	21.1
		400	16.5	9.6	22.0
		484	19.7	11.9	22.3

Analysis was done to determine if the PRF values could be related to selected watershed characteristics, including area, slope, percent developed, and percent agricultural land use. Due to the small number of watersheds and variability in the results, statistically significant relationships were not identified. However, other studies have found relationships between PRF and watershed slope (Sheridan et al., 2002; Lasco et al., 2022; Huang and Merwade, 2024). Since the LP watersheds generally have lower slopes (mean 1.77%, range 0.69-3.05%) than the UP watersheds (mean 3.19%, range 1.59-5.74%), it was initially recommended that the state be divided into two zones, with PRF = 300 used for LP watersheds and PRF = 350 used for UP watersheds. However, since only one storm event in one watershed in the eastern UP was analyzed (Black River near Garnet, slope of 1.59%), and PRF = 250 for that event, it is recommended that the region for PRF = 350 be limited to the western UP, specifically the following nine counties: Gogebic, Ontonagon, Houghton, Keweenaw, Baraga, Iron, Dickson, Marquette, and Menominee counties.

Time of Concentration Method

The velocity method for time of concentration (Tc) was applied to 30 small watersheds following the procedures outlined by EGLE staff. To evaluate the potential for developing an automated approach, the NRCS watershed lag method was applied to the same watersheds using GIS-based methods. Specifically, the Longest Flow Path (LFP) tool in ESRI ArcHydro was applied using a 10-meter DEM (or 1-meter DEM where available) to calculate the length of the longest flow path, and the average watershed slope was calculated using the Slope tool with the Spatial

Analyst extension. These values were used with the watershed lag equation (NRCS, 2010) to estimate Tc as follows:

$$T_c = (5/3) * L_{LFP}^{0.8} (1000/CN - 9)^{0.7} / (1900 * S^{0.5}) \quad (\text{Eq. 2})$$

where

L_{LFP} = Length of longest flow path (ft) as determined by GIS

S = Average watershed slope (%) as determined by GIS

CN = Watershed composite Curve Number

Comparison of the Tc values from the watershed lag and velocity methods found that in 28 out of 30 watersheds, the watershed lag method estimated a lower value of Tc than the velocity method, with the average Tc from the lag method equaling 60% of the average from the velocity method (range of 16% to 135%). These results indicate that replacing the velocity method with the watershed lag method in the current procedure would lead to significantly higher peak discharge estimates in most cases.

In addition, to automate a procedure similar to the currently used velocity method, the Flow Path tool was used to obtain the slope of the longest flow path, defined as change in elevation divided by the length between points 10 and 85 percent of the distance along the flow path. Results for each watershed are shown in Table 6.3 in Appendix A. Using regression analysis, the following relationship was found, which is consistent with the velocity method:

$$T_c = 6.165 * L_{LFP} / (S_{LFP})^{0.5} + 1.705 \quad (\text{Eq. 3})$$

where

L_{LFP} = Length of longest flow path as determined by GIS tool (miles)

S_{LFP} = Slope of the longest flow path between 10% and 85% of the length (ft/mile)

A second model was developed to incorporate the watershed CN value as follows:

$$\text{Log}(T_c) = 1.163 - 0.858 * \text{Log}(L_{LFP}) - 0.444 * \text{Log}(S_{LFP}) - \text{Log}(CN - 30) \quad (\text{Eq. 4})$$

Results of the two regression models are shown in Figure 3.10 and Figure 3.11, respectively, indicating the potential for using GIS-based tools to estimate time of concentration.

Concerns expressed by EGLE staff about automating time of concentration calculations were confirmed in two watersheds which were omitted from the regression analysis. In one case, the LFP tool was found to identify the outlet point incorrectly, even with a 1-meter DEM. In another case, the longest flow paths from the topo map and DEM deviated significantly from each other due to urban diversions and swales that resulted in winding flow paths. Based on these limitations, an update to the time of concentration method is not recommended at this time, but automated methods show potential for future application and should continue to be evaluated.

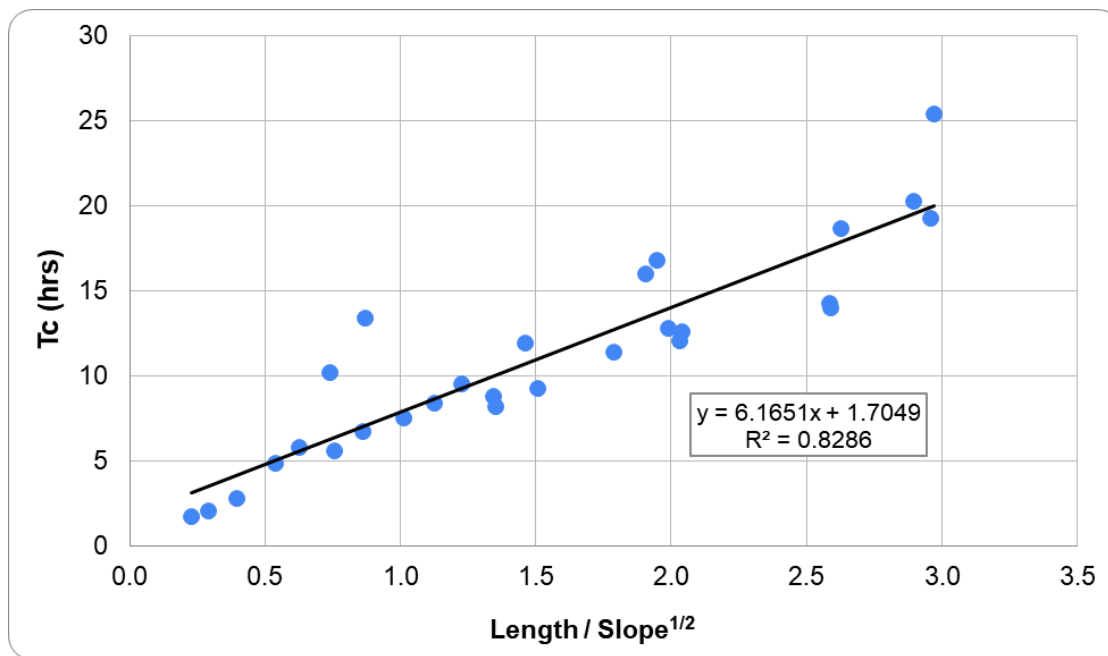


Figure 3.10. Relationship between time of concentration from the velocity method and parameters calculated with the longest flow path tool in ArcGIS Pro ($N = 28$).

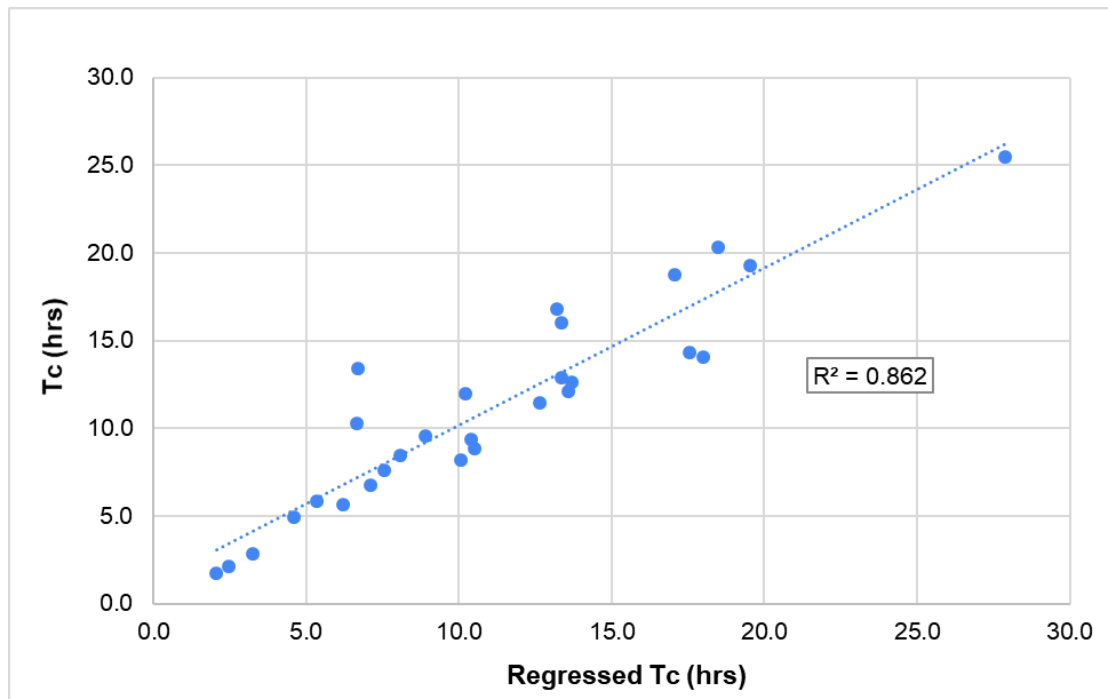


Figure 3.11. Relationship between time of concentration and regression model results based on longest flow path, slope, and watershed CN ($N = 28$).

Unit Peak Discharge Equations

Considering the recommended rainfall distributions (MSE3 and MSE4) and unit hydrographs (PRF = 300, 350), there are four regions in the state for which to develop unit peak discharge equations. Following NRCS procedures for developing state supplements to NOAA Atlas 14, unit peak discharge equations (curves) may be developed by running WinTR-20 for a range of times of concentration and Ia/P ratios of 0.1, 0.25, 0.3, 0.4 and 0.5, where Ia is initial abstraction and P is 24-hour storm rainfall, both in units of inches. Equations relating time of concentration (Tc) to unit peak discharge are then developed in the following form:

$$q_u = 10 ^ { (C1 + C2 * LOG(Tc) + C3 * (LOG(Tc))^2) } \quad (Eq. 5)$$

where q_u is the unit peak discharge (cfs/in-mi²), Tc is in units of hours, and C1, C2, and C3 are coefficients to fit the equation to WinTR-20 outputs.

Results are shown in Figure 3.12 and Table 3.3 for the MSE3 rainfall distribution with a UH PRF of 300. Complete results for Michigan are provided in Appendix A, Figures 6.1-6.3 and Table 6.4, for each region and for Tc values ranging from 1 to 40 hours. For Tc values greater than 15 hours, the unit peak discharge curves converge, and thus a single equation (curve) is derived for each region for Tc values ranging from 15 to 40 hours. For different values of Ia/P (ranging from 0.1 to 0.5), linear interpolation of the coefficients in Eq. (5) is recommended. It is also recommended to use a minimum Ia/P of 0.1 and a maximum of 0.5 (McCuen, 1989).

The coefficients in Eq. (5) were derived for Tc values between 1 and 40 hours. When evaluated for Tc values less than 1 hour, considering all four MSE/PRF regions, they were found to have no more than 5.2% error for Tc values as low as 0.5 hour. However, errors increase significantly for lower Tc values, reaching 20-30% for Tc = 0.1 hr.

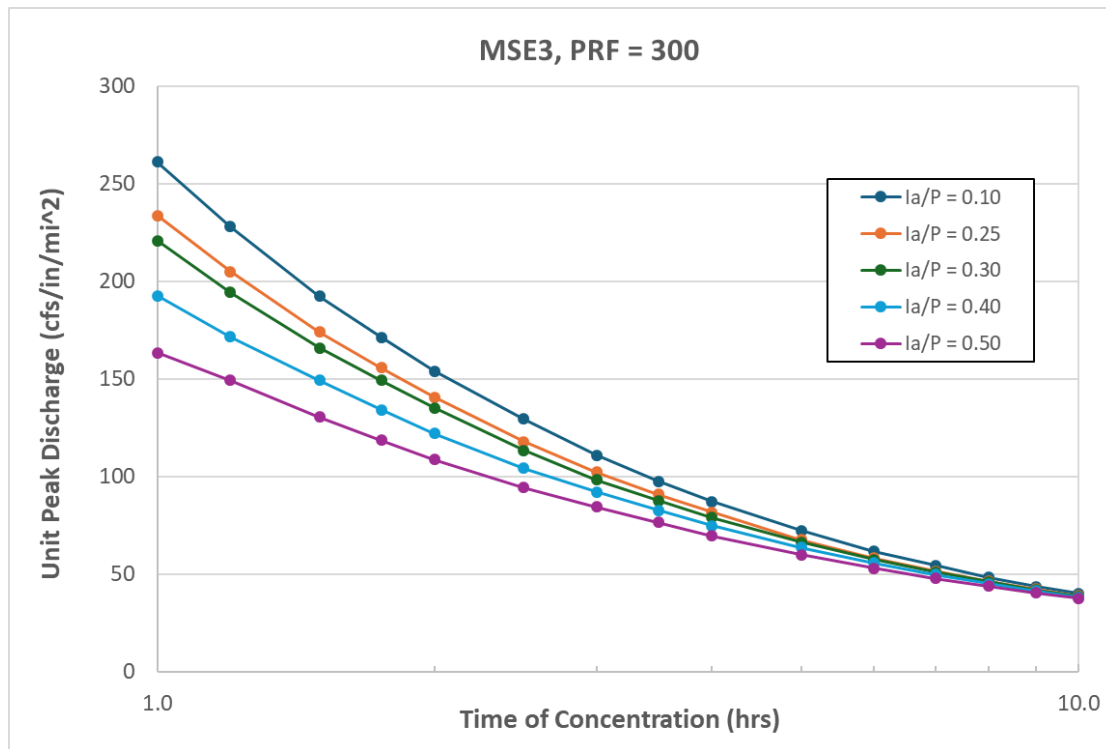


Figure 3.12. Unit Peak Discharge Curves for MSE3, PRF = 300.

Table 3.3. Unit Peak Discharge Equation Coefficients: MSE3, PRF = 300 ($T_c = 1$ to 15 hrs).

I_a/P	C1	C2	C3
0.1	2.4196	-0.7585	-0.0579
0.25	2.3730	-0.7482	-0.0336
0.3	2.3483	-0.7261	-0.0340
0.4	2.2875	-0.6510	-0.0541
0.5	2.2176	-0.5788	-0.0656

Pond and Swamp Adjustment Factor

The current EGLE SCS method (Sorrell, 2010) includes peak discharge reduction factors based on the ratio of ponding or swampy area (as shown by the USGS map symbol for “marsh”) to the total drainage area for a range of flood frequencies. Different adjustment factors are specified depending on where the ponding occurs in the watershed. It is stated that these values were determined by the NRCS (1975) for watersheds of less than 2,000 acres (3.1 mi²), but the factors may be used for larger basins until newer data become available. For percentages beyond the range in the tables (up to 20%), it is suggested that the data may be extrapolated on semi-log

paper with the reduction factor on the log scale. It is also stated that the adjustment may be applied more than once, i.e., an adjustment factor for scattered ponding throughout the watershed may be further reduced by a factor for ponding near the design location. For example, if the two separate adjustment factors are 0.8 and 0.9, respectively, the total reduction factor would be 0.72.

The original publication *Urban Hydrology for Small Watersheds, Technical Release No. 55* (NRCS, 1975) was not located by the project team, and the second edition (NRCS, 1986) includes only a small table (Table 4.2) of adjustment factors for percentages of pond and swamp areas up to 5% of the watershed. However, the textbook *Hydrologic Analysis and Design* by McCuen (1989) provides a detailed presentation of the NRCS Graphical Peak Discharge Method, including more extensive tables of pond and swamp adjustment factors similar to those in Sorrell (2010). As in NRCS (1986), but unlike Sorrell (2010), these tables also do not extend above 5% for the percentage of pond/swamp area – the final row in each table is “5.0[%] or greater.” Further, McCuen does not mention the procedure of applying the adjustment factor more than once, but indicates that one of the tables should be selected based on the primary location of pond/swamp area in the watershed. McCuen also states that the factor is not to be applied for pond/swamp areas that are within principal drainage ways, consistent with NRCS (1986) guidance that the adjustment factors can be applied only for ponds/swamps that are not in the T_c flow path.

Based on this review, it is recommended that the ponding adjustment factor be applied with caution, particularly in watersheds larger than 3 mi², where the percentage of pond/swamp area exceeds 5% of the total watershed area, or where adjustment factors are applied more than once. In the tables provided by McCuen (1989), which match the values in Sorrell (2010) for up to 5% of the watershed area, the adjustment factors for 5% or greater of pond/swamp area occurring near the design point range from 0.59-0.75 for the 2-yr to 100-yr frequency storms. For 5% or greater of pond/swamp areas occurring in upper reaches and central areas (or scattered throughout), the adjustment factors range from 0.80-0.88 and 0.65-0.78, respectively. Caution is recommended for applying adjustment factors below these values as they may be extrapolated from the original experimental data.

3.2.2.2 Validation and Model Comparisons

The updated procedure for small watersheds (contributing drainage area less than 20 mi²) was implemented using WinTR-20 with NOAA Atlas 14 rainfall frequency values and county-specific rainfall distributions (MSE3 or MSE4). The unit hydrograph PRF value was set to 300 for Lower Peninsula watersheds and 350 for Upper Peninsula watersheds (the U.P. watersheds under 20 mi² were all in the western counties). Runoff curve numbers (RCNs) were based on the NCLD21-MTRI land cover database. Time of concentration estimates were based on the velocity method, following EGLE procedures. Outputs from WinTR-20 were multiplied by ponding

factors, which were also developed using EGLE procedures. Results were generated for 31 small watersheds located throughout the state.

Results from the updated procedure were first compared to results from the current EGLE modified SCS method. As shown in Figure 3.13, discharge estimates from the updated procedure were consistently higher than estimates from the current method. For return periods of 10- to 100-years, estimates from the updated procedure ranged from 14% to 40% higher than previous estimates, on average, based on linear regression models fit to the estimates. The increased estimates from the updated procedure are attributed to updated rainfall frequency values in NOAA Atlas 14, as well as the updated rainfall distributions (MSE3 and MSE4), which have higher peak intensities than the previously used SCS Type II distribution. The updated unit hydrograph PRF values partially offset the increased rainfall intensities in the Lower Peninsula watersheds, where WinTR-20 runs with PRF = 300 resulted in approximately 15% lower peak discharges than runs with PRF = 350.

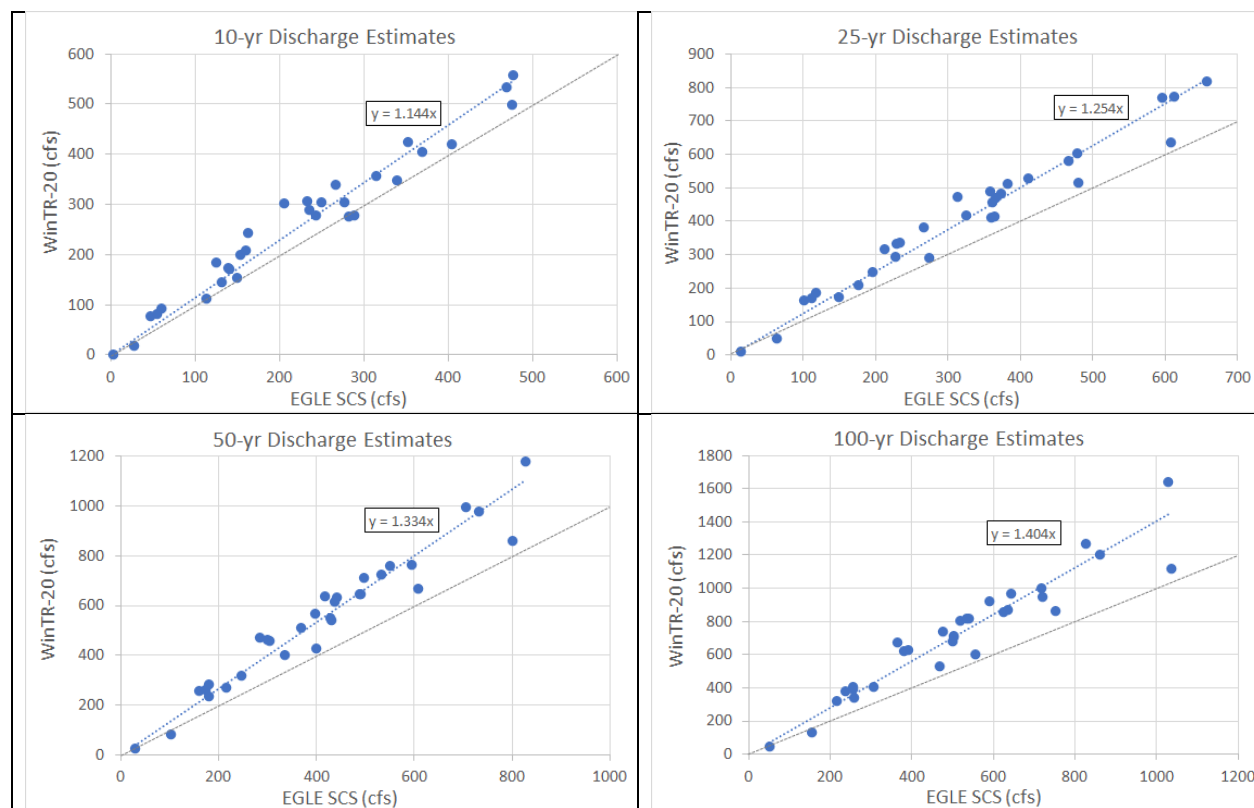


Figure 3.13. Comparison of results from the updated method implemented in WinTR-20 and the current EGLE modified SCS method. Shown on each graph are the 1:1 (45-degree) line and a linear regression with the intercept fixed at zero.

Results from the updated procedure were also compared with streamflow statistics at each gage site, based on Bulletin 17C procedures (England et al., 2018) implemented in the USGS software

PeakFQ version 7.5.1 (Flynn et al., 2006). As shown in Figure 3.14, discharge estimates from the updated procedure were generally lower than site statistics for the 10-year return period, and there was no systematic bias at the 25-year return period. However, for return periods of 50 and 100 years, estimates from the updated procedure were generally higher than site statistics. For the 50-year return period, estimates from the updated procedure were higher than gage statistics for 18 out of 31 sites, and for the 100-year return period, estimates from the updated procedure were higher than gage statistics for 21 out of 31 sites.

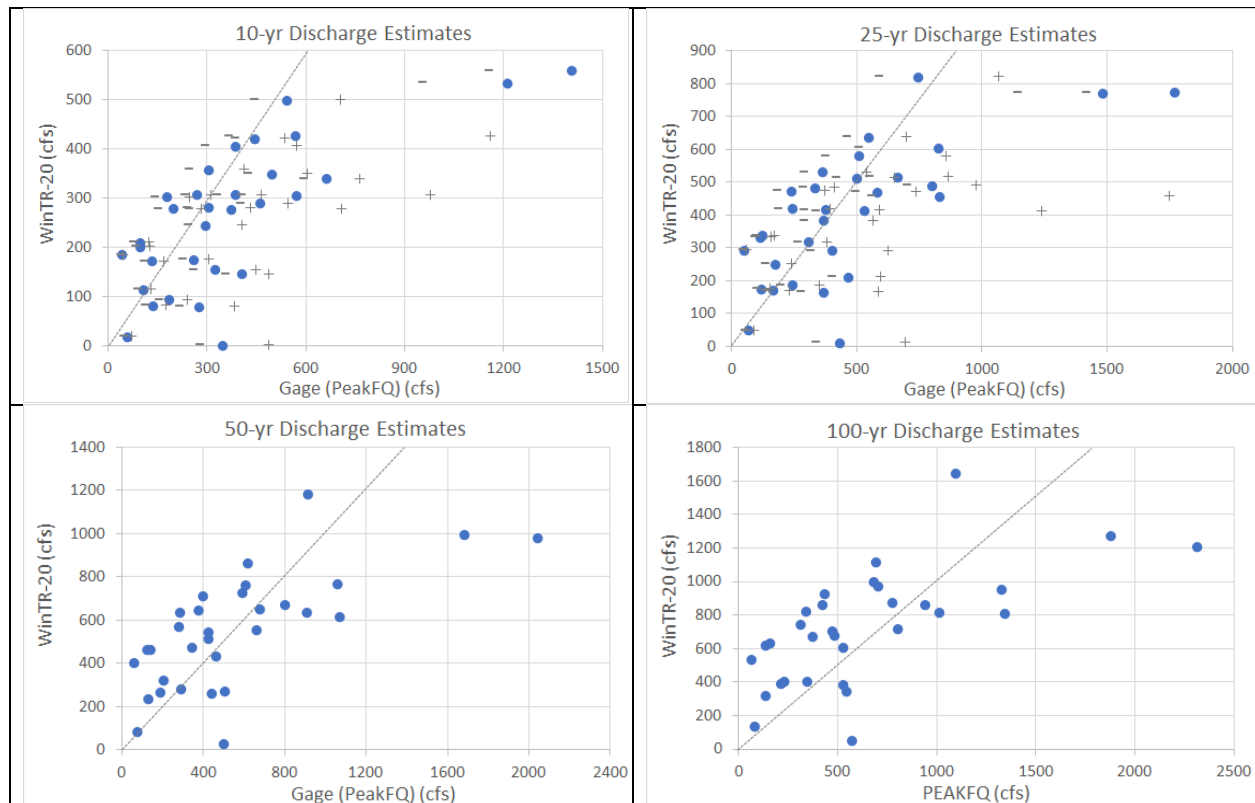


Figure 3.14. Comparison of results from the updated method implemented in WinTR-20 and site statistics from PeakFQ software. Shown on each graph is the 1:1 (45-degree), along with 5% (-) and 95% (+) confidence limits on the site estimates.

3.2.2.3 Automated Processes

Seventeen (17) watersheds in 17 counties were selected, in consultation with MDOT and EGLE, to determine functionality in automated hydro-enforcement and watershed delineation processes. The full list of test watersheds is shown in Table 3.4.

Table 3.4. Watersheds used to demonstrate functionality of the MTU Hydro-enforcement and Watershed Delineation tools.

Hydro-enforcement and Watershed Delineation Tested Watersheds	
Watershed Name	County
Little Rabbit River	Kent and Allegan
Blackwood Drain	Oakland
Peach Orchard Drain	Allegan
Duck Creek	Muskegon
Schnable Brook	Otsego
Hartel Drain	Sanilac
S Branch Pentwater River	Oceana
Little Swan Creek	Monroe
Mallets Creek	Washtenaw
Kalamazoo River	Allegan and Ottawa
Deer Creek	Houghton
Macatawa River	Allegan and Ottawa
Smith Creek	Cheboygan
Upper River Rouge	Oakland
Coon Creek	St. Clair and Macomb
Ogontz River	Delta
Tributary to Whaley Drain	Ingham

Figure 3.15 displays a hydro-enforcement comparison done in the Blackwood watershed in Oakland County. This figure displays the difference in a 2m DEM acquired through Michigan DTMB before and after hydro-enforcement. It also displays the difference in watersheds delineated with EGLE’s traditional workflow, compared to a watershed delineated using the automated Watershed Delineation tool and based on the hydro-enforced 2m DEM.

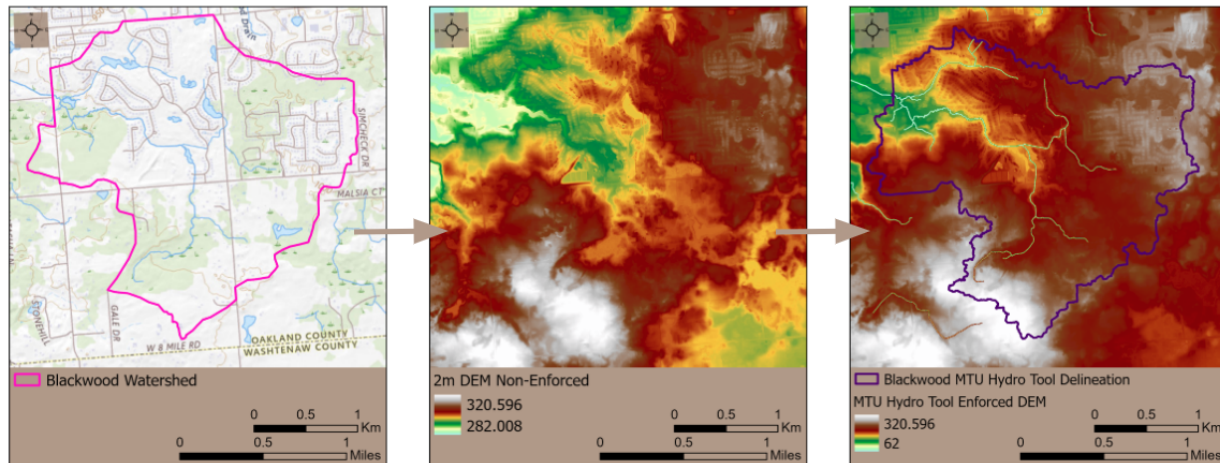


Figure 3.15. Side by side comparison of Blackwood watershed in Oakland County, MI. The left figure displays a watershed delineation based on a USGS 7.5' topographic map for the county. The middle figure shows the 2m LiDAR DEM provided for this area by the Michigan Department of Technology, Management & Budget (DTMB). The right figure shows both the results of a 200m stream burn-in on the 2m DEM, and a watershed delineation created based on the hydro-enforced DEM.

Figure 3.16 displays the difference for flow accumulation values between a hydro-enforced watershed and a non-hydro-enforced watershed in Little Rabbit watershed in Allegan and Kent counties. The non-hydro-enforced watershed has a pooling effect which results in a weaker delineation that is not likely to capture the watershed boundary accurately. With hydro-enforcement, water can flow and accumulate through the DEM raster cells during the watershed delineation process, resulting in a watershed boundary that better represents what most users would consider accurate, such as corresponding to ridgelines draining down to a common pour point.

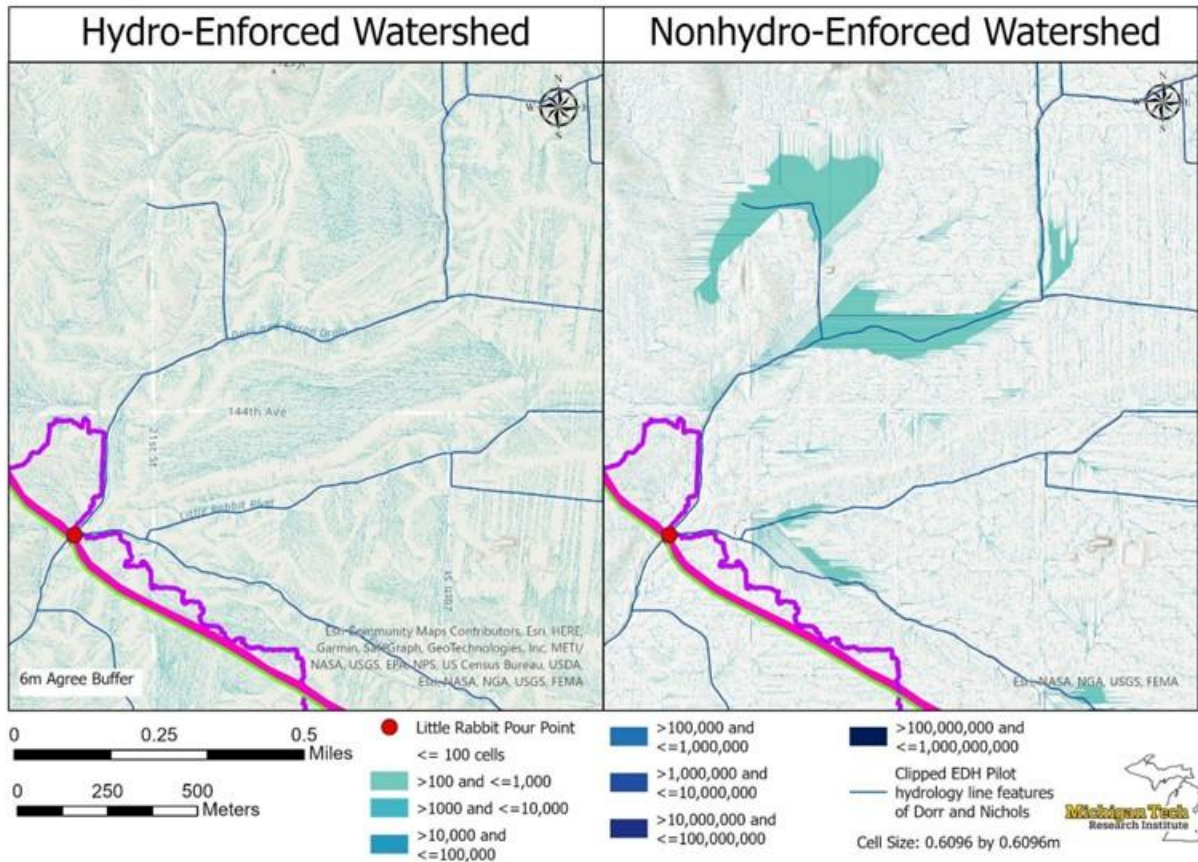


Figure 3.16. Comparison of flow accumulation values with and without hydro-enforcement of the DEM.

Figure 3.17 displays a comparison conducted in the Upper Rouge River in Oakland County. This analysis compared a watershed delineated with the traditional workflow implemented by EGLE, a watershed delineated with the Watershed Delineation Tool with a non-enforced DEM, and a watershed delineated with the Watershed Delineation Tool with a hydro-enforced DEM. The watershed boundary delineated automatically with the tool captures the ridgelines represented in the DEM, with the hydrology lines burned into the DEM to help this happen. Figure 3.18 shows the result of using the Stream Editor to improve watershed delineation for an area in Cheboygan, MI.

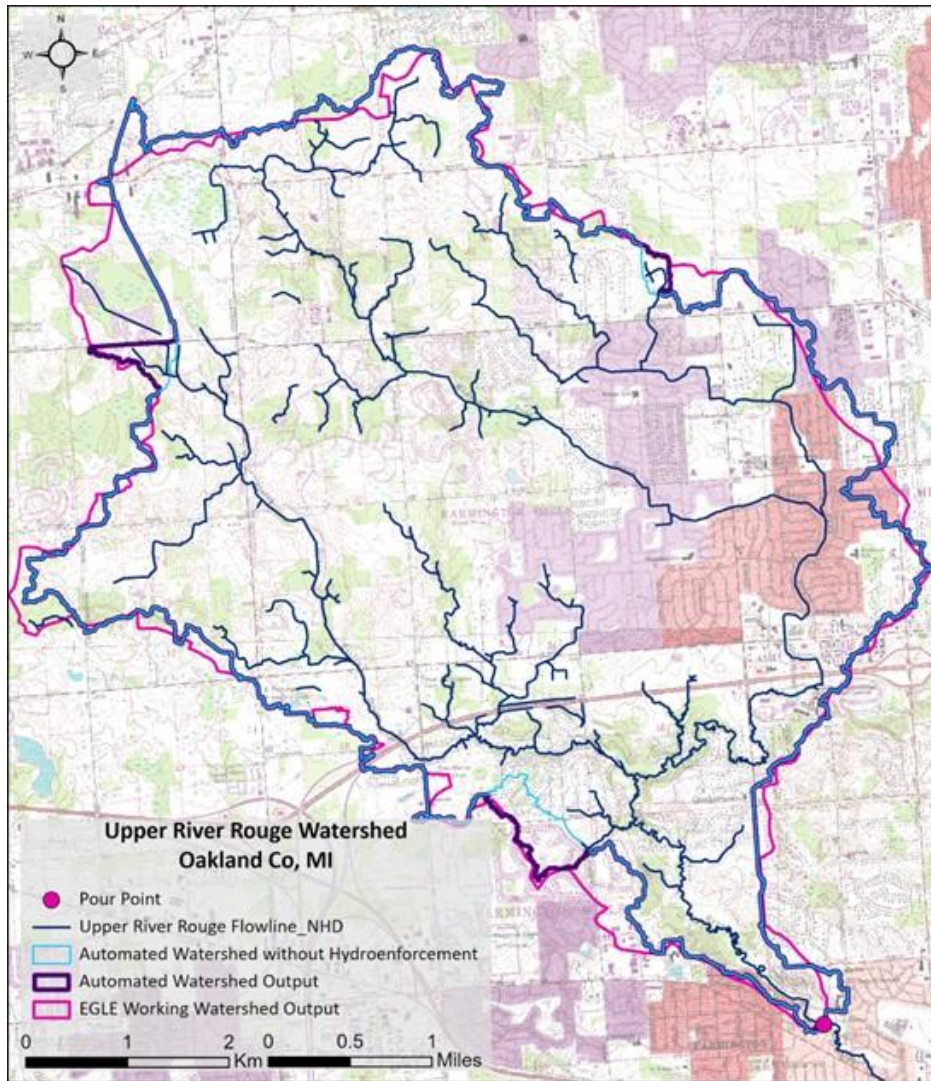


Figure 3.17. Upper River Rouge watershed delineation comparison.

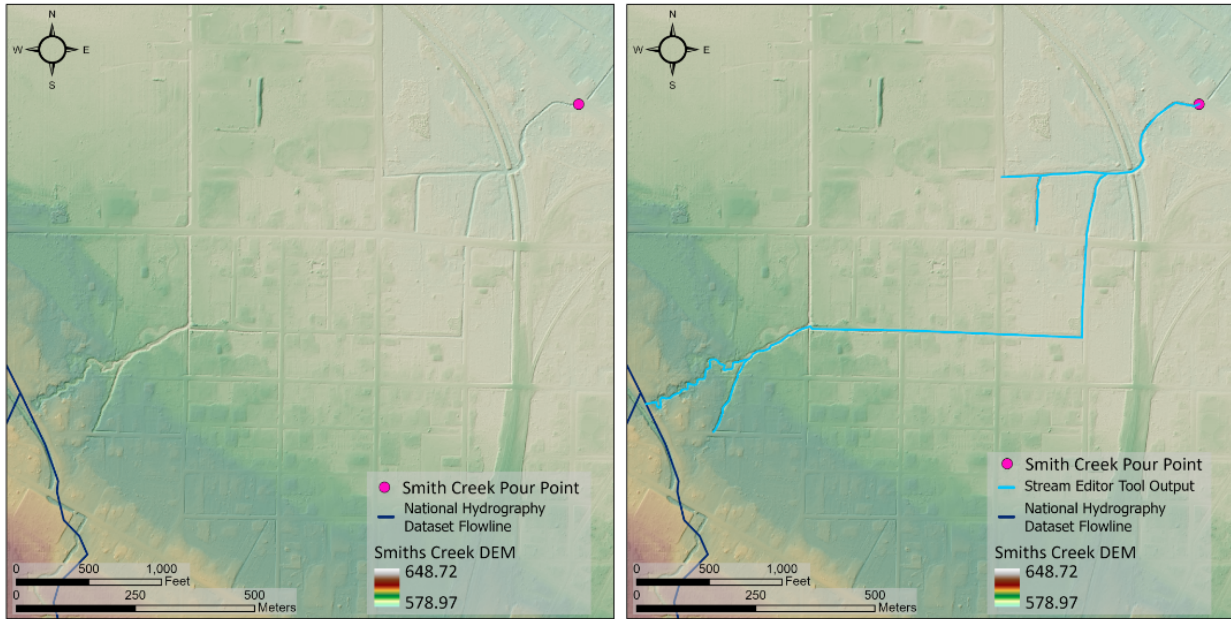


Figure 3.18. Example of Stream Editor tool output being used in Smiths Creek in Cheboygan County. In this watershed, the National Hydrography Dataset (NHD) flowline that was being utilized did not include a polyline for the creek featured in the figure. The image on the left depicts the original NHD polyline, and the image on the right depicts the NHD polyline dataset with the added stream editor output polyline, which has been joined to the original dataset.

3.2.3 Recommendations

The recommended procedures for analyzing small watersheds with a modified SCS Curve Number method, including updated data, methods, and tools from this study, are as follows:

1. Delineate watershed area manually from 2023 Topo maps in ArcGIS Pro, including ponded and non-contributing areas.
 - a. Compare manual delineation to automated delineation from DEM data using the MTU Hydro Toolbox, using automated processes whenever possible to speed up delineation.
 - i. Use the Stream Editor tool where hydrology lines need to be added or changed.
 - ii. Use the Hydro-enforcement tool as a standard process in automated delineation to improve accuracy of watershed boundaries that will match the input DEM data.
2. Calculate Tc using the velocity method and manual digitization from 2023 Topo maps, following rules for flow path types.
 - a. Compare manual delineation to results of the Longest Flow Path tool in ArcHydro with DEM data.

- b. Apply one (or both) of the regression models developed in this study to compare time of concentration estimates.
3. Determine the composite RCN using the RCN tool with the either MTRI/NLCD combined land cover data set or the NLCD-only data set, as preferred by MDOT and EGLE, with SSURGO.
4. Use precipitation frequency values and rainfall distributions from NOAA Atlas 14, Volume 8.
 - a. Lookup precipitation frequency values by TR zone.
 - b. Intersect watershed area with TR grid to compute spatial average rainfall.
 - c. Apply area reduction factor for watersheds over 10 mi².
 - d. Select 24-hr rainfall distribution (MSE3 or MSE4) based on county
5. Compute unit peak discharge factor, q_u , based on time of concentration.
 - a. Relationship between unit peak discharge factor and time of concentration depends on rainfall distribution (MSE3, MSE4) and unit hydrograph peak rate factor (300, 350).
6. Multiply by ponding factor
 - a. Use factors from current EGLE SCS spreadsheet.
 - b. Recommend caution if watershed is larger than 3 square miles, pond/swamp area is greater than 5% of the watershed area, or if more than one adjustment factor is applied.

3.3 Analyze GIS Data for Developing SCS Runoff Curve Numbers

3.3.1 Methodology

3.3.1.1 Update Land Use/Land Cover Datasets

As described at the beginning of this project, a range of new GIS data have become available since the current hydrologic analysis methods were developed. Advantages of using new land cover datasets include improved spatial resolution, representation of recent changes in land cover, higher land cover classification accuracy and detail, and simplification of the data format. Using either NLCD land cover alone, or NLCD/MTRI land cover to obtain improved wetlands information, is likely to lead to RCN values more representative of the current landscape than continuing to use an almost 50-year-old MIRIS layer. Our team began the process of updating the land use/land cover dataset by first conducting an analysis of the dataset currently used by MDOT and EGLE for SCS Runoff Curve Number (RCN) calculations, then analyzing and trying potential updated datasets.

The dataset currently being used by EGLE is the Michigan Resources Information System (MIRIS). This is a land use dataset that was compiled by the Michigan Department of Natural

Resources (MDNR) in 1978, using a combination of county and regional planning commission data with interpretation of color infrared aerial photography from the mid-1970s (EGLE 2021). The resolution of this dataset is 100 meters according to its metadata.

The two datasets being analyzed in this project are: 1) the National Land Cover Database (NLCD), and 2) the MTRI IDS 2010 dataset. The NLCD is produced by the USGS Multi-Resolution Land Characteristics Consortium (MLRCC) (<https://www.mrlc.gov/data>). This land cover product is updated periodically, normally every two years, with the most recent version of the NLCD showing 2021 land cover, and derived products such as urban imperviousness and tree canopy as a raster with 30-meter pixel size. One significant advantage of this dataset is that it provides land cover information using consistent classes across a large area over an extended period of time starting from 2001, and it should be updated regularly in the future.

The MTRI IDS 2010 dataset was created by MTRI for the Great Lakes Basin, with partial funding from a NASA Inter-Disciplinary Science (IDS) research project. It is a 12.5-meter resolution land cover dataset that provides recent, accurate wetland types for the Great Lakes region not available from other landcover datasets. This map was generated using a combination of optical and synthetic aperture radar (SAR) imagery to enable better distinction between land cover types (<https://www.mtu.edu/mtri/research/project-areas/environmental/wetlands/coastal-wetland-mapping/>; Bourgeau-Chavez et al. 2015).

Creation of combined NLCD/MTRI 2019 and 2021 land cover layer

The MTRI team built two combined raster datasets to demonstrate feasibility of a combined NLCD/MTRI Wetlands Landcover dataset, creating a layer that had the recentness of NLCD data and the useful Great Lakes wetlands type of the MTRI wetlands layer. The first dataset was completed in August of 2022, and used the 2019 iteration of the NLCD land cover dataset that was available at the time, and the wetland areas by type from the 2010 MTRI IDS Wetland Classification dataset. The second dataset was completed in April of 2024, and used the 2021 iteration of the NLCD land cover dataset that had recently been released, also merged with the wetlands from the 2010 MTRI wetland classification dataset. This work was done due to critiques made by EGLE regarding the lack of wetland classification in the NLCD datasets. NLCD only has two wetland classifications: “Woody Wetlands” and “Emergent Herbaceous Wetlands”. The 2010 MTRI wetland classification datasets enable the user to have greater accuracy in RCN calculation for 7 additional wetland types. These wetland types can be seen in Figure 3.19(b), with “_MTRI” behind the class name, and include Aquatic Bed, Wetland, Open Peatland, Wetland Shrub, Forested Wetland, Shrub Peatland/Treed Peatland, and Typha/Phragmites. The Shrub Peatland/Treed Peatland is a combination of two MTRI wetland classes, and was combined with the NLCD Woody Wetland class, and Typha/Phragmites is a combined pair of MTRI wetland classes, then combined with the NLCD Emergent Herbaceous class. This was done based on the expert input of Michael Battaglia, a MTRI employee who was

a co-author of the Bourgeau-Chavez et al. 2015 article that documents the process used to create these landcover types.

The workflow to build this merged landcover dataset is described in Figure 3.19(a) and is intended to be repeatable by GIS-knowledgeable staff in the future as needed, whenever a new NLCD layer is available. This workflow primarily depends on the use of the Raster Calculations geoprocessing tool to ensure that each land cover class has an individual value so classes are not overwritten when they are combined in the Mosaic to New Raster tool. Figure 3.19(b) shows the combined land cover types in the NLCD/MTRI layer. It is also important to update the RCN table used in the RCN tool when creating values for individual land cover classes so that RCN values come out as expected. An example of an updated RCN table is shown in Figure 3.19 below. MDOT and EGLE staff should review this type of table whenever integrating an updated source of land cover data, such as future NLCD datasets.

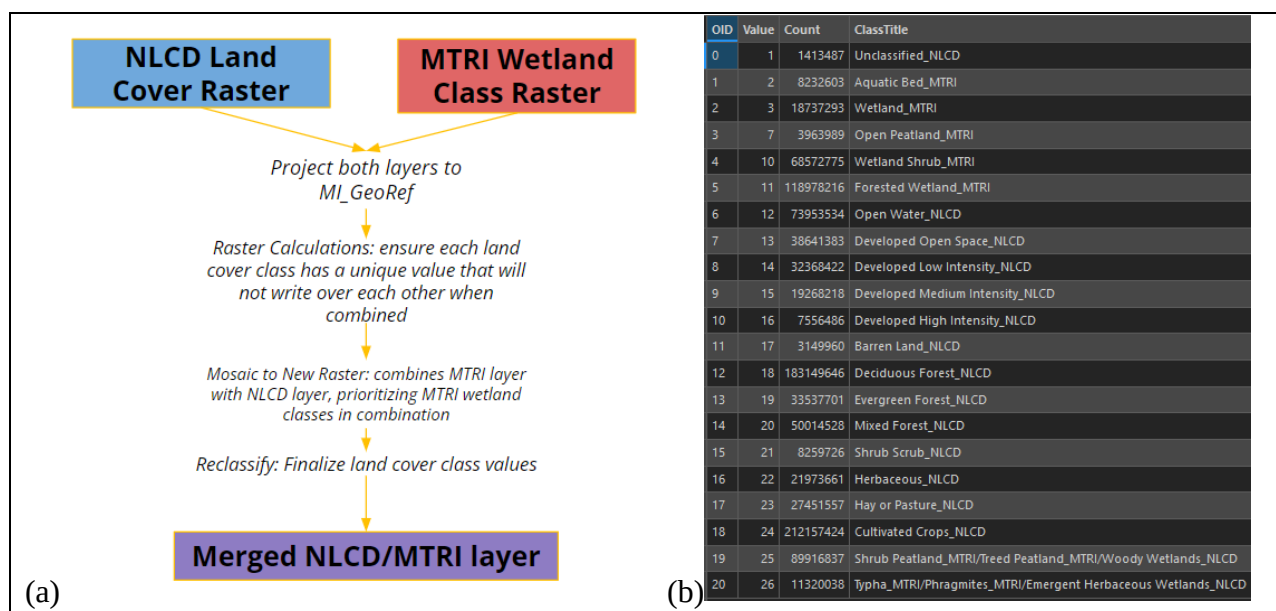


Figure 3.19. a) Abbreviated walkthrough on the process to combine two land cover datasets. b) Screen grab of the attribute table of the output NLCD/MTRI 2021 raster dataset.

Calculating RCN values using the SCS method

The workflow to calculate RCN depends on the intersection of two spatial layers (LULC and Soil layers) and four table joins (LULC, including land use for MIRIS, landcover for NLCD/MTRI and NLCD; general soils; county specific soils; and RCN). Following the MIRIS workflow, the joins follow as such, according to Susan Greiner:

“In the soils layer, the county-specific table is joined based on the MUSYM field, then the soils2cn_93 table is joined based on the hydrologic soil group. The land use table is

joined to landuse-cn2. Then the two layers are intersected. Value (from the soils layer) and Class (from the land use layer) are then summed, and the rcn-cn2 table is joined based on the field containing the sum of class and value.” (Greiner, 2021)

In order to understand the full workflow for the RCN tool, please refer to “Watershed Composite RCN Layer Intersection Workflow” in Appendix E. This documents EGGLE’s RCN workflow utilizing the SCS method.

In order to evaluate alternative datasets for automated workflows, updated LULC and RCN tables had to be created. First, to create updated LULC tables, the MTRI team built a spreadsheet to compare the classes in the three datasets, as shown in Figure 3.20 and in Appendix E in more detail. Through this comparison, a reasonable metric was generated to create “Class” values for the NLCD and MTRI land cover classes that could be incorporated into the RCN workflow.

Class	1						2						3		4						5						
IGDS Code	1	11	111	112	113	115	12	121	122	123	124	126	13	138	14	141	142	143	144	145	146	17	171	172	173		
IGDS Description	Urban	Residential	Multi-Family: High Rise	Multi-Family: Low Rise	Single Family	Mobile Home Park	Commercial	Primary/Center Business District	Shopping Center/Mall	Strip Commercial	Secondary/Neighborhood Business	Institutional	Industrial	Industrial Park	Transportation	Air Transportation	Rail Transportation	Water Transportation	Road Transportation	Communications	Utilities	Extractive	Open Pit	Underground	Wells		
MIRIS	residential						commercial, services, and institutional						Industrial		Transit, communication, utilities						Extractive						
NLCD-MTR Crosswalk	Developed, High Intensity	Developed, Medium Intensity	Developed, High Intensity	Developed, Medium Intensity	Developed, Low Intensity	Developed, Low Intensity	Developed, High Intensity						Developed, High Intensity		Developed, High Intensity						No Equivalent in NLCD						
SCS Runoff Crosswalk	res 1/8 acre	res 1/3 acre	res 1/8 acre	res 1/4 acre	res 1 acre	res 1/4 acre	Commercial						Industrial		paved	paved	paved	Industrial	paved	Industrial	Industrial	No Equivalent in SCS					
Class	6			7			8			9			10			11											
IGDS Code	19	193	194	2	21	29	22	23	24	3	31	32	33	4	41	42	411	412	413	414	421	422	423	429			
IGDS Description	Open Land	Outdoor Recreation	Cemeteries	Agriculture	Cropland	Other Agriculture	Orchards	Confined Feeding	Permanent Pasture	Open Field	Herbaceous	Shrub	Prairie	Woodland	Deciduous	Coniferous	Northern Hardwood	Central Hardwood	Aspen/White Birch	Lowland Hardwood	Pine	Other Upland Conifer	Lowland Conifer	Christmas Tree Plantation			
MIRIS	open and other			cropland, rotation, and permanent pasture			orchards, vineyards, and ornamental			confined feeding operations			permanent pasture			herbaceous rangeland			shrub rangeland			pine or oak opening (savanna)			forest land		
NLCD-MTR Crosswalk	Developed, Open Space			Cultivated Crops			Cultivated Crops			Hay/Pasture			Herbaceous			Shrub/Scrub			Herbaceous			Mixed Forest			Deciduous Forest		
SCS Runoff Crosswalk	open good: grass cover > 75% of area	open good: grass cover > 75% of area	open fair: grass cover 50-75% of area		Crop	Crop	Orchard	Industrial	Pasture		Meadow	Forest	Meadow														
Class	12					13					14					15			16	17							
IGDS Code	5	51	52	53	54	6	61	611	612	624	62	621	622	623	7	72	73	74	999								
IGDS Description	Water	Stream	Lake	Reservoir	Great Lakes	Wetland	Forested Wetland	Wooded Wetland	Shrub/Scrub Wetland	Submerged Aquatics	Nonforested Wetland	Aquatic Bed Wetland (non-forested)	Emergent Wetland	Flats Wetland	Barren	Beaches and Riverbanks	Sand Dune	Exposed Rock	Unidentified								
MIRIS		streams and waterways	lakes	reservoirs	great lakes	wetlands									Barren	beaches and riverbanks	Sand other than beaches	have exposed rock									
NLCD-MTR Crosswalk	Open water					Wetlands (NLCD includes Shrub, Peatland and Treed Peatland from MTRI)	Forested Wetland (MTRI)	Wetlands (NLCD includes Shrub, Peatland and Treed Peatland from MTRI)	Wetland (MTRI)	Aquatic Bed (MTRI)	Wetland (MTRI)	Aquatic Bed (MTRI)	Emergent Wetlands (NLCD includes Typha and Phragmites from MTRI)	Open Peatland (MTRI)	Barren Land			Barren Land	Unclassified								
SCS Runoff Crosswalk	Water					swamp veg					swamp w /water at least 1/3 is open					swamp veg					Fallow						

Figure 3.20. LULC dataset comparison, in which the MTRI team worked to find reasonable comparisons in the NLCD and MTRI land cover datasets against the MIRIS land use dataset. A larger version of this figure can be found in Appendix E.

Second, RCN tables had to be created that could be used with the NLCD/MTRI and NLCD datasets. These tables were created through analyzing the RCN table provided for the MIRIS 1978 dataset, which can be seen in Figure 3.21. This table has one column titled ‘Comp-Code’, which joins with the sum of the ‘Class’ column in the Landuse table, and the ‘Value’ column in

the General Soils table. This match-up is then used to match an RCN to a combination of soil and land use (for example, a polygon within an analyzed watershed with a soil value of 100 and a land use class of 1 receives an RCN of 77).

General Soils Table

	OID	SoilClass	Value
1	0	A	100
2	1	A/B	200
3	2	A/C	300
4	3	A/D	400
5	4	B	500

SumClassvalue
 $"100" + "1" = "101"$

MIRIS RCN Table

	OID	COMP-CODE *	RCN
1	0	101	77
2	1	102	89
3	2	103	81
4	3	104	98
5	4	105	0
6	5	106	39
7	6	107	65
8	7	108	45
9	8	109	49

	OID	IGDS_TEXT	CLASS	CODE	DESCRIPTIO
1	0	1	1	1	Urban
2	1	11	1	1	Residential
3	2	111	1	1	Multi-Family: High Rise
4	3	112	1	1	Multi-Family: Low Rise
5	4	113	1	1	Single Family
6	5	115	1	1	Mobile Home Park
7	6	12	2	1	Commercial

MIRIS Landuse Table

Figure 3.21. Workflow to find RCN based on land use table and general soils table for the MIRIS land use layer. This workflow is fully described in the RCN Tool workflow document in Appendix B.

Figure 3.22 below displays the RCN table that was created by MTRI to be used for the merged NLCD/MTRI 2019 and 2021 landcover datasets. This table has four columns - the first is Classvalue, which is the equivalent to CompCode in the MIRIS RCN table. RCN Updated displays the RCN values given to Classvalues that match up to NLCD classes only. RCN values in this column were determined using a land use and soil lookup table generated by the United States Army Corps of Engineers (USACE 2023). The Crosswalk Column was created through assigning RCN values based on the comparison crosswalk created between the MIRIS, NLCD, and MTRI datasets. The USACE column was created through assigning MTRI landcover classes RCN values based on the comparison crosswalk created between the MIRIS, NLCD, and MTRI datasets, and assigning NLCD landcover classes with RCN values generated by the USACE (2023). If using the NLCD only landcover, the table is similar and is shown in Figure 3.23.

Classvalue	RCNUpdated	Crosswalk	USACE
114	<Null>	85	85
414	<Null>	85	85
514	<Null>	85	85
714	<Null>	85	85
814	<Null>	85	85
914	<Null>	85	85
1014	<Null>	85	85
1014	<Null>	85	85
107		67	65
407		89	65
507		78	76
707		89	76
807		85	84
907		89	84
1007		89	88
1007		89	88
111		45	45
411		83	79
511		66	60
711		83	79
811		77	73
911		83	79
1011		83	79
1011		83	79
101		81	77
401		93	77

Generated by adding "Value" in the General Soil table to "Class" in the land use/cover layer

NLCD 2019 Curve Numbers assigned by United States Army Corps of Engineers

NLCD 2019 and MTRI 2010 outputs based on mimicking MDOT workflow for MIRIS

NLCD 2019 assigned USACE curve numbers, MTRI 2010 layers based on mimicking MDOT workflow for MIRIS

Figure 3.22. Descriptions of each column in the RCN table generated to match the NLCD/MTRI 2019 and 2021 land cover datasets.

Classvalue	RCNNLCD
114	30
414	78
514	58
714	78
814	71
914	78
1014	78
1014	78
107	67
407	89
507	78
707	89
807	85
907	89
1007	89
1007	89

Generated by adding "Value" in the General Soil table to "Class" in the land use/cover layer

NLCD 2019 Curve Numbers assigned by United States Army Corps of Engineers

Figure 3.23. The RCN table created for use with the NLCD only landcover layer.

3.3.1.2 Develop GIS Tools

The MTRI team leveraged previously developed RCN workflows created by EGLE to generate an automated process in ArcGIS Pro, described below.

Development and workflow of RCN Tool

Development on the RCN Tool began in May 2023. This tool was developed to follow the workflow created by Susan Greiner and EGLE to conduct SCS analyses. The initial development of this tool came from an interpretation of the ArcView Avenue code, 'LWM_rcn.ave,' provided by S. Greiner from an existing script developed in the late 1990s by previous staff members; Avenue code was used in ESRI ArcView prior to the implementation of ESRI ArcMap in the early 2000s. This algorithm operates under the methodology for calculating RCN under the SCS method (Sorrell 2010). This workflow combines a hydrologic soil group and a land use/treatment class into a hydrologic soil-cover complex, each of which is assigned an RCN value. This is an index to its runoff potential on soil (Sorrell 2010). Greiner's algorithm for processing this analysis was transformed from an ArcView script into an up-to-date Python script usable in ArcGIS Pro 2.9.x and 3.x, which could be implemented as a Geoprocessing tool within the MTU

Hydro Toolbox developed for this project. The parameters in this tool are related to land use/land cover, hydrologic soil group and condition, and antecedent soil moisture condition in the drainage basin. As shown in Figure 3.24, inputs to this tool include:

- *Directory*: Folder where all required files are saved. Only required if ‘County Specific Soils Table’ is not filled out
- *Output Folder*: Folder where output files will be saved.
- *County*: Shapefile that holds county information – used to direct tool to appropriate County Specific Soils Table
- *Soils Layer*: Soils shapefiles from the Soil Survey Geographic Database (SSURGO).
- *Landuse Layer*: Land use/Land cover (LULC) layer. Must be a vector file. Can use the three LULC layers provided to MDOT/EGLE from MTRI.
- *Watershed Layer*: Shapefile that will clip other layers to the study area, typically a shapefile of a watershed created with the Watershed Delineation tool.
- *RCN Table*: Reference table built for the specific land cover/land use spatial layer – sum of ‘Class’ + ‘Value’ is joined to this table after the intersection between the Soils and the Landuse spatial layers are conducted.
- *Landuse Table*: Reference table for land use spatial layer – matches land cover description to ‘Class’ column.
- *County Specific Soils Table*: Reference table to specific soil names in different counties.
- *General Soils Table*: Reference table matching soil class to ‘Value’



Figure 3.24. Screen grab of the MTU RCN Tool as seen in "MTU_Hydro_Tool_1.0.5".

A full step-by-step description on how to use this tool can be found in the “MTU Hydro Toolbox Walkthrough” included as Appendix C - an 82-page document that provides detailed instruction on how to run each automated tool developed in this project.

Process of incorporating RCN tool into MDOT/EGLE workflows

Several iterations of this tool have been delivered to MDOT/EGLE. The first iteration of this tool was delivered prior to an in-person meeting at the MDOT Earle center on October 10, 2023. It was provided in two toolboxes: “MDOT_Tool 0.9.4_Arcpro3.1” (Figure 3.25) and “MDOT_Tool 0.9.4_Arcpro2.9.5”, due to issues in creating a tool that would run in versions of ArcGIS Pro 2.9.5, and versions of ArcGIS Pro 3.0 and above. This version of the tool had the capacity to create RCN values for a single watershed at a time, and that watershed had to be within a single county. The land use/cover layers available in this tool were the 2019 iteration of the NLCD/MTRI land cover layer (available within the version of the tool titled “LWM_RCNTool_0.01_NLCDMTRI”), and the MIRIS 1978 land use layer available within the

version of the tool titled “LWM_RCNTool_0.01_MIRIS”. The only soil layer that could be run in this version of the tool was the “MUPolygon” shapefile provided to MTRI by EGLE for testing, with Soil Specific County Tables also provided by EGLE. Recommendations coming from MDOT/EGLE on this version of the tool included:

- Creating the ability to process watersheds in multiple counties
- Allowing for the use of updated soil spatial layers from SSURGO
 - Through this suggestion, it was recommended that our team create a directory function for this tool in order to ensure that the correct County Specific Soil Table is selected when using updated soil spatial layers.
- Ensuring that any land use/cover polygons labelled as “Water” would receive an RCN of 100
- Ensuring that any polygons that hold an RCN of “0” would not be incorporated into the calculation of the final RCN statistic for the watershed
- Creating a smoother workflow for pre-processing a vector layer of the land use/cover dataset being utilized

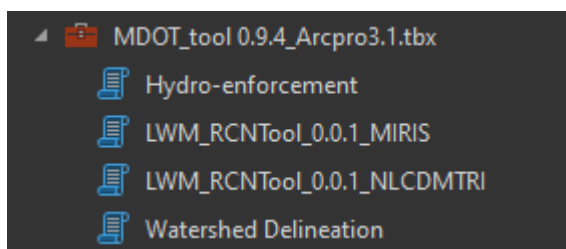


Figure 3.25. Screenshot of MDOT_tool 0.9.4_Arcpro3.1.tbx. This version of the tool could only be run in ArcGIS Pro Versions 3 and above, and contained two separate RCN tools for the MIRIS Land use layer and the NLCDMTRI land use layer.

The next draft of this tool was provided prior to an in-person meeting on April 11, 2024, at the MDOT Earle Center. This iteration, within the toolbox “MDOT_tool_0.9.5_AllArcproversions”, was titled “RCNToolCombined” as it was the first iteration of the tool that could be run in *both* ArcGIS Pro version 2.9.5 and versions above 3.0. It had the capacity to create RCN values for a single watershed at a time, and that watershed could be within multiple counties. The land use/cover layers available in this tool were the 2019 iteration of the NLCD/MTRI land cover layer, and the MIRIS 1978 land use layer. All statistics recommendations were addressed for the MIRIS and NLCD/MTRI land use/cover workflows. This tool also introduced the concept of saving files to a single directory that would then pull the appropriate County Specific Soil table based on the appropriate county for the watershed being processed. However, this version of the tool was restricted to using Country Specific Soil Tables associated with the MUPolygon shapefile, rather than utilizing the County Specific Soil Tables that are provided when

downloading updated versions of soil layers from SSURGO. Recommendations coming from MDOT/EGLE on this version of the tool included:

- The capability to run multiple watersheds at the same time, and output different statistics tables for each watershed.
- Adding a pop-up window for times when the soil spatial layer does not properly join with the county specific soils table
- Allowing the tool to be processed with NLCD 2021 as its own input land cover layer, rather than only having access to the NLCD layer through the NLCD/MTRI 2019 layer provided.

The next draft of this tool was provided prior to an in-person meeting on September 11, 2024, at the MDOT Earle Center. This iteration, held in the toolbox titled “MDOT_tool_1.0.0” (Figure 3.26) was titled “RCNToolCombined”. The land use layers available in this tool were MIRIS 1978, a newly-created 2021 iteration of the NLCD/MTRI land cover layer, and the 2021 version of NLCD. Additionally, the directory function was refined to utilize the County Specific Soil Tables (titled “muaggatt.txt” within the download package) that are provided when downloading updated soil spatial data from SSURGO. A pop-up window was still provided in this tool to ensure proper join of the soil spatial layer and the County Specific Soils Table. This version of the tool could also run multiple watersheds at the same time, and output different statistics tables for each watershed. Recommendations coming from MDOT/EGLE on this version of the tool included:

- Consideration of situations where soil names are the same in multiple counties, but values within the soil type are different
- Renaming the toolbox to “MTU Hydro Toolbox”

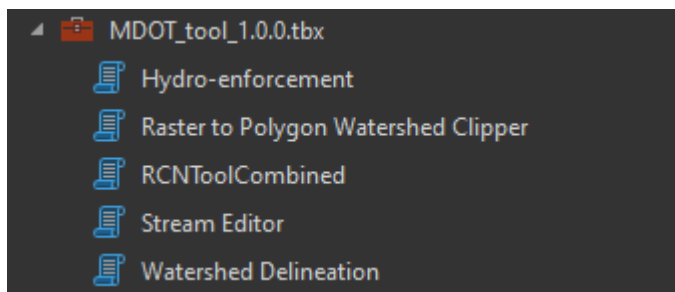


Figure 3.26. Screenshot of MDOT_tool_1.0.0.tbx. This version of the tool could be run by any ArcGIS Pro version above 2.9.5, and introduced the Raster to Polygon Watershed Clipper and Stream Editor tools.

The next phase of feedback on the tool was provided in the virtual Intermediate meeting on October 17, 2024. At this meeting, it was decided that the RCN Table provided for the 2021 NLCD/MTRI Landcover layer should have updated column names to better reflect the source of

the RCN values provided. Additionally, it was suggested that users have the ability to switch between columns in the RCN table before running the tool. Lastly, it was noted that the implementation of the NLCD 2021 layer was missing the statistical fix where a polygon identified as water should always be seen as having an RCN of 100.

Between the October 17, 2024 and the February 6, 2025 intermediate meetings, three iterations of the tool (in “MTU_Hydro_Tool_1.0.1” uploaded to Projectwise on October 17, 2024, “MTU_Hydro_Tool_1.0.2” uploaded to Projectwise on October 28, 2024, and “MTU_Hydro_Tool_1.0.3” uploaded to Projectwise on December 20, 2024) were shared with MDOT and EGLE addressing feedback presented in the October 17 Intermediate meeting. In these toolboxes, different issues related to general running and workflow of the toolbox were addressed.

By the February 6, 2025 meeting, the MTRI team had resolved all of the issues referenced in previous meetings. An input had been added to the tool to allow the user to input the appropriate column title to switch between different RCN value columns in the RCN table, the team had ensured that the tool selects the appropriate soil hydrologic value in cases where there are soil names are the same in a multi-county watershed, but the soil hydrologic values are different, and the statistical issue regarding Water equaling an RCN of 100 in the NLCD 2021 layer was nearly resolved. Feedback in this meeting coming from EGLE requested a change in the title of the final RCN column, and for the tool to calculate polygon size in square meters instead of square miles.

A then-final version of this tool was presented at an in-person meeting at the MDOT Earle Center on April 9, 2025. This version of the tool, presented in “MTU_Hydro_Tool_1.0.4”, was titled “MTU RCN Tool”, and incorporated all edits and feedback provided by EGLE and MDOT. (The final version, after one more set of updates, was version 1.0.5.)

Development and workflow of Raster to Polygon Watershed Clipper Tool

The Raster to Polygon tool was introduced in toolbox “MDOT_tool_0.9.5_AllArcproversions” on April 11, 2024. Development on this tool began in February 2024. This tool was developed to simplify the workflow needed to convert the land use/cover datasets. It allows the user to clip a raster layer to an appropriate size for the watershed you are working on building RCN values for, and then converts the layer from a polygon to a shapefile. This allows one to have the statewide layer saved in an easily viewable and reasonably sized raster layer, while being able to quickly convert it into a vector layer for functionality. As shown in Figure 3.27, inputs for this tool include:

- *Output Folder:* Folder where output files will be saved.
- *Watershed Outline:* Shapefile or feature class that holds the outline of the watershed you’d like to clip to. You can also use a shapefile of a county or any other required study site outline.
- *Raster Layer:* Input Land use/cover Raster Layer

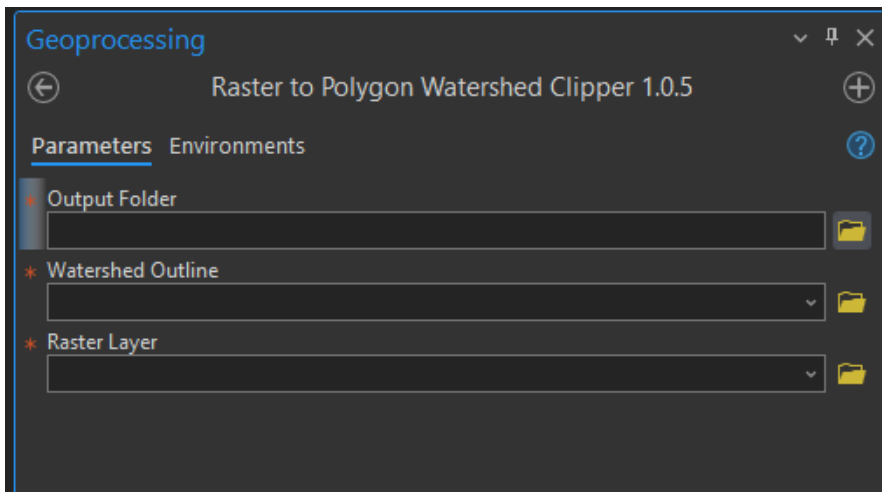


Figure 3.27. Screen grab of the Raster to Polygon Watershed Clipper as seen in "MTU_Hydro_Tool_1.0.5".

Process of incorporating this tool into MDOT/EGLE workflows

This tool has had one update since its initial introduction. At the April 11, 2024 in-person meeting, it was suggested that the output vector layer be named in accordance with the title of the watershed input into the tool. This change was addressed and introduced at the September 11, 2024 in-person meeting.

3.3.2 Results

Nineteen (19) watersheds in 24 counties were used to determine RCN tool functionality. These watersheds are listed in Table 3.5. Figure 3.28 provides an example of how the difference in LULC dataset used can affect the total RCN for a watershed. This figure displays the total RCN calculated for Adams Drain in Tuscola and Lapeer shifts when calculated using the MIRIS 1978 layer compared to the NLCD/MTRI 2021 layer. While the value itself has not shifted drastically (74.5 vs 78.7), it is clear that land cover has shifted in the 43 years between the two datasets, and many of the polygons inside the watershed have different RCN values.

Table 3.5. Watersheds used to test the RCN tool.

RCN Tool Tested Watersheds	
Watershed Name	County
Little Rabbit River	Kent and Allegan
Red Run	Allegan
Tributary to Betsie River	Grand Traverse and Benzie
Sugar River	Gladwin
Cedar River	Barry
Lovejoy Drain	St. Clair
Macatawa River	Allegan and Ottawa
South Branch Boyne River	Otsego, Antrim, and Charlevoix
Shoepac River	Schoolcraft and Alcona
Baltimore River	Ontonagon
Deer Creek	Houghton
Tributary to Mill Creek	Washtenaw
S Br Pentwater River	Oceana
Mallets Creek	Washtenaw
Coon Creek	St. Clair and Macomb
East Pond Creek	Lapeer, Oakland, and Macomb
Lake Drainage to Grand Traverse Bay	Leelanau
Adams Drain	Tuscola and Lapeer
Tributary to Whaley Drain	Ingham

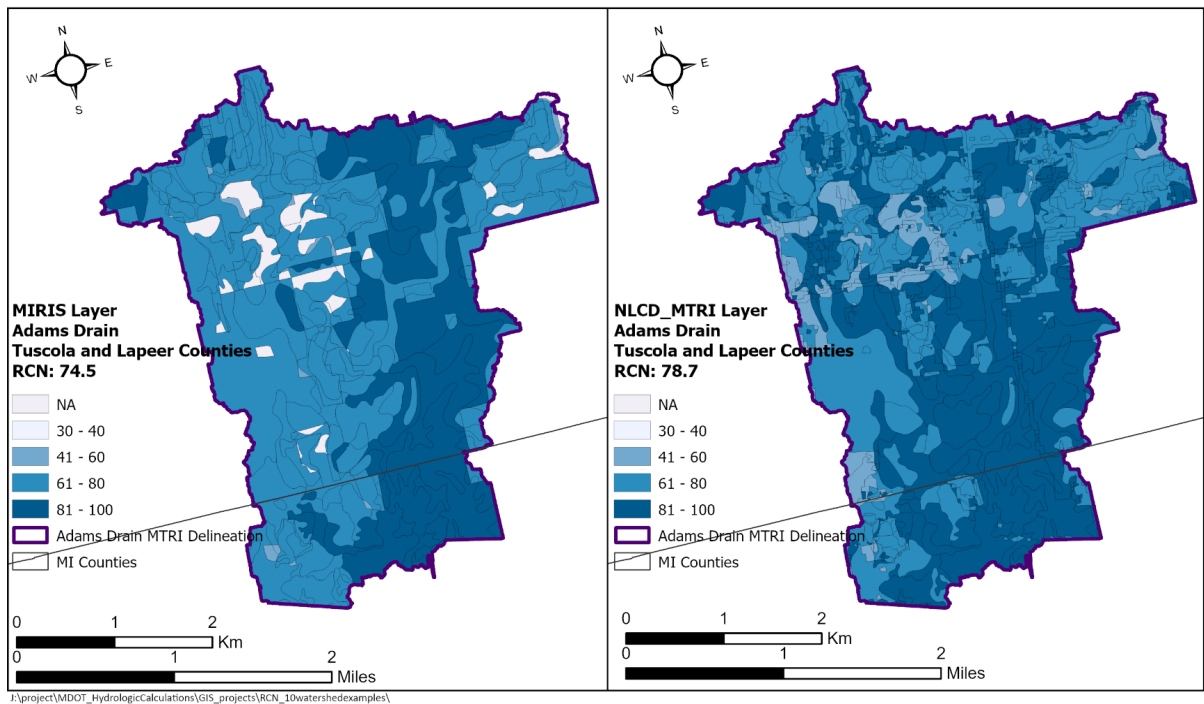


Figure 3.28. Demonstration of differences that can be found in the total RCN of Adams Drain in Tuscola and Lapeer counties based on which LULC dataset was utilized.

3.4 Update the 1984 Michigan Regression Equations

The existing procedures for estimating peak discharges for larger watersheds are based on regional flood quantile models developed using ordinary least squares (OLS) regression (Holtzschlag and Croskey, 1984). Inputs to the regression models include watershed parameters (e.g., drainage area, main channel length and slope, length passing through water bodies, slenderness ratio, forested area, surficial geologic material), climate variables (snowfall, rainfall, temperature), and flood quantiles estimated using Bulletin 17B (IACWD, 1982) procedures applied to historical data at 180 streamflow gaging stations. Overall, regression models were developed for five regions covering the state of Michigan, formed to improve the predictive power of the regression models relative to statewide models.

In the decades since these regression models were developed, numerous advances have been made in hydrologic statistics, including those documented in Bulletin 17C (England et al., 2018), which provides updated guidelines for determining flood flow frequency. The new procedures include improved quantile estimation methods that can be combined with the additional data available at USGS gaging stations to update estimates of flow quantiles for input into the regression analysis. Also discussed in Bulletin 17C are recommendations for improved

utilization of regional skew information. The longer gage record lengths now available also improve quantile estimates.

In addition to improving the flood quantile estimates for input to the regression analysis, the physiographic parameters employed within the model are improved using newer GIS data sets. Additional parameters such as mean basin elevation (e.g., Griffis and Stedinger, 2007), soil permeability (e.g., Walker & Krug, 2003), and hydrologic soil groups (e.g., Lorenz et al., 2010) were considered. Further, storage measured as the percent of drainage area as open water or wetlands (e.g., Koltun, 2003; Griffis and Stedinger, 2007) were investigated as an alternative to the length associated with water bodies as currently employed in the regression equations. Rainfall metrics based on updated rainfall data were also used. During the regression analysis, the condition number (Griffis and Stedinger, 2007; Montgomery et al., 2012) was evaluated to check for issues with multicollinearity between the parameters employed.

After compiling the new/updated physiographic parameters and flood quantiles, the regression analysis was performed using generalized least squares (GLS) regression rather than OLS regression as used in the development of the existing regression equations. GLS regression appropriately separates the sampling error in the flood quantile estimates from the regression model error to improve predictive power (e.g., Tasker and Stedinger, 1986; Koltun, 2003; Walker and Krug, 2003; Griffis and Stedinger, 2007; Veilleux, 2009; Lorenz et al., 2010; Mastin et al., 2016; Koltun, 2019; Levin and Sanocki, 2023).

3.4.1 Methodology

3.4.1.1 Site Selection

Sites were selected from the surface-water gaging station network maintained by the U.S. Geological Survey. The sites chosen had 10 years or more of annual peak flow observations. Sites with evidence of regulation or land use change throughout the record were removed. Standardized distance and drainage ratio metrics (Kolton, 2019) were utilized to check for potential site redundancy. Out of 267 sites meeting prior criteria, 28 were subsequently omitted due to potential redundancy (see Section 3.4.1.5), resulting in a total of 239 being used for further analyses, as shown in Figure 3.29. Mann-Kendall trend tests revealed that statistically significant trends ($p < 0.01$) exist at 18 of the 239 sites, which violates the requirement for stationarity of the data in flood frequency analyses; however, these sites were retained within the data set for the development of the regression models. A list of the sites used in the regression models is given in Table 6.5 in Appendix A, with those having statistically significant trends indicated.

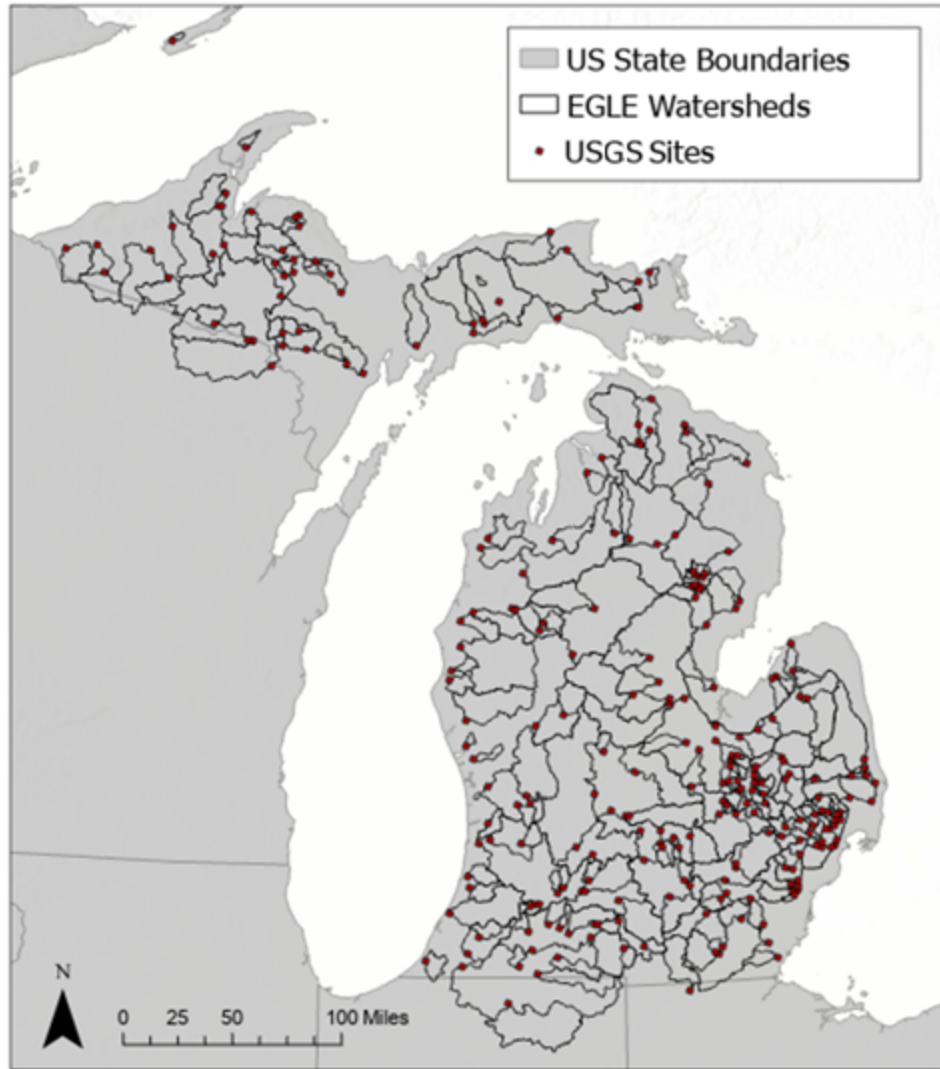


Figure 3.29. Watersheds selected for regional regression analysis.

3.4.1.2 Calculation of Streamflow Statistics

Streamflow statistics at each site were evaluated following Bulletin 17C procedures (England et al, 2018) implemented using USGS software PeakFQ version 7.5.1 (Flynn et al., 2006). In particular, the Expected Moments Algorithm (EMA) was used to fit the Log-Pearson Type 3 (LP3) distribution to the annual maximum flood series for each site. EMA includes the ability to handle censoring of low outliers or Potentially Influential Low Flows (PILFs) identified using the Multiple Grubbs-Beck test, missing values from an incomplete record, and to incorporate regional skew information, as well as historical flood information when available. In general, the fitted LP3 distribution resulting from EMA is comparable to that obtained using the more traditional method of moments approach within Bulletin 17B; however, EMA provides a more

accurate representation of the data in cases wherein censored/missing values are accounted for (e.g. Griffis, 2003; Griffis et al., 2004; Griffis, 2008).

Output from the PeakFQ software includes the mean, standard deviation, and weighted skew of the fitted LP3 distribution, as well as the estimated discharge corresponding to a number of annual exceedance probabilities (AEPs). For this study, AEPs of 0.5, 0.2, 0.1, 0.04, 0.02, 0.01, 0.005, and 0.002 were selected. These AEPs correspond to return periods $T = 2, 5, 10, 25, 50, 100, 200,$ and 500 years, respectively. Figure 3.30 shows an example of graphical output from PeakFQ, illustrating the data, fitted frequency curve, and confidence limits (5%, 95%).

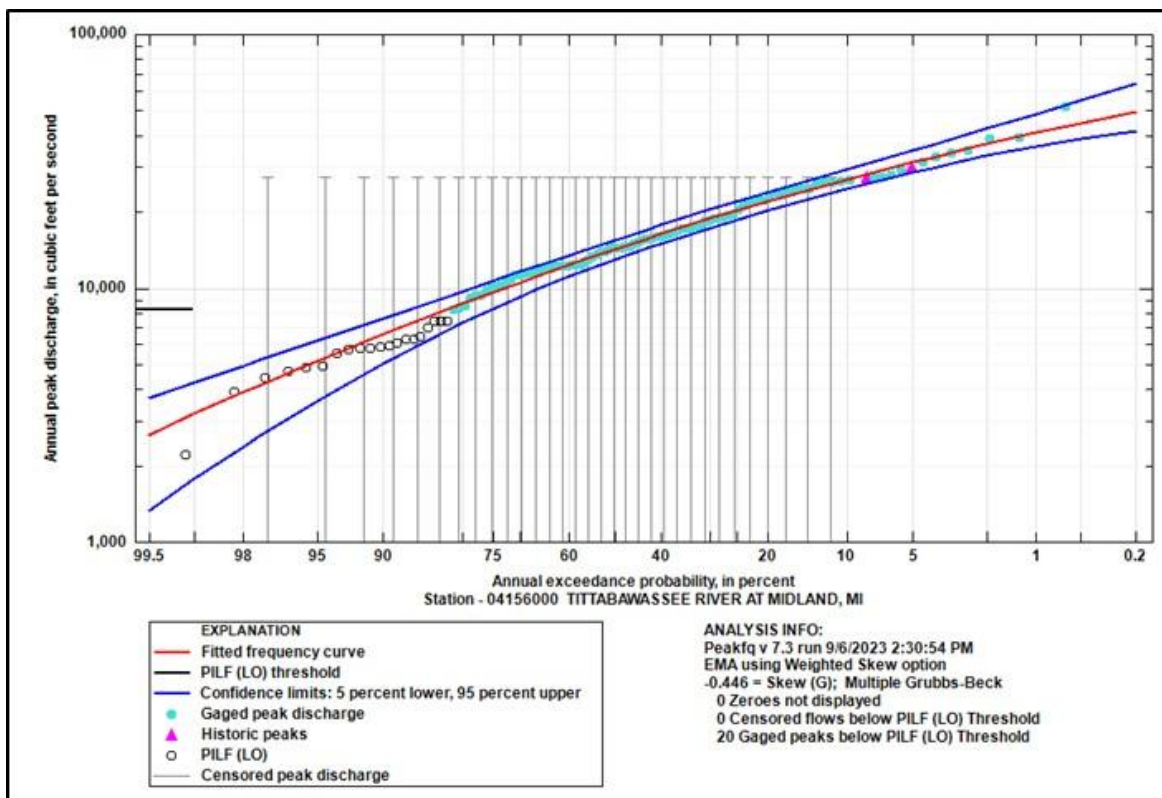


Figure 3.30. Graphical output from PeakFQ software.

3.4.1.3 Determination of Drainage Basin Characteristics

Basin characteristics were used as potential explanatory variables in regional regression equations. A set of 18 variables representing basin characteristics (e.g., climate, geophysical, land-use characteristics) were determined for each stream gage site in the study. The basin characteristics were chosen based on Michigan's previous regional regression analysis (Holtschlag and Croskey, 1984) and characteristics used by surrounding states Wisconsin (Walker et al., 2017; Levin & Sonocki, 2022), Minnesota (Lorenz, 2009; Levin & Sonocki,

2023), and Ohio (Koltun, 2019). The following is the complete list of the potential explanatory variables considered in the study, with details on their development provided in Appendix F:

- Drainage Area (*DA*), in square miles, is the total drainage area contributing to the stream gage. Watershed delineations were executed by the Michigan Department of Environment, Great Lakes, and Energy (EGLE).
- Longest Flow Path Slope (*LFPSL*), in feet per mile, is the slope of the longest flow path defined by the longest flow path tool in ESRI ArcHydro using 10-meter DEM. The slope is the change in elevation divided by the length between points 10 and 85 percent of the distance along the longest flow path.
- Watershed Slope (*WS_SLOPE*), measured in degrees. The mean basin slope was computed using the ArcGIS Pro slope tool, which returns the average slope value.
- Circularity Ratio (*CR*), dimensionless, is a measure of the basin shape (Koltun, 2002), determined as $CR = PERIMETER / \sqrt{(4\pi (DASQMI))}$, where *PERIMETER*, in miles, is the perimeter of the total drainage area of the watershed.
- Slenderness Ratio (*SLENRAT*), dimensionless, is the length of the longest flow path squared divided by the total drainage area.
- Mean Annual Snowfall (*SNOW*), in inches, for the years 1991-2020.
- 24-hour precipitation indices (*RAIN_{24,2}*, *RAIN_{24,100}*), in inches, are the maximum 24-hour precipitation depths that occur on average once every 2 and 100 years, respectively. Values are obtained from NOAA Atlas 14.
- Saturated Hydraulic Conductivity (*KSAT*), in micrometers per second, is the ease in which water can move through a medium. The Soil Data Development Toolbox by USDA was utilized to create the layer in ArcMap from the SSURGO database.
- Hydrologic Soil Groups (*SOILA*, *SOILD*), the percentage of the total drainage area of hydrologic soil units A and D.
- Channel Swamp (*CHSWAMP*), the percentage of the longest flow path that passes through swamp, lake, or pond polygons of the National Wetland Inventory (NWI) dataset.
- Land-use categories (from the merged NLCD/MTRI 2021 layer) were computed in ArcGIS Pro as the percentage of the total drainage area. Land use categories used in this study include forest (*FOREST*), wetland (*WETLAND*), developed land (*DEV*), cultivated crops and hay (*CRPHAY*), herbaceous upland (*HERB*), and open water (*WATER*).

3.4.1.4 Development of Regression Equations

Regression equations were developed using generalized least squares (GLS) regression to relate basin characteristics to flood quantiles (Q_{AEP}). Models were developed for each quantile with the following form:

$$Q_{AEP} = 10^a x_1^{b_1} x_2^{b_2} x_3^{b_3} \dots x_n^{b_n} \quad (2)$$

where

Q_{AEP} = dependent variable (flood quantile estimated using fitted LP3 model with specified AEP at a given site)

x_i (for $i = 1, \dots, n$) = explanatory variable (e.g. basin characteristic)

a = regression constant

b_i (for $i = 1, \dots, n$) = regression coefficient.

GLS regression accounts for differences in record lengths from site to site, as well as spatial correlation among the sites arising from concurrent flow events. In addition, GLS regression provides better metrics for assessing predictive accuracy of the regression models because the sampling error in the quantile estimates employed in the analysis is able to be quantified and separated from the actual error in the regression model. The sampling error arises due to uncertainty in the sample moments used to fit the LP3 distribution to streamflow records. More details of the GLS procedure are provided by Tasker & Stedinger (1985), Tasker & Stedinger (1989), and Eng et al. (2009). Therein, however, the sampling error only encompasses the uncertainty in the mean and standard deviation. This study employed the extension of the sampling error quantification to incorporate uncertainty in the skew proposed by Griffis & Stedinger (2007).

The existing regression equations presented by Holtschlag & Croskey (1984) are based on the state divided into five regions (see Figure 3.31). Prior to performing regression analyses in this study, the region delineation was reconsidered on the basis of spatial variations in climate and physiographic characteristics that affect hydrological response of drainage basins. Overall, the regions currently employed align well with the results of clustering analyses performed with mean annual snowfall (SNOW), mean annual runoff (MAR), and percent forest cover (FOREST). In addition, the existing regions align well with the major physiographic regions of the state of Michigan as illustrated in Figure 3.32 (Figure 4.6 in *Michigan: A Geography* by Sommers, 1984). Therefore, the existing regions were utilized for development of regression models in this study.

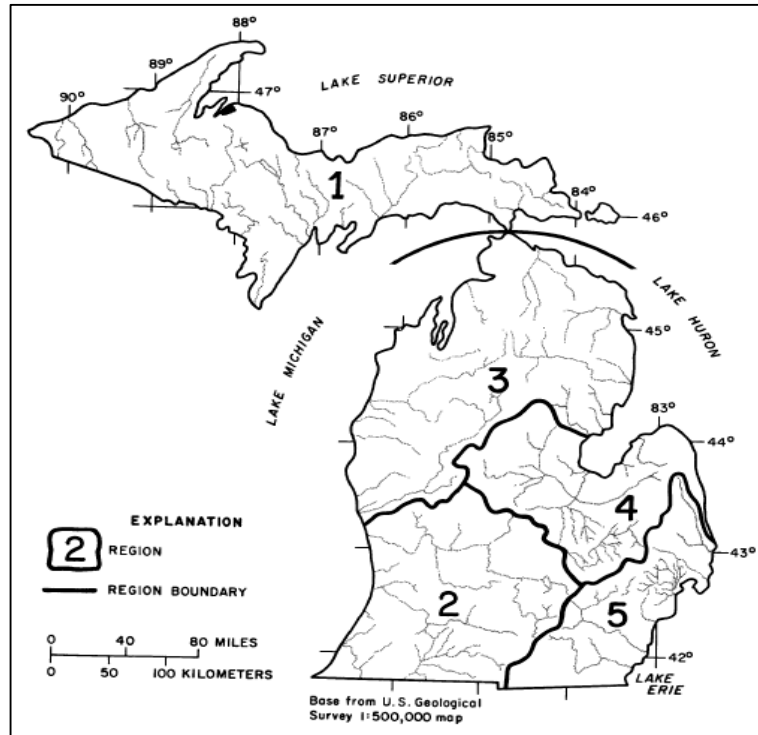


Figure 3.31. Regions from Holschlag and Croskey (1984) adopted in this study.

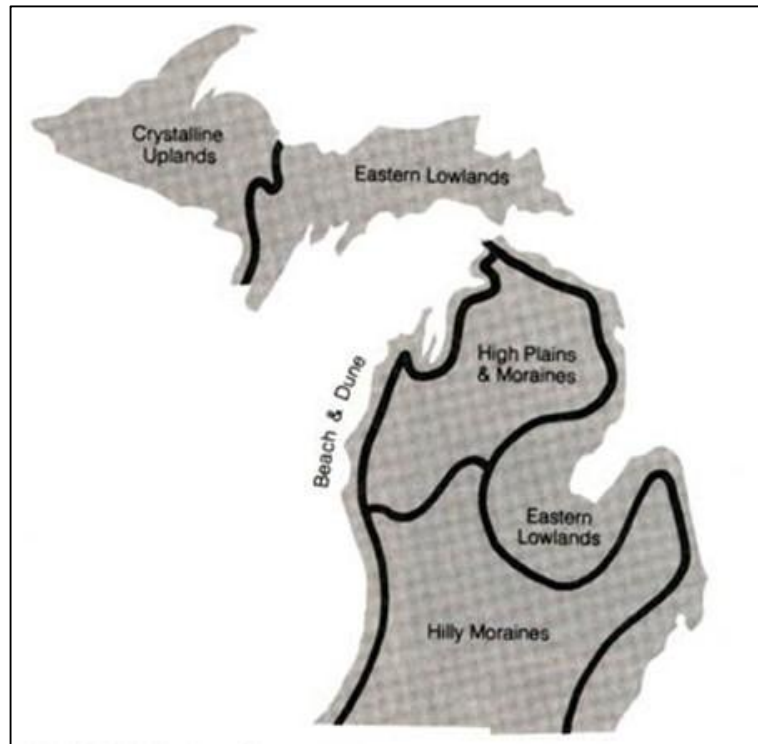


Figure 3.32. Major Physiographic Regions of the State of Michigan.

Regression models were developed on a regional basis beginning with a potential set of explanatory variables, then using a stepwise approach successively eliminating the least significant variables until those that remained were all significant at or below the 5% level (i.e., p -value less than or equal to 0.05). The potential set of variables used differed for each region, as they were selected at the regional level such that no two variables had a Pearson's R correlation coefficient greater than 0.6 (e.g., Levin and Sanocki, 2023). Limiting the cross correlation among the explanatory variables is necessary to reduce the potential for multicollinearity, which leads to unreliable estimates of the regression coefficients and their standard errors. The potential set of variables used in each region was as follows:

- Region 1 – DA, CRPHAY, DEV, HERB, WATER, FOREST, WS_SLOPE, SOILA, SOILD, RAIN_{24,100}, CR, KSAT, LFPSL, and CHSWAMP;
- Region 2 - DA, DEV, HERB, WATER, WS_SLOPE, SOILD, RAIN_{24,100}, CR, and CHSWAMP;
- Region 3 - DA, CRPHAY, DEV, HERB, WATER, WETLAND, WS_SLOPE, SOILD, RAIN_{24,100}, CR, LFPSL, CHSWAMP, and SLENRAT;
- Region 4 - DA, CRPHAY, DEV, HERB, WATER, WETLAND, SOILD, RAIN_{24,100}, CR, LFPSL, and CHSWAMP;
- Region 5 - DA, DEV, WATER, FOREST, WS_SLOPE, SOILD, RAIN_{24,100}, CR, CHSWAMP, and SLENRAT.

For each region, the final set of explanatory variables was selected with the aim of maintaining consistency across all AEPs, as well as minimizing the model error variance (MEV) and the average variance of prediction (AVP), while maximizing the pseudo coefficient of determination (pseudo- R^2). The model error variance is the variance of the residuals, representing the actual error in the regression model, because the sampling variability in the flood quantile estimates has already been accounted for as part of the GLS regression procedure. Under the assumption that the gauged data used in model development were collected at sites representative of all contained within the region, the average variance of prediction is an indicator of how well the regression equation predicts the true value of the flood quantile on average. The pseudo- R^2 is akin to the traditional coefficient of determination (R^2) in that it is a measure of the portion of the variability in the LP3 flood quantile estimates explained by the variables included in the regression model, however, it is computed differently due to the partition of the sampling error and the model error within the GLS procedure. More details regarding the computation of these metrics are provided by Griffis & Stedinger (2007). In addition, the condition number (CN) was computed as a measure of the degree of multicollinearity within the model. In general, CN less than 100 indicates issues with multicollinearity do not exist, while values between 100 and 1000 suggest moderate to strong multicollinearity exists, and values greater than 1000 indicate that severe multicollinearity exists (Montgomery et al., 2012).

3.4.1.5 Redundancy Analysis

An important assumption within regional regression analysis is that spatial observations are independent. If two stream gages are located too close together, then they are expected to provide nearly the same information in response to a given storm, thereby truly representing only one spatial observation. The potential redundancy of pairs of stream gages was evaluated based on the distance between the basin centroids, and the ratio of the basin drainage areas following Koltun (2019) and other previous studies.

The particular metrics evaluated were (1) the ratio of the drainage area of larger basin to the drainage area of the smaller basin, referred to as DAR, and (2) the standardized distance computed as:

$$SD_{ij} = \frac{D_{ij}}{\sqrt{0.5(DA_i + DA_j)}} \quad (3)$$

where

D_{ij} = distance, in miles, between centroid of basin i and basin j

DA_i = drainage area in square miles of basin i

DA_j = drainage area in square miles of basin j

Previous studies (e.g., Veilleux, 2009; Mastin et al., 2016; Koltun, 2019; Levin & Sanocki, 2023) indicate that values of SD_{ij} less than or equal to 0.5 combined with DAR less than or equal to 5 indicates that two basins are potentially nested. Based on this criteria, 79 pairs of sites were identified as potentially redundant. Each pair of sites was further investigated in terms of their hydrography, considering whether they were nested and/or similar enough to not be considered independent observations. Ultimately, 28 sites were removed for redundancy concerns, leaving a total of 239 sites employed in the regression analyses.

3.4.2 Results

3.4.2.1 Updated Regression Equations

The final regression equations for each region are provided below in conjunction with the regression coefficients in Tables 3.6-3.10. The regression coefficients are all statistically significant below the $p = 0.05$ level, except for one coefficient for $Q_{0.002}$ in Region 1 (p -value = 0.0591) and one coefficient for $Q_{0.5}$ in Region 3 (p -value = 0.0679). These coefficients are denoted by an asterisk in Tables 3.6 and 3.8 and were retained to provide consistency in the model forms and resulting quantile estimates within a given region. Performance metrics for each model are provided in Tables 3.11-3.15. Table 3.16 summarizes the number of gaging stations used to develop these regression equations and the ranges of the basin characteristics associated with those gaging stations. The regression equations should be used with caution

when applied with values outside of these ranges as the resulting flood quantile estimates will have greater uncertainty.

$$\text{Region 1: } Q_{AEP} = 10^a \text{DASQMI}^{b_1} \text{SOILD}^{b_2} \text{KSAT}^{b_3} \quad (4a)$$

$$\text{Region 2: } Q_{AEP} = 10^a \text{DASQMI}^{b_1} \text{WATER}^{b_2} \text{SOILD}^{b_3} \text{CHSWAMP}^{b_4} \quad (4b)$$

$$\text{Region 3: } Q_{AEP} = 10^a \text{DASQMI}^{b_1} \text{CRPHAY}^{b_2} \text{SOILD}^{b_3} \text{CHSWAMP}^{b_4} \quad (4c)$$

$$\text{Region 4: } Q_{AEP} = 10^a \text{DASQMI}^{b_1} \text{WATER}^{b_2} \quad (4d)$$

$$\text{Region 5: } Q_{AEP} = 10^a \text{DASQMI}^{b_1} \text{WATER}^{b_2} \text{FOREST}^{b_3} \quad (4e)$$

Table 3.6. Region 1 Regression Equation Coefficients.

	a	b₁	b₂	b₃
Q_{0.5}	0.7834	0.5896	0.5699	0.2218
Q_{0.2}	0.8665	0.5840	0.6127	0.2067
Q_{0.1}	0.9133	0.5799	0.6348	0.1986
Q_{0.04}	0.9676	0.5748	0.6569	0.1896
Q_{0.02}	1.0049	0.5713	0.6702	0.1835
Q_{0.01}	1.0410	0.5679	0.6810	0.1778
Q_{0.005}	1.0755	0.5647	0.6903	0.1724
Q_{0.002}	1.1199	0.5607	0.7003	0.1655*

Table 3.7. Region 2 Regression Equation Coefficients.

	a	b₁	b₂	b₃	b₄
Q_{0.5}	1.0282	0.8455	-0.1655	0.6711	-0.4945
Q_{0.2}	1.1849	0.8328	-0.1788	0.7497	-0.5429
Q_{0.1}	1.2297	0.8265	-0.1920	0.7780	-0.5409
Q_{0.04}	1.3784	0.8130	-0.1945	0.8092	-0.5861
Q_{0.02}	1.4476	0.8053	-0.2004	0.8224	-0.5975
Q_{0.01}	1.5121	0.7979	-0.2060	0.8310	-0.6064
Q_{0.005}	1.5730	0.7908	-0.2115	0.8360	-0.6132
Q_{0.002}	1.6500	0.7817	-0.2185	0.8381	-0.6199

Table 3.8. Region 3 Regression Equation Coefficients.

	a	b₁	b₂	b₃	b₄
Q_{0.5}	1.6929	0.6538	0.2329	0.1917*	-0.4459
Q_{0.2}	1.8735	0.6197	0.2615	0.2691	-0.5081
Q_{0.1}	1.9508	0.6007	0.2807	0.2983	-0.5240
Q_{0.04}	2.0254	0.5795	0.3023	0.3242	-0.5327
Q_{0.02}	2.0687	0.5654	0.3170	0.3388	-0.5340
Q_{0.01}	2.1041	0.5524	0.3308	0.3505	-0.5323
Q_{0.005}	2.1339	0.5403	0.3441	0.3602	-0.5287
Q_{0.002}	2.1673	0.5255	0.3612	0.3701	-0.5218

Table 3.9. Region 4 Regression Equation Coefficients.

	a	b₁	b₂
Q_{0.5}	1.1175	0.8565	-0.2894
Q_{0.2}	1.3046	0.8510	-0.3069
Q_{0.1}	1.4042	0.8447	-0.3092
Q_{0.04}	1.5130	0.8350	-0.3068
Q_{0.02}	1.5849	0.8273	-0.3024
Q_{0.01}	1.6506	0.8194	-0.2966
Q_{0.005}	1.7115	0.8116	-0.2896
Q_{0.002}	1.7848	0.8016	-0.2795

Table 3.10. Region 5 Regression Equation Coefficients.

	a	b₁	b₂	b₃
Q_{0.5}	1.6370	0.8599	-0.3073	-0.4263
Q_{0.2}	1.8194	0.8553	-0.3369	-0.4344
Q_{0.1}	1.9105	0.8497	-0.3503	-0.4337
Q_{0.04}	2.0044	0.8413	-0.3630	-0.4292
Q_{0.02}	2.0625	0.8354	-0.3704	-0.4243
Q_{0.01}	2.1154	0.8278	-0.3764	-0.4181
Q_{0.005}	2.1617	0.8211	-0.3815	-0.4113
Q_{0.002}	2.2168	0.8120	-0.3870	-0.4016

Table 3.11. Goodness-of-fit metrics for Updated Regression Equations for Region 1.

	Q_{0.5}	Q_{0.2}	Q_{0.1}	Q_{0.04}	Q_{0.02}	Q_{0.01}	Q_{0.005}	Q_{0.002}
CN	32.79	32.79	32.79	32.79	32.79	32.79	32.79	32.79
MEV	0.039	0.035	0.036	0.034	0.033	0.033	0.032	0.030
AVP	0.043	0.039	0.039	0.038	0.038	0.037	0.036	0.035
Pseudo-R²	0.851	0.865	0.859	0.860	0.861	0.862	0.863	0.865

Table 3.12. Goodness-of-fit metrics for Updated Regression Equations for Region 2.

	Q_{0.5}	Q_{0.2}	Q_{0.1}	Q_{0.04}	Q_{0.02}	Q_{0.01}	Q_{0.005}	Q_{0.002}
CN	44.42	44.42	44.42	44.42	44.42	44.42	44.42	44.42
MEV	0.041	0.046	0.050	0.053	0.056	0.058	0.059	0.061
AVP	0.045	0.051	0.056	0.059	0.062	0.064	0.067	0.069
Pseudo-R²	0.879	0.862	0.850	0.839	0.830	0.823	0.815	0.807

Table 3.13. Goodness-of-fit metrics for Updated Regression Equations for Region 3.

	Q_{0.5}	Q_{0.2}	Q_{0.1}	Q_{0.04}	Q_{0.02}	Q_{0.01}	Q_{0.005}	Q_{0.002}
CN	47.80	47.80	47.80	47.80	47.80	47.80	47.80	47.80
MEV	0.019	0.022	0.024	0.025	0.027	0.027	0.028	0.028
AVP	0.021	0.025	0.027	0.029	0.030	0.032	0.033	0.034
Pseudo-R²	0.901	0.875	0.860	0.842	0.830	0.820	0.811	0.802

Table 3.14. Goodness-of-fit metrics for Updated Regression Equations for Region 4.

	Q_{0.5}	Q_{0.2}	Q_{0.1}	Q_{0.04}	Q_{0.02}	Q_{0.01}	Q_{0.005}	Q_{0.002}
CN	7.895	7.895	7.895	7.895	7.895	7.895	7.895	7.895
MEV	0.019	0.020	0.021	0.022	0.023	0.023	0.023	0.022
AVP	0.021	0.022	0.024	0.025	0.026	0.026	0.026	0.025
Pseudo-R²	0.951	0.948	0.944	0.939	0.938	0.936	0.936	0.936

Table 3.15. Goodness-of-fit metrics for Updated Regression Equations for Region 5.

	Q_{0.5}	Q_{0.2}	Q_{0.1}	Q_{0.04}	Q_{0.02}	Q_{0.01}	Q_{0.005}	Q_{0.002}
CN	12.01	12.01	12.01	12.01	12.01	12.01	12.01	12.01
MEV	0.026	0.028	0.030	0.033	0.035	0.036	0.038	0.040
AVP	0.029	0.031	0.033	0.036	0.038	0.040	0.042	0.045
Pseudo-R²	0.900	0.896	0.889	0.878	0.871	0.864	0.856	0.848

Table 3.16. Regional Ranges of Drainage Basin Characteristics and Gage Statistics

Region	1	2	3	4	5
Number of Gaging Stations	43	55	47	45	49
Total Peak Flow Observations	1705	2688	1879	1665	2330
DA (mi²)	7.47-2461.5	6.15-4900.9	1.14-1599.0	4.01-5990.5	8.65-1041.0
SOILD (%)	7.95-94.1	6.52-39.7	5.40-58.4	14.5-59.3	9.98-60.7
CHSWAMP (%)	19.3-95.6	8.72-83.1	18.7-85.4	0.55-65.0	0.01-79.6
CRPHAY (%)	0.001-45.5	11.7-73.5	0.79-45.5	10.7-89.0	0.01-73.7
WATER (%)	0.001-8.13	0.02-11.0	0.01-10.1	0.01-4.67	0.05-8.32
FOREST (%)	1.70-74.2	3.95-32.2	3.42-65.0	1.35-34.6	0.94-35.6
KSAT (µm/s)	0.06-14.6	0.01-6.73	0.02-15.7	0.02-7.70	0.02-3.21

Overall, the performance metrics presented in the tables above show that the models are well defined with condition numbers (CN) indicating multicollinearity is not an issue, relatively small model error variances (MEV) and average variances of prediction (AVP), and pseudo-R² values ranging from 80.2% to 95.1%. In addition, standard linear regression model assumptions appear to be satisfied based on plots of the residuals, as illustrated in Figure 3.33 for the 1% AEP quantiles throughout the state. Further, the regression equations produce quantile estimates that are in good agreement with the at-site LP3 quantile estimates, as shown in Figures 3.33-3.39 for the 1% AEP flood discharge.

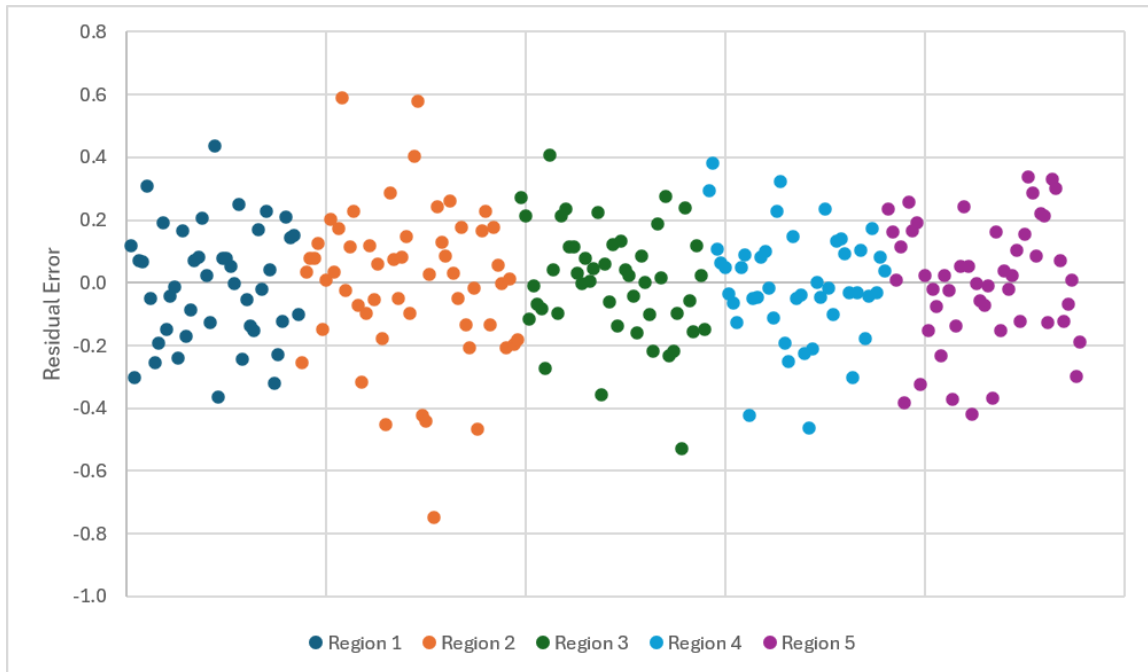


Figure 3.33. Residual errors for models of the 1% AEP quantile by region. 239 sites total. Units are fraction of Log_{10} of discharge (cfs).

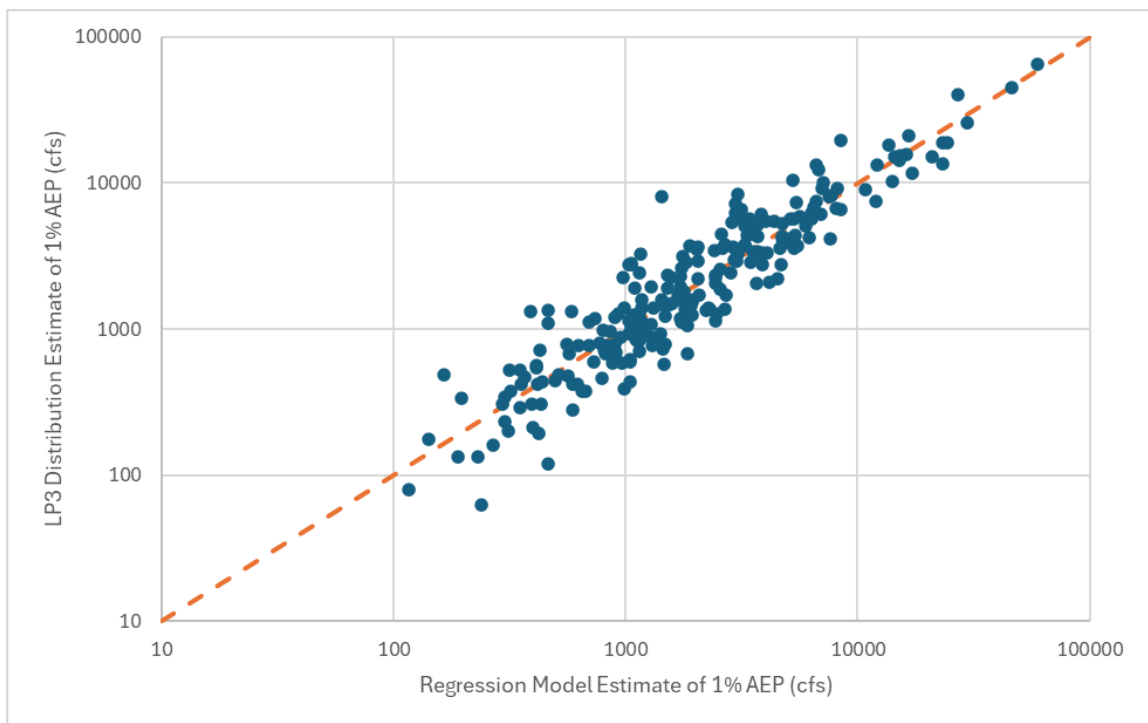


Figure 3.34. Comparison of the 1% AEP quantile estimated by the at-site LP3 distribution and the regression equations for the entire state of Michigan.

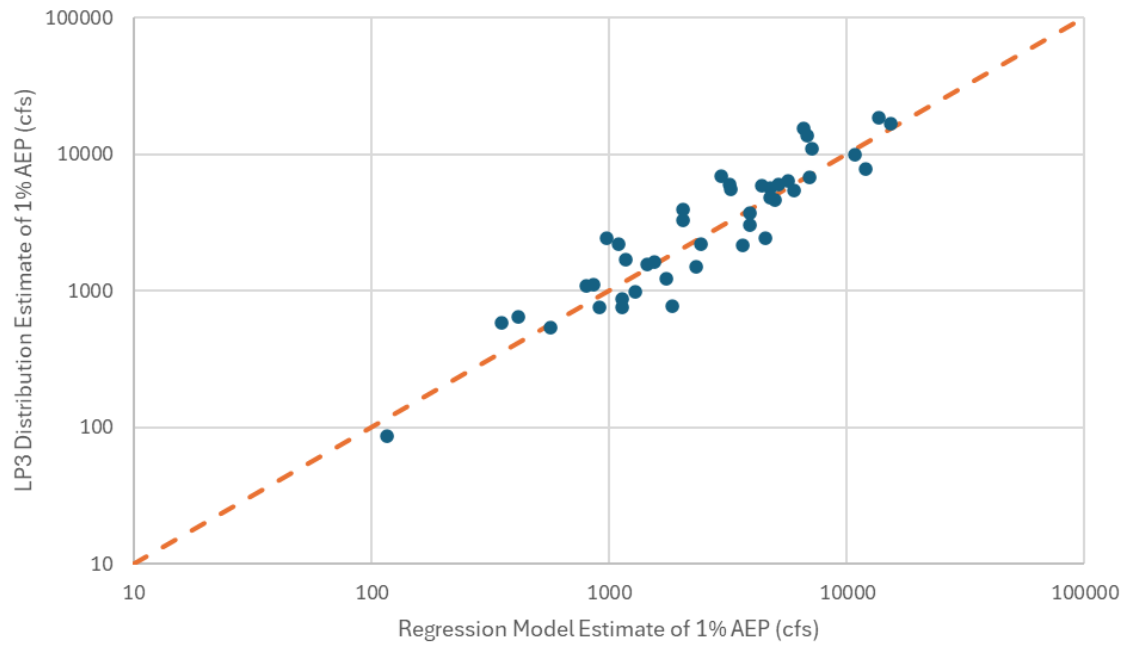


Figure 3.35. Comparison of the 1% AEP quantile estimated by the at-site LP3 distribution and the regression equations for Region 1.

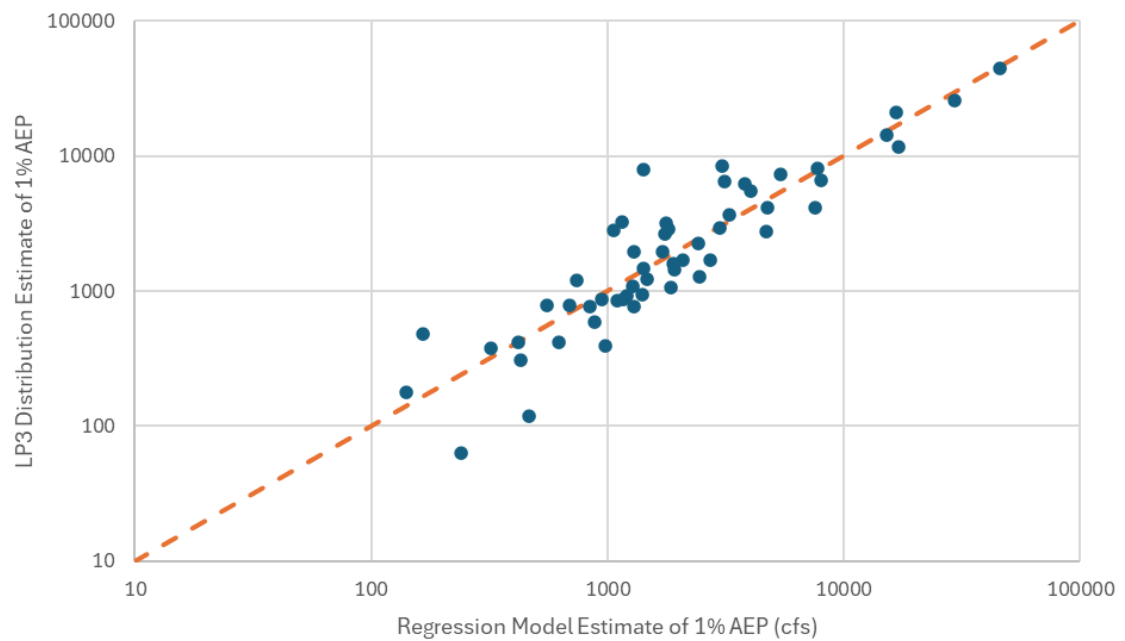


Figure 3.36. Comparison of the 1% AEP quantile estimated by the at-site LP3 distribution and the regression equations for Region 2.

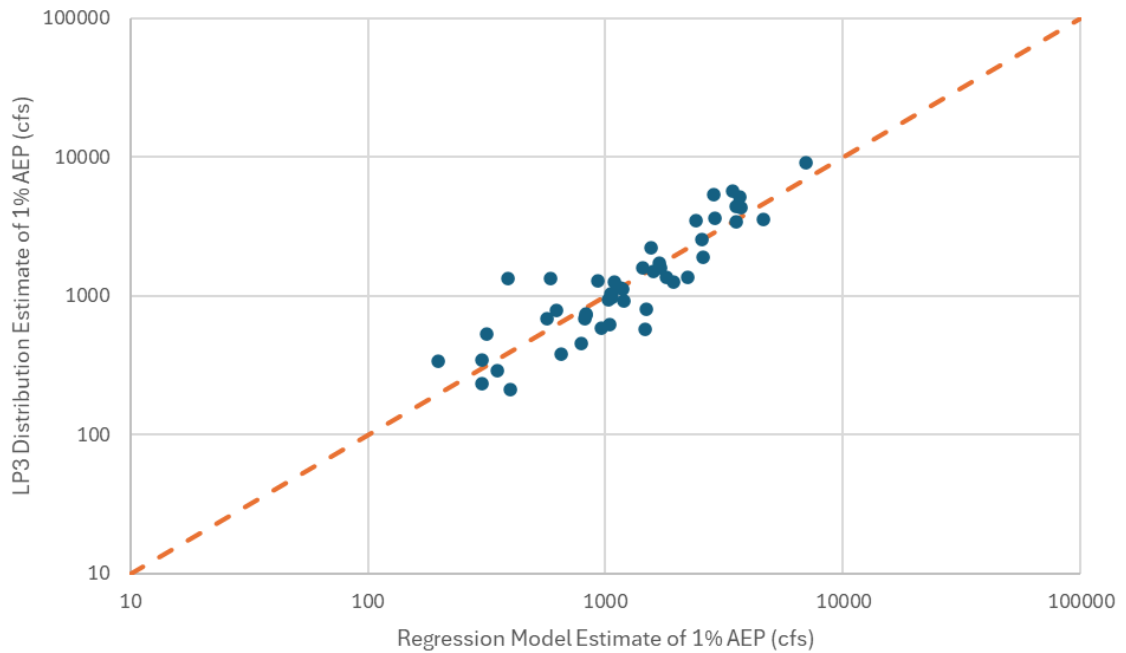


Figure 3.37. Comparison of the 1% AEP quantile estimated by the at-site LP3 distribution and the regression equations for Region 3.

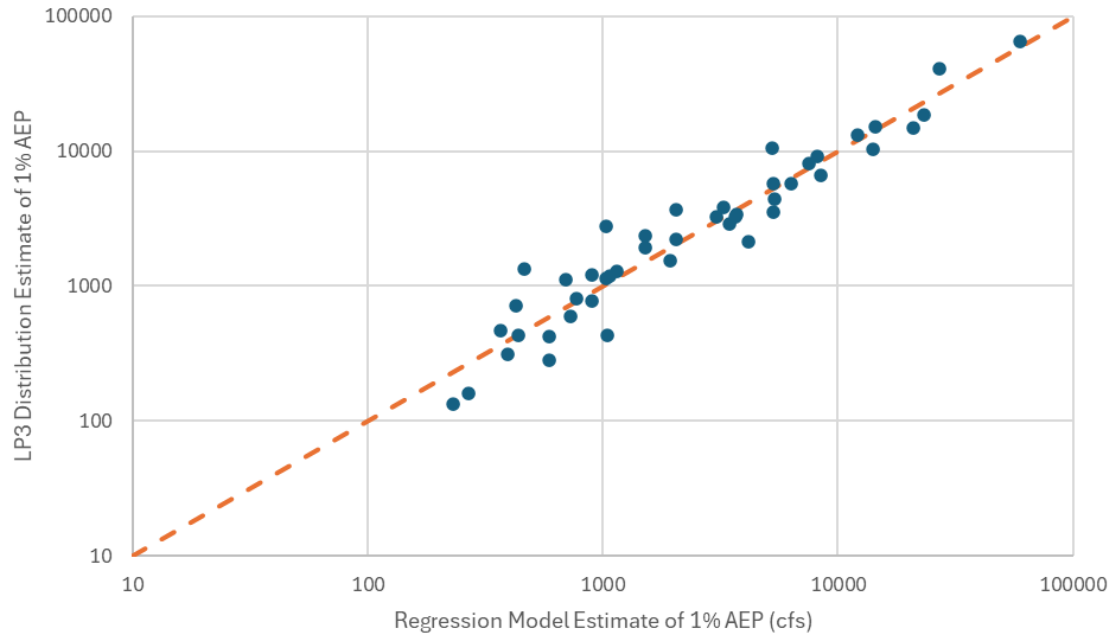


Figure 3.38. Comparison of the 1% AEP quantile estimated by the at-site LP3 distribution and the regression equations for Region 4.

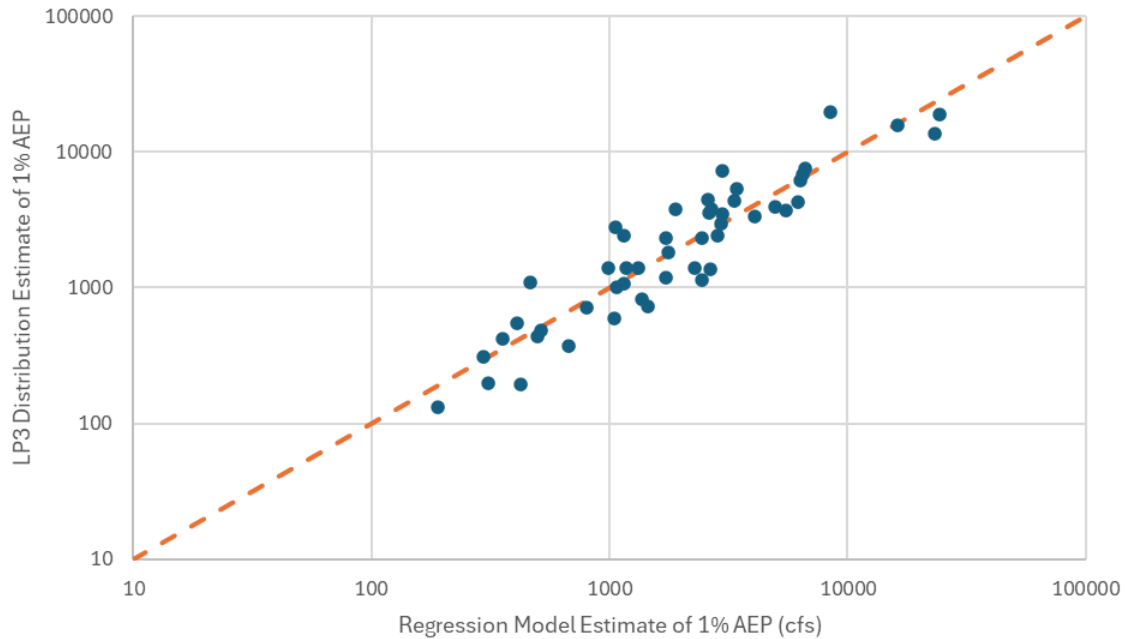


Figure 3.39. Comparison of the 1% AEP quantile estimated by the at-site LP3 distribution and the regression equations for Region 5.

3.4.2.2 Validation and Model Comparisons

Comparisons were made between the discharges computed by Holtschlag & Croskey (1984) and the discharges computed by the updated regression equations obtained in this study. Comparisons were made for a subset of the 239 sites employed for model development herein because Holtschlag & Croskey (1984) only present estimates of the 1% AEP flood discharge (see Table 4 of Holtschlag & Croskey, 1984) for 141 of those sites. For those sites, the residual errors of the 1% AEP flood discharges based on the updated [New] regression equations relative to the residuals of the estimates based on Holtschlag & Croskey (1984) [HC] are shown in Figure 3.40. The residual errors for 1% AEP flood discharge estimates for both versions of regression models were computed relative to the 1% AEP flood discharge estimates obtained using PeakFQ with Bulletin 17C procedures obtained in this study. In general, the magnitude of the residual errors is comparable, although the residuals based on Holtschlag & Croskey have a slightly smaller range in four of the five regions, despite the updated statistical techniques applied and the increase in available data. However, a direct comparison is difficult for a couple reasons. First, the comparison includes a higher proportion of sites used in the Holtschlag & Croskey study than in the present study – 141 out of 185 (76%) compared to 141 out of 239 (59%) – which biases the comparison. Second, the performance of the Holtschlag & Croskey models would change if applied with updated climate and land use information.

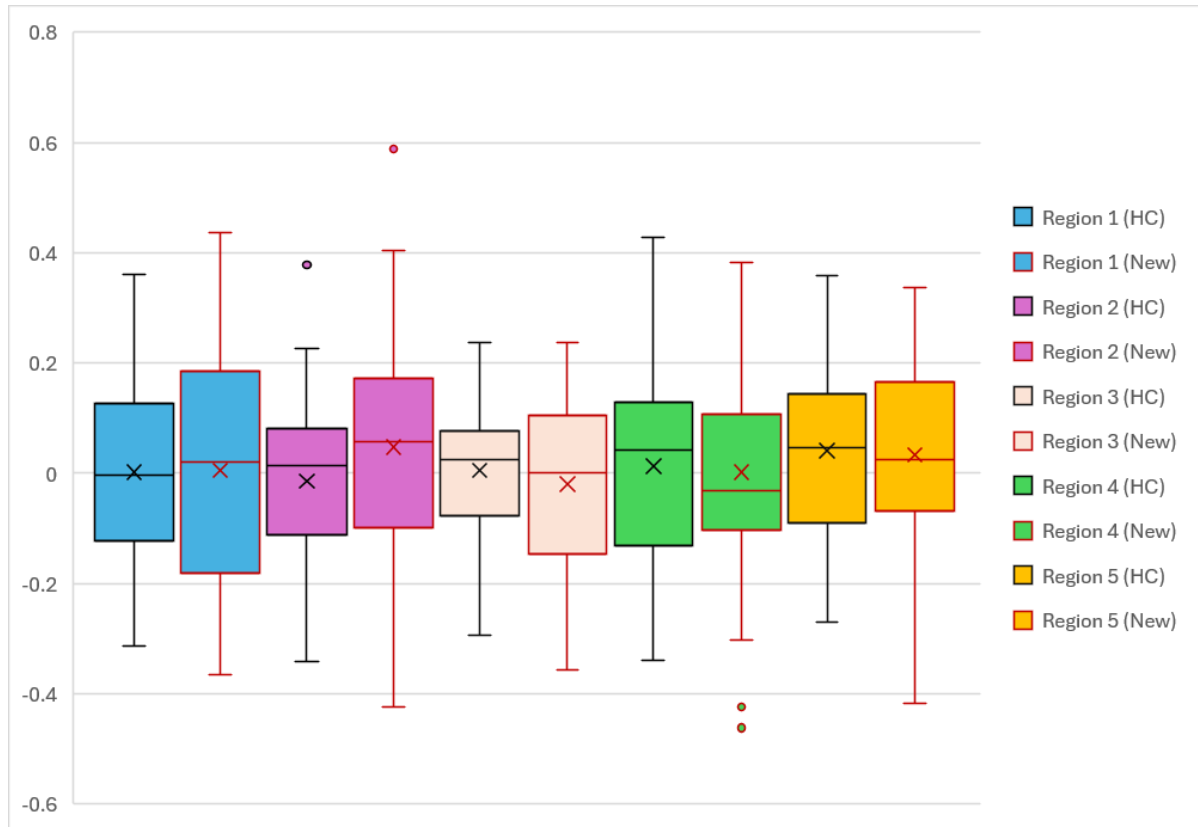


Figure 3.40. Comparison of residual errors of the 1% AEP quantile estimated using the Holtzschlag & Croskey (HC) and the updated (New) regression models based on 141 sites separated by the revised region delineation. Units are fraction of Log_{10} of discharge (cfs).

For a comparison station by station, Figure 3.41 shows the difference in the residual errors of the 1% AEP flood discharge estimated using the Holtzschlag & Croskey (1984) regression models versus the updated regression models. This shows that the two models tend to overestimate or underestimate the LP3 distribution quantile estimates at approximately the same rate. Finally, Figure 3.42 shows residual errors for updated models of the 1% AEP flood discharge as a function of drainage area, indicating no bias across the range of watershed drainage areas.

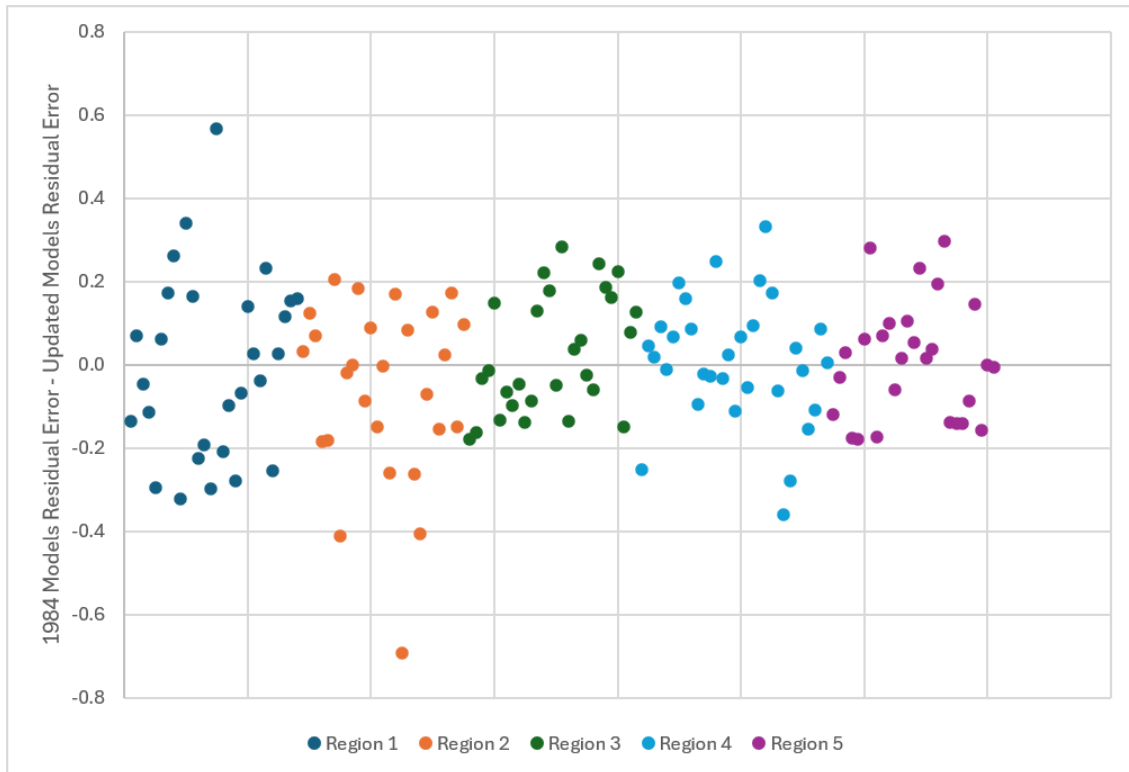


Figure 3.41. Difference in residual errors of the 1% AEP flood discharge estimated by the Holschlag & Croskey (1984) regression equations and the updated (new) regression equations (141 sites). Units are fraction of $\log_{10}$ of discharge (cfs).

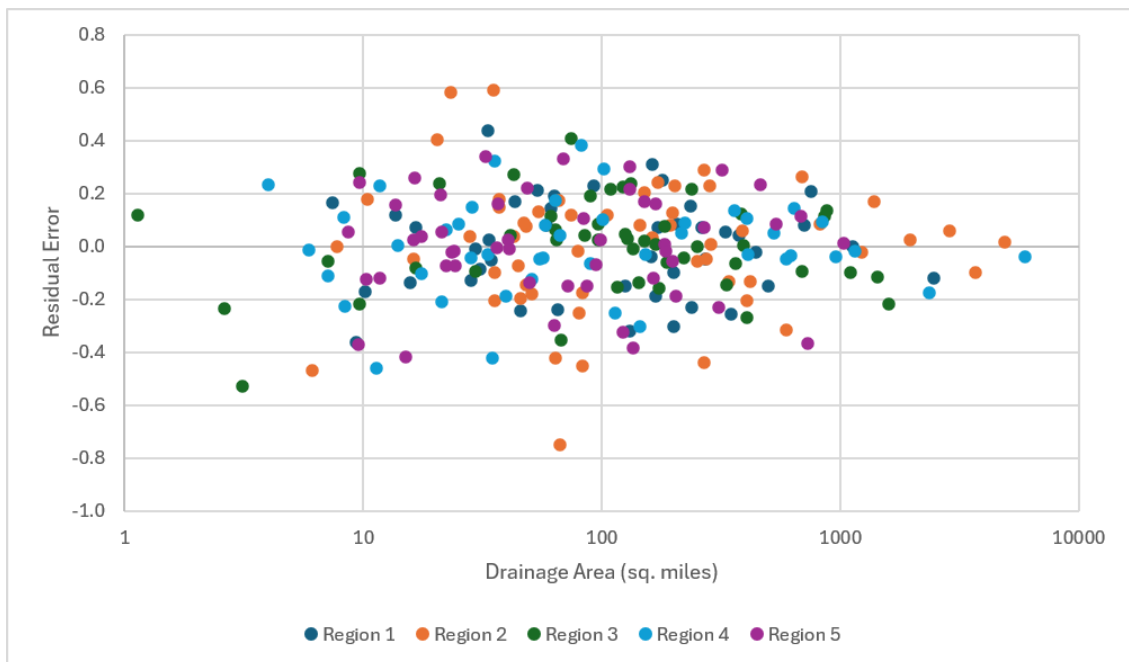


Figure 3.42. Residual errors for updated (new) models of the 1% AEP flood discharge as a function of drainage area (239 sites).

Comparisons were also made between the updated regression equations and the updated RCN-based method (implemented in WinTR-20 with pond/swamp factors applied) for small watersheds. Results were available from both methods for a total of 30 small watersheds (contributing drainage area less than 20 mi²) located throughout the state. Results of each method were compared to the site statistics from PeakFQ software, and the results are summarized in Tables 3.17-3.19. Shown are the average relative difference (expressed as a fraction of the site estimate), the standard deviation of the relative differences, the maximum relative difference (largest overprediction), and the minimum relative difference (largest underprediction). For watersheds with CDA less than 20 mi² (Table 3.17), results are mixed, with the RCN-based resulting in smaller variation from site statistics for return periods below 25 years, but the regression equations performing better for more extreme events. The maximum differences (overpredictions) range from approximately 250% to 750% due to one outlier -- USGS 04106400 West Fork Portage Creek at Kalamazoo. The drainage area for this site was inspected and found to have a chain of lakes upstream of the gage site, likely resulting in significant attenuation of peak discharges, although USGS does not flag the site as regulated.

Table 3.17. Comparison of results from updated smaller watersheds method and regional regression equations relative to site statistics. Results are for all watersheds with contributing drainage area (CDA) less than 20 mi² (N = 30). Maximum differences are for USGS 04106400.

	Difference: WinTR-20 - PeakFQ					Difference: Regression models - PeakFQ				
	0.2	0.1	0.04	0.02	0.01	0.2	0.1	0.04	0.02	0.01
AVG	-0.19	-0.03	0.24	0.49	0.77	0.07	0.07	0.08	0.09	0.09
STDEV	0.67	0.83	1.09	1.33	1.61	0.87	0.88	0.94	0.96	0.96
MAX	2.47	3.44	4.87	6.15	7.53	4.25	4.28	4.55	4.58	4.56
MIN	-1.00	-1.00	-0.97	-0.94	-0.91	-0.60	-0.62	-0.66	-0.68	-0.70

For watersheds with CDA in the range of 10-20 mi², with USGS 04106400 omitted, the regression equations perform better overall than the RCN-based method (Table 3.18). The average variation in the regression equation predictions is approximately 10% (underprediction), with smaller standard deviations and ranges in variation compared to the RCN-based method. The RCN-based method tends to overestimate larger return period events (50- and 100-yr) because, for CN values above 70-75, there is a nearly 1:1 ratio of rainfall to runoff above rainfall depths of about 4 inches. However, for watersheds with CDA less than 10 mi², results are somewhat mixed (Table 3.19). While the regression equations perform better on average for the larger return periods, they have approximately the same standard deviation and range in variation from the site statistics compared to the RCN-based method.

Table 3.18. Comparison of results from updated smaller watersheds method and regional regression equations relative to site statistics. Results are for watersheds with CDA of 10-20 mi², omitting USGS 04106400 (N = 15).

	Difference: WinTR-20 - PeakFQ					Difference: Regression models - PeakFQ				
	0.2	0.1	0.04	0.02	0.01	0.2	0.1	0.04	0.02	0.01
AVG	-0.34	-0.21	0.02	0.23	0.47	-0.10	-0.10	-0.09	-0.09	-0.09
STDEV	0.49	0.61	0.83	1.03	1.28	0.37	0.39	0.41	0.43	0.45
MAX	0.88	1.21	1.96	2.76	3.69	0.69	0.70	0.69	0.75	0.81
MIN	-1.00	-1.00	-0.97	-0.94	-0.91	-0.60	-0.62	-0.65	-0.68	-0.70

Table 3.19. Comparison of results from updated smaller watersheds method and regional regression equations relative to site statistics. Results are for watersheds with CDA less than 10 mi² (N = 14).

	Difference: WinTR-20 - PeakFQ					Difference: Regression models - PeakFQ				
	0.2	0.1	0.04	0.02	0.01	0.2	0.1	0.04	0.02	0.01
AVG	-0.22	-0.09	0.14	0.36	0.61	-0.04	-0.05	-0.05	-0.05	-0.05
STDEV	0.40	0.40	0.44	0.49	0.59	0.40	0.42	0.45	0.48	0.50
MAX	0.46	0.69	1.00	1.23	1.43	0.74	0.79	0.84	0.86	0.89
MIN	-0.87	-0.71	-0.54	-0.41	-0.28	-0.58	-0.62	-0.66	-0.68	-0.70

3.4.3 Recommendations

The updated regression models are based on updated streamflow records and improved statistical techniques compared to the previous equations. They also use readily available geospatial datasets and are more efficient in that fewer parameters are fit for each region.

Technically the regression models apply to the smallest drainage area used to develop them: 7.47 mi² for Region 1, 6.15 mi² for Region 2, 1.14 mi² for Region 3, 4.01 mi² for Region 4, and 8.65 mi² for Region 5. Considering this, along with the comparisons with site statistics, the regression equations are recommended for use in watersheds with areas as small as 10 mi². Given the mixed results for the small number of watersheds analyzed with drainage areas less than 10 mi², it is recommended that the RCN-based approach continue to be used for watersheds in this size range. However, comparisons of the two approaches should continue.

The updated regression equations can easily be implemented in a spreadsheet tool. All GIS layers and calculation procedures will be made available to determine the independent variables (watershed and hydroclimatic parameters) in the regression models.

3.5 Investigate Alternative Techniques

3.5.1 Incorporating Climate Projections into Hydrologic Calculation Procedures

3.5.1.1 Methodology

The Federal Highway Administration (FHWA) developed the CMIP Climate Data Processing Tool 2.1 to process readily available downscaled climate projections at local levels for use by transportation planners (Killgore, et al., 2021). Version 2.1 of the tool works with the statistically downscaled CMIP5 Localized Constructed Analog (LOCA) dataset, which provides statistically downscaled projections of temperature and precipitation at 1/16-degree resolution. Input data for the tool is obtained from the U.S. Bureau of Reclamation's Downscaled CMIP5 Climate and Hydrology Projections (DCHP) website. The tool includes methods for calculating future return period precipitation and scaling factors that can be applied to current precipitation frequency estimates.

For this study, we downloaded daily precipitation data from the historical record (1950-2005) and from four GCMs with LOCA downscaling for the RCP 4.5 scenario and a future period of 2041-2070. The four GCMs were selected following Great Lakes Ensemble guidelines for climate models that represent the Great Lakes. These included the Beijing Climate Center Climate System Model (BCC-CSM1.1), the Community Climate System Model (CCSM4.6), the Community Atmosphere Model (CESM-CAM5), and the Model for Interdisciplinary Research On Climate (MIROC5) (Briley et al., 2021).

3.5.1.2 Results

Using the CMIP Climate Data Processing Tool, precipitation scaling factors were developed for 1/16-degree grids corresponding to the centroid of each of Michigan's climatic zones, as shown in Figure 3.43. Results for Zones 1 and 10 are summarized in Tables 3.18 and 3.19, respectively, with results for all zones provided in Table 6.6 in Appendix A. Scaling factors from the individual models generally ranged from 1.1 to 1.3 for return periods of 2 years to 500 years (AEP of 0.5 to 0.002), although there were some notable differences between models and across regions of the state. The highest scaling factors were computed for Zones 1 and 2 in the Upper Peninsula, with the mean factors from the four models ranging from 1.06 to 1.25 for the 2-yr to 500-yr return periods (AEP 0.5 to 0.002). Conversely, none of the mean scaling factors for Zones 7-10 were greater than 1.10, with the mean scaling factors for the 25-yr return period (AEP 0.04) and above even being slightly below 1.0. Some scaling factors from individual models seemed anomalously low, which brought down the four-model averages, including factors as low as 0.52 from the MIROC5 model for the 500-yr return period in Zone 6, and 0.73 from the BCC-CSM1.1 model for 500-yr return period in Zone 7. In each of the ten zones, the greatest variability across models was observed for the 500-yr return period.

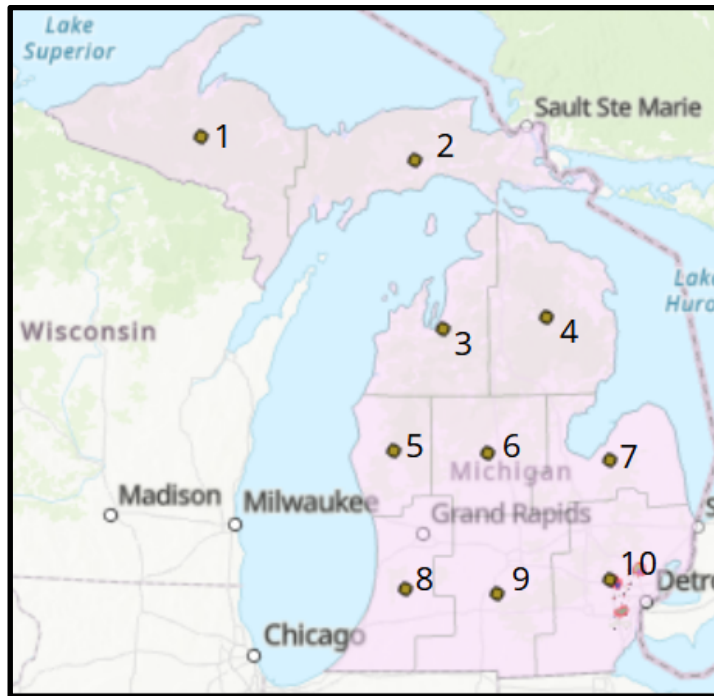


Figure 3.43. Michigan climatic zones used in climate projection modeling.

Table 3.20. Precipitation scaling factors for Zone 1.

Zone 1	bcc-csm1	ccsm4.6	cesm1-cams5	miroc5	Mean
2-yr	1.04	1.10	1.06	1.04	1.06
5-yr	1.09	1.19	1.13	1.10	1.13
10-y	1.12	1.24	1.16	1.13	1.16
25-yr	1.15	1.28	1.19	1.15	1.19
50-y	1.16	1.31	1.21	1.17	1.21
100-yr	1.18	1.33	1.22	1.18	1.23
500-yr	1.20	1.36	1.25	1.20	1.25

Table 3.21. Precipitation scaling factors for Zone 10.

Zone 10					
2-yr	1.09	0.91	1.15	0.98	1.03
5-yr	1.17	0.93	1.18	0.94	1.06
10-y	1.21	0.93	1.20	0.92	1.07
25-yr	1.25	0.94	1.22	0.90	1.08
50-y	1.27	0.94	1.22	0.89	1.08
100-yr	1.29	0.94	1.23	0.89	1.09
500-yr	1.32	0.95	1.25	0.87	1.10

3.5.1.3 Recommendations

Due to model and downscaling uncertainty, mean scaling factors from the four model runs are recommended for use in estimating future precipitation intensities. These results should be compared with NOAA Atlas 15 rainfall frequency estimates, when available, since Atlas 15 will include estimates that incorporate nonstationary statistical methods and climate model projections to account for potential future trends. Atlas 15 methods will also include updated climate models from CMIP6, along with advanced statistical downscaling methods. Published results are expected to be available for use and application in 2026.

A primary limitation of applying only a precipitation scaling factor to predict future flood discharge frequencies is that other hydroclimatic factors may be changing. For example, the precipitation seasonality, temperature, evapotranspiration, snowfall and snowpack dynamics, and soil moisture can also be changing, and each of these hydrologic processes can affect the relationship between precipitation and flooding. Physically based or statistical models incorporating these processes may offer improvements for flood prediction under future conditions, but additional research is needed before they can be operationalized.

3.5.2 Rain on Grid Modeling

3.5.2.1 Literature Review

The Rain-on-Grid (RoG) modeling technique, also known as direct rainfall modeling, is a method in which precipitation is input directly to grid cells in a hydrodynamic model. This method integrates hydrologic and hydraulic calculations in a single model, eliminating the need for sequential application of a rainfall-runoff model with a flood hydraulics model. In contrast to traditional flood hydraulic modeling, inflows are modeled continuously along the waterways rather than through defined boundary conditions. Downsides of the approach include the computational demand of hydrodynamic routing between grid cells across the entire watershed, and potentially extensive data and calibration requirements (Rangari et al., 2019; David and Schmalz, 2021; Zeiger and Hubbart, 2021).

Early development and application of the RoG approach was in Australia in the early 2000s (Rehman et al, 2003). Rehman et al (2007) compared RoG routing with traditional routing methods in urban and semi-rural watersheds and found significant variation in the resulting overland flow hydrographs. Clark et al. (2008) conducted early research to determine the impact of grid cell size on model calibration and illustrated the need for adequate channel definition. Caddis et al. (2008) and Bailey and Margetts (2008) presented early case studies in urban watersheds that showed promising results when compared to traditional hydrologic models.

Since these early studies, industry acceptance of the RoG approach has increased, but determining its applicability, addressing known limitations, and developing recommendations for application remain active research areas. For example, David and Schmalz (2021) evaluated the impact of mesh size and DEM resolution on RoG model results. Results of 49 runs with DEM resolutions of 0.25 to 5 meters and mesh sizes of 2 to 30 meters were compared with a high-resolution benchmark (mesh resolution of 1m and DEM resolution of 0.25 m). In the studied watershed, a DEM resolution of 0.25 to 1 meter and mesh size of 3 to 5 meters was determined to optimize the tradeoff between computational efficiency and model accuracy. It also was found that coarse meshes (10 m and above) tend to create shallow, artificial depressions that greatly delay the runoff. Costabile et al. (2022) focused on the impacts of DEM depression filling using high resolution DEMs (1 to 5 m) and incorporated inertial and pressure terms in the flow equations, finding that the effects of filling depressions need to be evaluated on a case-by-case basis. Hariri et al. (2022) addressed computational time and computer memory issues when applying RoG models for large watersheds. They applied a domain decomposition method combining 2D sub-basin meshes and 1D channels with relevant boundary conditions to model a 1,747 km² watershed. Balancing computational load for a sparse parallel solver in HEC-RAS software (Brunner, 2016) was found to greatly reduce computational time.

Several studies have evaluated different software tools for RoG modeling, along with different models of hydrologic processes, in specific watershed settings. Costabile et al. (2021) published one of the first studies to assess the accuracy of HEC-RAS 2D for RoG simulations, whereas previous studies had applied HEC-RAS 2D with effective rainfall simulated by a hydrologic model, such as SWAT (Zeiger and Hubbard, 2021). More recently, Godara et al. (2024) compared two hydrodynamic models, TELEMAC-2D and HEC-RAS 2D, for their RoG model performance with a focus on runoff generation processes in a small and steep catchment. The CN method was applied in both the models to simulate single storm events up to 20 h of duration, and the Green-Ampt Redistribution (GAR) method was applied in HEC-RAS 2D for a multi-peak flood event. Results indicated that both models are capable of reproducing short duration single-storm floods, but they were not able reproduce the long- duration multi-peak flood event due to their inability to account for infiltration and sub-surface flow that contributes to river flow. In another recent case study, Chaitanya et al. (2024) applied RoG modeling to a river basin in India, finding that RoG models can be as accurate as coupled hydrologic and hydraulic models. Kumar et al. (2025) evaluated the accuracy of RoG simulations with variations in spatial resolution and simulation time steps, finding that coarser grid resolutions combined with finer temporal scales can achieve reduced errors and optimized computational efficiency for both micro- and macro-scale modeling.

3.5.2.2 Recommendations

The general steps in developing and applying a RoG model are as follows:

1. Determine watershed mesh scale and connectivity. While mesh scales of 30-50 meters may be suitable for some larger watershed areas, smaller scales (less than 10 meters) have been recommended to ensure model accuracy. Mesh scales of 3-5 meters, or even more refined, may be needed to represent channel flow areas.
2. Hydro-enforce and refine the mesh. This typically requires an iterative process with repeated simulations to correct anomalous flow patterns.
3. Rainfall or flood event selection. Design storm precipitation or single-peak flood events are typically used. Storm transposition with radar rainfall fields may also be used for flood frequency analysis, but this requires a large dataset of bias-adjusted radar rainfall events, which may not be readily available (Wright et al., 2014).
4. Determine inflows from upstream areas. Unless the entire watershed is represented by the mesh, inflow hydrographs may still need to be specified as upstream boundary conditions.
5. Determine downstream boundary conditions. This may be important if the downstream boundary of the model is affected by backwater conditions.
6. Validate and calibrate the model. Calibration parameters typically include infiltration model parameters (e.g., Runoff Curve Number) and flow resistance parameters (e.g., Manning's roughness). Flow resistance parameters must be estimated for both the watershed area and channel flow areas.

In summary, the benefits of RoG modeling include the following (Rehman, 2011; Vasconcelos et al., 2023):

- Recent studies have demonstrated the potential for integrated hydrologic and hydraulic models and have not found any inherent limitations of RoG modeling.
- For watersheds with low relief, RoG models with high-resolution DEMs and refined meshes may provide more accurate representation of flow distribution in the watershed.
- RoG models can take into account the watershed shape, as demonstrated by Rehman et al. (2003).
- RoG models provide high definition of flood behavior, including flow rates, depths, and velocities at the mesh scale for any location in the watershed, supporting the choice of flow management measures at different scales.

The limitations of RoG models include the following:

- Differences in handling of the convective momentum term of the shallow water equations in the solution scheme can produce different flow behavior in the steeper parts of the basin, resulting in different overland flow travel times.
- Flow resistance (roughness) applicable to shallow depths of overland flow may be difficult to estimate. In general, roughness coefficients would be much higher for shallow flow depths than for deeper flows.

- An appropriate rainfall loss model is required for accurate modeling of runoff, and current 2D modelling systems may not accommodate different rainfall loss methods. Incorporating more complex rainfall loss models, or including subsurface flow, would increase the computational demand of the model.
- Mesh size may impact overland flow behavior, and for large watersheds or watersheds with high drainage density, mesh size may become a limitation due to high computational demands.
- Due to a limited number of applications and a lack of detailed guidelines, the RoG approach should preferably be used in watersheds where calibration data is available. Thus, the approach may have limited applicability in rural basins.

4. Conclusions

4.1 Conclusions from the Study

This study developed recommendations for updated methods for estimating flood discharges in ungaged watersheds for MDOT and EGLE. A curve number-based method for small watersheds (drainage areas generally less than 20 square miles) was updated to use rainfall frequency values and storm distributions from NOAA Atlas 14, Volume 8: Midwestern States (Perica et al., 2013). Analyses were also conducted to update the unit hydrograph model used in Michigan, with new peak rate factors and unit peak discharge equations derived for regions of the state. In addition, automated GIS-based tools were developed for hydro-enforcement and watershed delineation, and the current manual method for estimating time of concentration was evaluated for possible automation using GIS tools.

Another major task completed in this study was to analyze GIS data for developing SCS (NRCS) Curve Numbers. Land use/land cover datasets were evaluated for their potential to improve hydrologic calculations, and updated land use/land cover datasets were developed and recommended for use. The new dataset uses the latest National Land Cover Database combined with a Michigan-specific wetlands layer previously developed by Michigan Tech researchers at MTRI. Automated GIS-based tools were developed for deriving weighted CN values from the updated land use/land cover dataset combined with the SSURGO soils database, with extensive feedback from MDOT and EGLE end-users.

The regional regression models for flood discharges in Michigan, typically used for flood discharge calculations in larger watersheds, were also revised. The revised regression models are based on updated streamflow records and improved statistical techniques compared to the previous equations. They also use readily available geospatial datasets and are more efficient in that fewer parameters are fit for each region. Comparison of flood discharge estimates from the regression models and from the curve number-based method found that the regression model estimates more closely match the site-specific statistics for watersheds with contributing drainage areas as small as 10 mi², indicating that the regression model equations should also be considered for application to watersheds in this size range.

Both the updated curve number-based method and regression equations can easily be implemented in spreadsheet tools. To facilitate implementation of the curve-number based method, unit peak discharge equations were derived for each combination of rainfall distribution and unit hydrograph peak rate factor. All GIS layers and calculation procedures are made available to determine the independent variables (watershed parameters) in the regression models.

Integrated hydrologic-hydraulic modeling (i.e., rain-on-grid) approaches were reviewed and determined to be insufficiently developed, or standardized, for flood frequency analyses at this

time. However, incorporation of climate projections and non-stationary statistical approaches in rainfall frequency analysis is becoming more widely accepted, and the anticipated publication of NOAA Atlas 15 in 2026 will provide future precipitation estimates that account for trends and projected changes.

4.2 Recommendations for Further Research

Floods in Michigan can be caused by heavy rainfall that exceeds soil infiltration capacity, rainfall occurring on saturated soils, rapid snowmelt, and rain-on-snow events. Bulletin 17C recommends that observed peak flow values used in flood frequency estimation be separated by flood generation type. However, this step is often overlooked due to limited available data and minimal guidance on techniques to identify flood-generating mechanisms. Separating flood events by type can explain trends in flood magnitude and timing and improve flood frequency analysis (Gudmundsson, 2019; Villarni and Slater, 2017; Mallakpour and Villarini, 2015).

A second recommendation for future research is to explore nonlinear relationships between basin characteristics and flood frequency estimates using machine learning (ML) tools. Basin attributes have complex relationships that influence water storage and water flow through a watershed. Many related fields have utilized ML to analyze relationships between land and climate characteristics, including agriculture, ecology, wetland classification, landcover classification, and hydrology (Brunner et al., 2018; Trambly, 2024). Several studies have specifically investigated the use of nonlinear methods for flood discharge estimation, including artificial neural networks (Aziz et al., 2014), generalized additive models (Rahman et al., 2018), multivariate adaptive regression splines (Msilini et al., 2020; Pezhman 2020), and random forest regression (Pezhman 2020; Desai, 2021; Esmaeili-Gisavandani, 2023; Mangukiya, 2023; Trambly, 2024). Studies that employed ML in regional flood frequency analysis have found that the techniques were able to identify nonlinear relationships between basin physiometeorological attributes and flood frequency, even in areas with sparse data (Mangukiya, 2023), and that ML techniques outperformed multiple linear regression in predicting peak flows (Esmaeili-Gisavandani et al., 2023).

Two specific factors in the current RCN-based method that may be evaluated in future research are the pond/swamp reduction factors and precipitation areal reduction factors. This study reviewed the procedure used to apply pond/swamp reduction factors, but revised factors were not considered in the watershed analyses. Doing so may be challenging without additional data, because there are multiple parameters in the method that need to be estimated, and different combinations of parameter values may give similar results. Precipitation areal reduction factors were also not evaluated in this study, as NOAA Atlas 14 does not provide updates and recommends the continued use of curves in US Weather Bureau TP 29 (US Weather Bureau, 1960). Updates may be available in Atlas 15.

Future hydrologic studies should attempt to expand the rain and streamflow gage network used in the analyses. While more hydroclimatic gages throughout the state would be beneficial, there is a particular need for additional gages in the northern Lower Peninsula and eastern Upper Peninsula. New data sources should also be explored. Investigation of satellite-based datasets in this study found them to have low fidelity (both spatially and temporally) for modeling individual storm events, but a recently developed gage-adjusted radar rainfall dataset for southeastern Michigan proved useful. A standardized storm event database, as was used in recent related studies in Indiana (Huang and Merwade, 2024) and Texas (Lasco et al, 2022), would also be very useful.

Finally, with additional time and funding, it is possible that more of the workflow processes and updated equations, including time of concentration and pond/swamp area calculations, could be integrated into automated software tools, as was done for watershed delineation and RCN calculations in the MTU Hydro Tools for ArcGIS Pro. It may also be possible to move some tools online for ready access and updating.

4.3 Recommendations for Implementation

The primary recommendation for implementation is for MDOT and EGLE to adopt the processes, equations, and ArcGIS tools developed through this project. The main steps recommended for implementation are:

- Provide training opportunities for newer staff to ensure that MDOT and EGLE staff are aware of and able to use the project's outputs and products.
- Maintain a MDOT/EGLE group with regular meetings to ensure coordination on tool usage and documenting common questions arising from their use.
- Provide a method to continue working with groups knowledgeable about hydrologic calculations with a geospatial focus, such as the Michigan Tech team. This will also provide a way for GIS tool questions to be answered quickly, and to enable rapid updates when ESRI introduces new versions of ArcGIS Pro. This could be done with a "basic" support contract for maintaining the current version of the MTU Hydro Tools for ArcGIS Pro, with support to answer user questions.

The costs of implementation will vary depending on the value that MDOT and EGLE find in using the project's tools, processes, and equations. MDOT has historically had a staff training budget that could potentially help cover staff training costs mentioned above. The recommendation to keep working with our research team can be provided at a reasonable cost, now that primary tool development is completed, and can be arranged as a service support contract through a Job Number. The project team would look forward to the opportunity to help MDOT be a leader in the use of advanced hydrologic methods and tools.

5. Bibliography

American Society of Civil Engineers (ASCE), 2009, Curve Number Hydrology – State of the Practice, ASCE/EWRI Runoff Curve Number Hydrology Task Committee.

Asquith, W., and R. Slade, 1997, Regional Equations for Estimation of Peak Streamflow Frequency for Natural Basins in Texas, USGS Water-Resources Investigations Report 96-4307.

Aziz, K., Rahman, A., Fang, G. et al., 2014, Application of artificial neural networks in regional flood frequency analysis: a case study for Australia. *Stoch Environ Res Risk Assess* 28, 541–554 (2014). <https://doi.org/10.1007/s00477-013-0771-5>.

Bailey, A. and Margetts, J., 2008, 2D Runoff Modelling – A Pipe Dream or the Future?, WaPUG Autumn Conference: The Chartered Institution of Water and Environmental Management, Blackpool, November 2008.

Barnhart, T.B., Smith, M., Rea, A., Kolb, K., Steeves, P., and McCarthy, P., 2020, StreamStats Data Preparation Tools, version 4: USGS Software Release, <https://doi.org/10.5066/P9UM2NUL>.

Bonnin, G. M., K. Maitaria, and M. Yekta, 2011, Trends in Rainfall Exceedances in the Observed Record in Selected Areas of the United States. *Journal of the American Water Resources Association (JAWRA)* 47(6): 1173–1182. DOI: 10.1111/j.1752-1688.2011.00603.x

Briley, L. J., Rood, R. B., and Notaro, M., 2021, Large lakes in climate models: A Great Lakes case study on the usability of CMIP5. *Journal of Great Lakes Research*, 47(2), 405–418. <https://doi.org/10.1016/j.jglr.2021.01.010>.

Brunner G. W., 2016, HEC-RAS River Analysis System, 2D Modeling User's Manual Version 5.0. U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis.

Brunner, M. I., Furrer, R., Sikorska, A. E., Viviroli, D., Seibert, J., and Favre, A.-C., 2018, Synthetic design hydrographs for ungauged catchments: A comparison of regionalization methods. *Stochastic Environmental Research and Risk Assessment*, 32(7), 1993–2023. <https://doi.org/10.1007/s00477-018-1523-3>.

Caddis, B.M., Jempson, M.A., Bell, J.E., and Syme, W.J., 2008, Incorporating Hydrology into 2D Hydraulic Models – The Direct Rainfall Approach, 9th National Conference on Hydraulics in Water Engineering: Engineers Australia, Darwin, NT, September 23-26, 2008.

Chaitanya, J. C., Sridharan, B., and Kuiry, S. N., 2024, The rain-on-grid modeling approach in hydrological and hydraulic processes over a river basin. In *World Environmental and Water Resources Congress 2024* (pp. 221-232).

Clark, K.M., Ball, J.E. and Babister, M.K., 2008, Can Fixed Grid 2D Hydraulic Models be Used as Hydrologic Models?, International Conference on Water Resources and Environment Research: Engineers Australia, Adelaide, SA, 2008.

Costabile, P., Costanzo, C., Gandolfi, C., Gangi, F., and Masseroni, D. (2022). Effects of DEM depression filling on river drainage patterns and surface runoff generated by 2D rain-on-grid scenarios. *Water*, 14(7), 997.

Costabile, P., Costanzo, C., Ferraro, D., and Barca, P. (2021). Is HEC-RAS 2D accurate enough for storm-event hazard assessment? Lessons learnt from a benchmarking study based on rain-on-grid modelling. *Journal of Hydrology*, 603, 126962.

David, A., and Schmalz, B., 2021, A systematic analysis of the interaction between rain-on-grid-simulations and spatial resolution in 2D hydrodynamic modeling. *Water*, 13(17), 2346.

David, A., and Schmalz, B., 2020, Flood hazard analysis in small catchments: Comparison of hydrological and hydrodynamic approaches by the use of direct rainfall. *Journal of Flood Risk Management*, 13(4), e12639.

Desai, S., and Ouarda, T. B. M. J., 2021, Regional hydrological frequency analysis at ungauged sites with random forest regression. *Journal of Hydrology*, 594, 125861.
<https://doi.org/10.1016/j.jhydrol.2020.125861>.

EGLE, 2019. LiDAR: A new way to view Michigan's terrain.
<https://www.michigan.gov/mienviroment/0,9349,7-385-90161-510934--,00.html>.

EGLE, 2021. Michigan Resource Inventory System (MIRIS) Wetland Classes,
https://gis-michigan.opendata.arcgis.com/datasets/ee0328e42b1a433795b3e67c40385728_7

Eng, K., Chen, Y.-Y., and Kiang, J.E., 2009, User's guide to the weighted-multiple-linear-regression program (WREG version 1.0): U.S. Geological Survey Techniques and Methods, book 4, chap. A8, 21 p., <https://pubs.usgs.gov/tm/tm4a8/>.

England, J.F., Jr., Cohn, T.A., Faber, B.A., Stedinger, J.R., Thomas, W.O., Jr., Vielleux, A.G., Kiang, J.E., and Mason, R.R., Jr., 2018, Guidelines for determining flood flow frequency– Bulletin 17C (ver. 1.1, May, 2019): U.S. Geological Survey Techniques and Methods, book 4, chap. B5, 148 p., <https://pubs.usgs.gov/publication/tm4B5>.

Esmaeili-Gisavandani, H., Zarei, H., and Fadaei Tehrani, M. R., 2023, Regional flood frequency analysis using data-driven models (M5, random forest, and ANFIS) and a multivariate regression method in ungauged catchments. *Applied Water Science*, 13(6), 139.
<https://doi.org/10.1007/s13201-023-01940-3>.

Kilgore, R., Bhat, Sharar-Salgado, C., and Kafalenos, R., 2021, Coupled Model Intercomparison Project (CMIP) Climate Data Processing Tool 2.1 User's Guide.

- Flynn, K.M., Kirby, W.H., and Hummel, P.R., 2006, User's manual for program PeakFQ, annual flood frequency analysis using Bulletin 17B guidelines: U.S. Geological Survey Techniques and Methods, book 4, chap. B4, 42 p., <https://pubs.usgs.gov/tm/2006/tm4b4/tm4b4.pdf>.
- Greiner, S. "Small Watersheds". Received by S. Toivonen and M.K. Watkins, Dec 22, 2021.
- Griffis, V.W., 2003, Evaluation of log-Pearson Type 3 Flood Frequency Analysis Methods Addressing Regional Skew and Low Outliers, MS Thesis, Cornell University.
- Griffis, V.W., 2008, EMA with historical information, low outliers, and regional skew. Proceedings of the World Environmental & Water Resources Congress 2008: Ahupua'a, Editors R. W. Babcock and R. Walton, American Society of Civil Engineers, Reston, VA.
- Griffis, V.W., Stedinger, J.R., and Cohn, T.A., 2004, LP3 quantile estimators with regional skew information and low outlier adjustments, *Water Resources Research*, vol.40, W07503, doi:10.29/2003WR002697.
- Griffis, V.W., and Stedinger, J.R., 2007, The Use of GLS Regression in Regional Hydrologic Analyses, *Journal of Hydrology*, 344(1-2), 82-95.
- Gudmundsson, L., Leonard, M., Do, H. X., Westra, S., and Seneviratne, S. I., 2019, Observed Trends in Global Indicators of Mean and Extreme Streamflow. *Geophysical Research Letters*, 46(2), 756–766. <https://doi.org/10.1029/2018GL079725>.
- Hariri, S., Weill, S., Gustedt, J., and Charpentier, I., 2022. A balanced watershed decomposition method for rain-on-grid simulations in HEC-RAS. *Journal of Hydroinformatics*, 24(2), 315-332.
- Hellweger, F., 1997, AGREE - DEM Surface Reconditioning System. TXDOT. <https://www.caee.utexas.edu/prof/maidment/gishydro/ferdi/research/agree/agree.html>
- Holtschlag, D.J., and Croskey, H.M., 1984, Statistical models for estimating streamflow characteristics of Michigan streams: U.S. Geological Survey Water-Resources Investigations Report 84-4207, 80 p.
- Huang, T., and Merwade, V., 2024, Developing Customized NRCS Unit Hydrographs for Ungauged Watersheds in Indiana. *Journal of Hydrologic Engineering*, 29(4), 04024022.
- Huff, F.A., and Angel, J.R., 1992, Rainfall Frequency Atlas of the Midwest. Illinois State Water Survey, Bulletin 71, Champaign, IL. <https://www.isws.illinois.edu/pubdoc/B/ISWSB-71.pdf>
- Jabri, B., and Hessane, M.A., 2020, Production of a Curve Number map using GIS Techniques in the watershed of the high Sebou (Morocco), E3S Web of Conferences, https://www.e3s-conferences.org/articles/e3sconf/pdf/2020/10/e3sconf_ed72020_03003.pdf.
- Koltun, G.F., and Whitehead, M.T., 2002, Techniques for estimating selected streamflow characteristics of rural, unregulated streams in Ohio: U.S. Geological Survey Water-Resources Investigations Report 2002-4068, 50 p., <https://doi.org/10.3133/wri024068>.

Koltun, G.F., 2003, Techniques for Estimating Flood-Peak Discharges of Rural, Unregulated Streams in Ohio, 2nd Edition: U. S. Geological Survey Water-Resources Investigations Report 03-4164, 76 p.

Koltun, G.F., 2019, Flood-frequency estimates for Ohio streamgages based on data through water year 2015 and techniques for estimating flood-frequency characteristics of rural, unregulated Ohio streams: U.S. Geological Survey Scientific Investigations Report 2019-5018, 25 p., <https://doi.org/10.3133/sir20195018>.

Kunkel, K. E., Karl, T. R., Easterling, D. R., Redmond, K., Young, J., Yin, X., and Hennon, P., 2013, Probable maximum precipitation and climate change. *Geophysical Research Letters*, 40(7), 1402-1408.

Lasco, J. D. D., Olivera, F., and Sharif, H. O., 2022, Unit hydrograph peak rate factor estimation for Texas watersheds. *Journal of Hydrologic Engineering*, 27(11), 04022026.

Levin, S.B., and Sanocki, C.A., 2023, Estimating flood magnitude and frequency for unregulated streams in Wisconsin: U.S. Geological Survey Scientific Investigations Report 2022-5118, 25 p., <https://doi.org/10.3133/sir20225118>. [Supersedes Scientific Investigations Report 2016-5140.]

Lorenz, D.L., Sanocki, C.A., and Kocian, M.J., 2010, Techniques for estimating the magnitude and frequency of peak flows on small streams in Minnesota based on data through water year 2005: U.S. Geological Survey Scientific Investigations Report 2009-5250, 54 p.

Lyne, V., and Hollick, M., 1979, Stochastic time-variable rainfall-runoff modelling. In *Institute of engineers Australia national conference* (Vol. 79, No. 10, pp. 89-93). Barton, Australia: Institute of Engineers Australia.

Mallakpour, I., and Villarini, G., 2015, The changing nature of flooding across the central United States. *Nature Climate Change*, 5(3), 250-254. <https://doi.org/10.1038/nclimate2516>

Mangukiya, N. K., Kumar, A., and Sharma, A., 2023, Machine learning-based regional flood frequency analysis of Indian watersheds. *CLEAN – Soil, Air, Water*, n/a(n/a), 2300120. <https://doi.org/10.1002/clen.202300120>

Mastin, M.C., Konrad, C.P., Veilleux, A.G., and Tecca, A.E., 2016, Magnitude, frequency, and trends of floods at gaged and ungaged sites in Washington, based on data through water year 2014 (ver 1.2, November 2017): U.S. Geological Survey Scientific Investigations Report 2016-5118, 70 p., accessed November 28, 2018, at <http://dx.doi.org/10.3133/sir20165118>.

Melching, C.S., and Marquardt, J.S., 1997, Equations for Estimating Synthetic Unit-Hydrograph Parameter Values for Small Watersheds in Lake County, Illinois: U.S. Geological Survey Water-Resources Investigations Report 96-474.

McCuen, R.H., 1989, *Hydrologic Analysis and Design*, Prentice-Hall, Upper Saddle River, NJ.

Michigan Department of Transportation (MDOT), 2006, MDOT Drainage Manual Chapter 3 Hydrology: 3.3.8 Hydrologic Analysis. https://www.michigan.gov/mdot/0,4616,7-151-9621_11041_91575_91583-93193--,00.html.

Montgomery, D.C., Peak, E.A., and Vining, G.G., 2012, Introduction to Linear Regression Analysis, 5th Edition, John Wiley & Sons, Inc, Hoboken, NJ. ISBN: 978-0-470-54281-1.

Msilini, A., Masselot, P., and Ouarda, T. B. M. J., 2020, Regional Frequency Analysis at Ungauged Sites with Multivariate Adaptive Regression Splines. *Journal of Hydrometeorology*, 21(12), 2777–2792.

North Dakota Natural Resources Conservation Service (NRCS), 2017, Supplement to NEH Part 650, Engineering Field Handbook Chapter 2 (EFH-2).

Papalexiou, S. M., and Montanari, A., 2019, Global and regional increase of precipitation extremes under global warming. *Water Resources Research*, 55(6), 4901-4914.

Perica, S., D. Martin, S. Pavlovic, I. Roy, M. St. Laurent, C. Trypaluk, D. Unruh, M. Yekta, G. Bonnin, 2013, NOAA Atlas 14 Volume 8 Version 2, Precipitation-Frequency Atlas of the United States, Midwestern States. NOAA, National Weather Service, Silver Spring, MD. https://www.weather.gov/media/owp/oh/hdsc/docs/Atlas14_Volume8.pdf.

Pezhman, A.-F., Mehdi, V., Hadi, K.-F., and Elke, H., 2020, Regional Flood Frequency Analysis Through Some Machine Learning Models in Semi-arid Regions. *Water Resources Management*, 34(9), 2887–2909. <https://doi.org/10.1007/s11269-020-02589-2>

Rahman, A., Charron, C., Ouarda, T. B. M. J., and Chebana, F., 2018, Development of regional flood frequency analysis techniques using generalized additive models for Australia. *Stochastic Environmental Research and Risk Assessment*, 32(1), 123–139. <https://doi.org/10.1007/s00477-017-1384-1>

Rehman, H., 2011, Rainfall-on-Grid Modelling-a Decade of Practice, Proceedings of the 34th IAHR World Congress, Brisbane, June 26 - July 1, 2011.

Rehman, H., Thomson, R and Watterson, E., 2007, Hydrology in Urban Areas – ‘Rainfall on the Grid’ Versus Traditional Methodologies, 47th Floodplain Management Authorities Conference: Floodplain Management Authority of NSW, Gunnedah, NSW, February 27 – March 2, 2007.

Rehman, H., Zollinger, M.W and Collings, G.B., 2003, Hydrological vs Hydraulic Routing Possibilities with Two-Dimensional Hydraulic Modelling, 28th International Hydrology and Water Resources Symposium: The Institution of Engineers Australia, Wollongong, NSW, November 2003.

Rossman, L.A., 2015, Storm Water Management Model User's Manual Version 5.1, EPA/600/R-14/413b, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Sanocki, C.A., and Levin, S.B., 2023, Techniques for estimating the magnitude and frequency of peak flows on small streams in Minnesota, excluding the Rainy River Basin, based on data through water year 2019: U.S. Geological Survey Scientific Investigations Report 2023–5079, 15 p., <https://doi.org/10.3133/sir20235079>.

Sheridan, J.M., Merkel, W.H., and Bosch, D.D., 2002, Peak Rate Factors For Flatland Watersheds, *Transactions of the ASAE*, 18(1): 65-69.

Soil Survey Staff, 2021, Natural Resources Conservation Service, United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database, <https://sdmdataaccess.sc.egov.usda.gov>.

Sommers, L.M. (1984). *Michigan: A Geography*, Westview Press, Boulder, CO.

Sorrell, R.C., 2010, Computing Flood Discharges for Small Ungaged Watersheds. https://www.michigan.gov/documents/deq/wrd-scs_558239_7.pdf.

Stedinger, J.R., and Tasker, G.D., 1985, Regional hydrologic analysis: 1. Ordinary, weighted and generalized least squares compared, *Water Resources Research*, 21(9), 1421-1432.

Stedinger, J.R., and Tasker, G.D., 1989, An operational GLS model for hydrologic regression, *Journal of Hydrology*, 111(1), 361-375.

Tasker, G.D., and Stedinger, J.R., 1986, Regional Skew with Weighted LS Regression, *Journal of Water Resources Planning and Management*, 112(2), 225–237.

Tramblay, Y., Villarini, G., Saidi, M.E. et al., 2022, Classification of flood-generating processes in Africa. *Sci Rep* 12, 18920. <https://doi.org/10.1038/s41598-022-23725-5>.

US Army Corps of Engineers (USACE), 2020, Hydrologic modeling system HEC-HMS: User's manual, version 4.7, US Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA.

USACE, 2023. Creating a Curve Number Grid and Computing Subbasin Average Curve Number Values. USACE Hydrologic Engineering Center. <https://www.hec.usace.army.mil/confluence/hmsdocs/hmsguides/gis-tutorials-and-guides/creating-a-curve-number-grid-and-computing-subbasin-average-curve-number-values#CreatingaCurveNumberGridandComputingSubbasinAverageCurveNumberValues-DatasetsforCreatingtheCurveNumberGrid>.

US Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS), 1975, Urban Hydrology for Small Watersheds, Technical Release No. 55 (TR-55), Washington, D.C.

USDA, NRCS, 1986, Urban Hydrology for Small Watersheds, Technical Release No. 55 (TR-55), 2nd edition, Washington, D.C.

USDA, NRCS, 2004, WinTR-20 User's Guide (draft), Washington, D.C.

- USDA, NRCS, 2007, Part 630 Hydrology: National Engineering Handbook, Chapter 16 Hydrographs.
<https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/manage/hydrology/?cid=stelprdb1043063>
- USDA, NRCS, 2010, Part 630 Hydrology: National Engineering Handbook, Chapter 15 Time of Concentration.
- USDA, NRCS, 2019, Part 630 Hydrology: National Engineering Handbook, Chapter 4 Storm Rainfall Depth and Distribution.
- US Geological Survey (UGGS), n.d., Multi-Resolution Land Characteristics (MRLC) Consortium. United States Geological Service (USGS) Multi-Resolution Land Characteristics Consortium Land Cover raster set. <https://www.mrlc.gov/data>.
- U.S. Weather Bureau, 1960, Rainfall intensity-frequency regime. U.S. Weather Bureau Technical Paper No. 29.
- Vasconcelos, J. G., Fang, X., Geller, V. G., Nicolaico, G. G., and Reyes, E. M., 2023, Resilient Design with Distributed Rainfall-Runoff Modeling, NCHRP Project 20-05, Topic 53-11.
- Veilleux, A.G., 2009, Bayesian GLS regression for regionalization of hydrologic statistics, floods and Bulletin 17 skew: Ithaca, N.Y., Cornell University, master's thesis, 155 p.
- Villarini, G., and Slater, L., 2017, Climatology of flooding in the United States. Oxford University Press. <https://doi.org/10.1093/acrefore/9780199389407.013.123>.
- Walker, J.F., and Krug, W.R., 2003, Flood-Frequency Characteristics of Wisconsin Streams: U.S. Geological Survey Water-Resources Investigations Report 03–4250.
- Walker, J.F., Peppler, M.C., Danz, M.E., and Hubbard, L.E., 2017, Flood-frequency characteristics of Wisconsin streams (ver. 2.2, April 2020): Reston, Virginia, U.S. Geological Survey Scientific Investigations Report 2016–5140, 33 p., 1 plate, 2 appendixes, <https://doi.org/10.3133/sir20165140>.
- Wright, D.B., Smith, J.A., and Baeck, M.L., 2014, Flood frequency analysis using radar rainfall fields and stochastic storm transposition, Water Resources Research 50(2), 1592-1615. <https://doi.org/10.1002/2013WR014224>.
- Wright, D. B., Bosma, C. D., and Lopez-Cantu, T., 2019, US hydrologic design standards insufficient due to large increases in frequency of rainfall extremes. Geophysical Research Letters, 46(14), 8144-8153.

6. Appendices

Appendix A: Supplemental Results

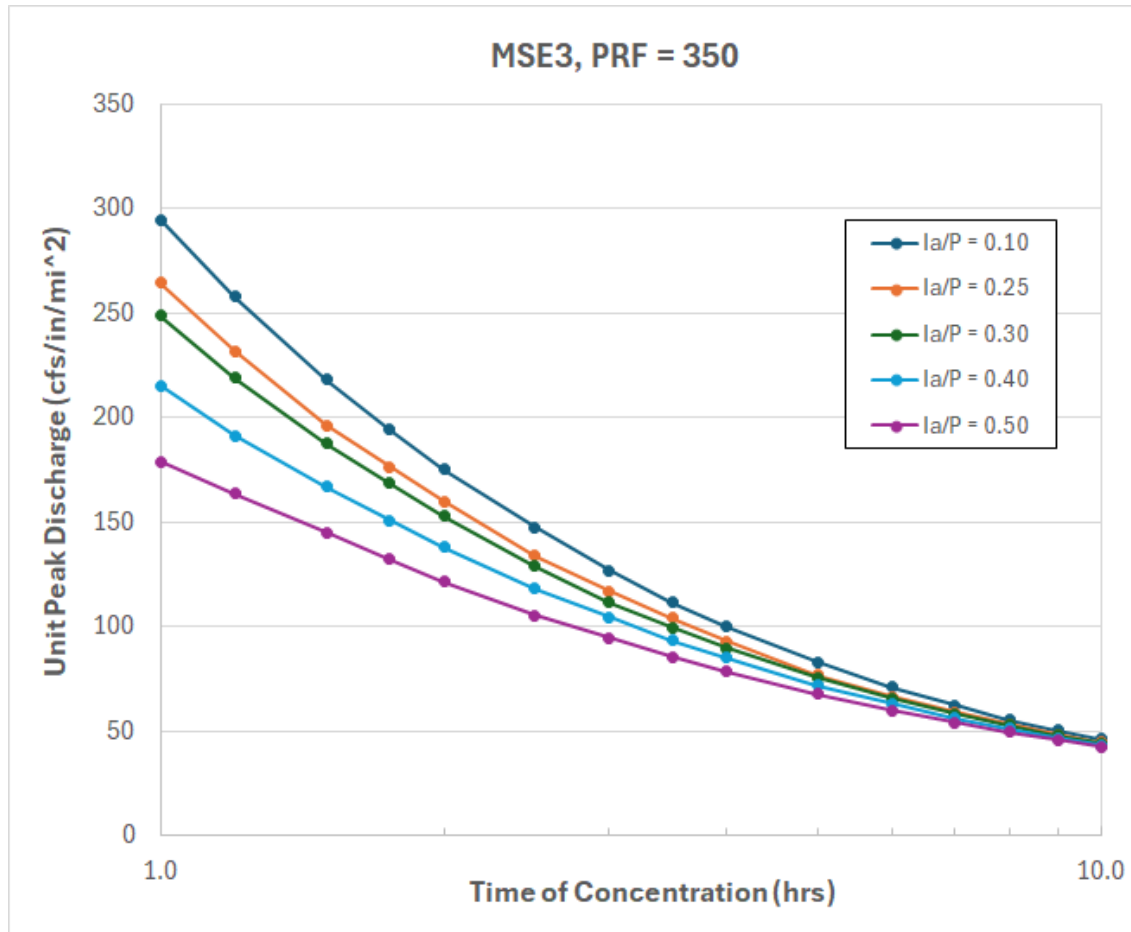


Figure 6.1. Unit peak discharge curves for MSE3, PRF = 350.

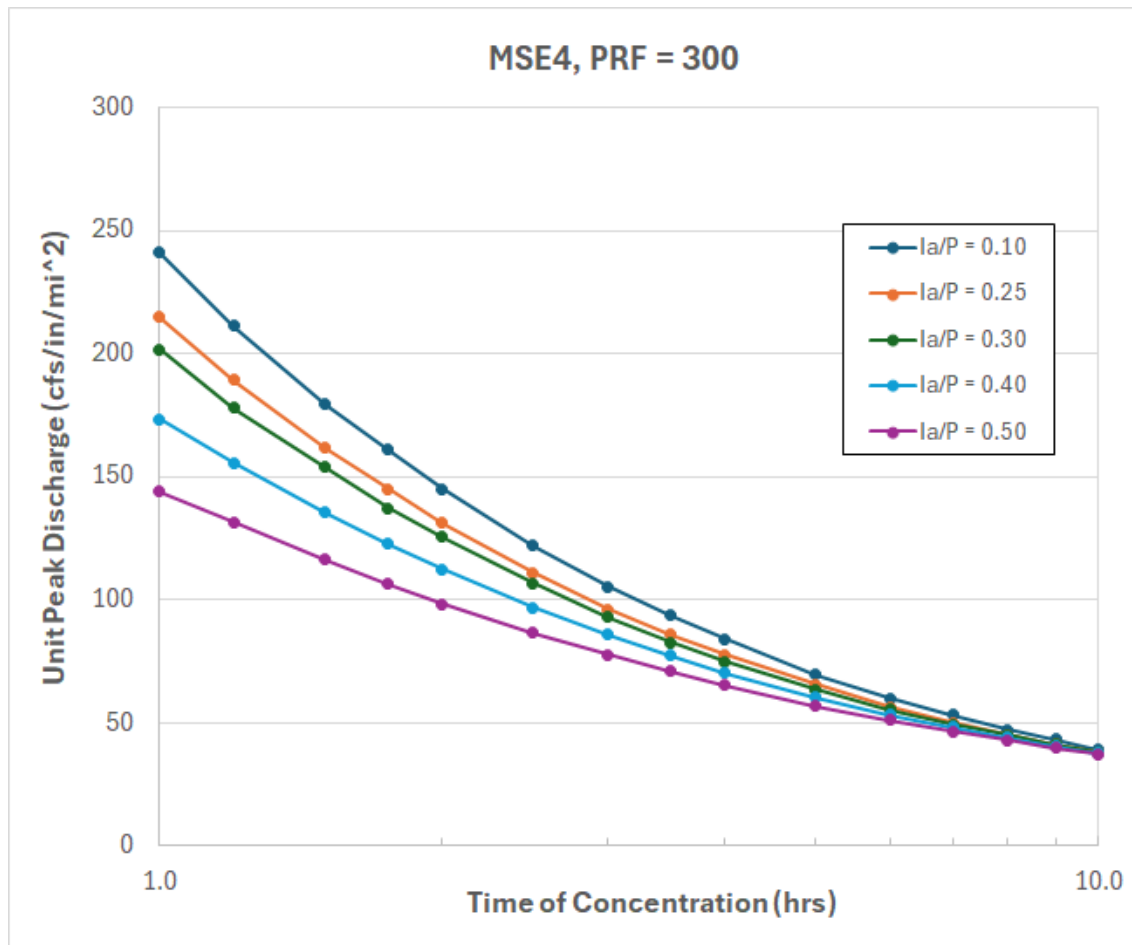


Figure 6.2. Unit peak discharge curves for MSE4, PRF = 300.

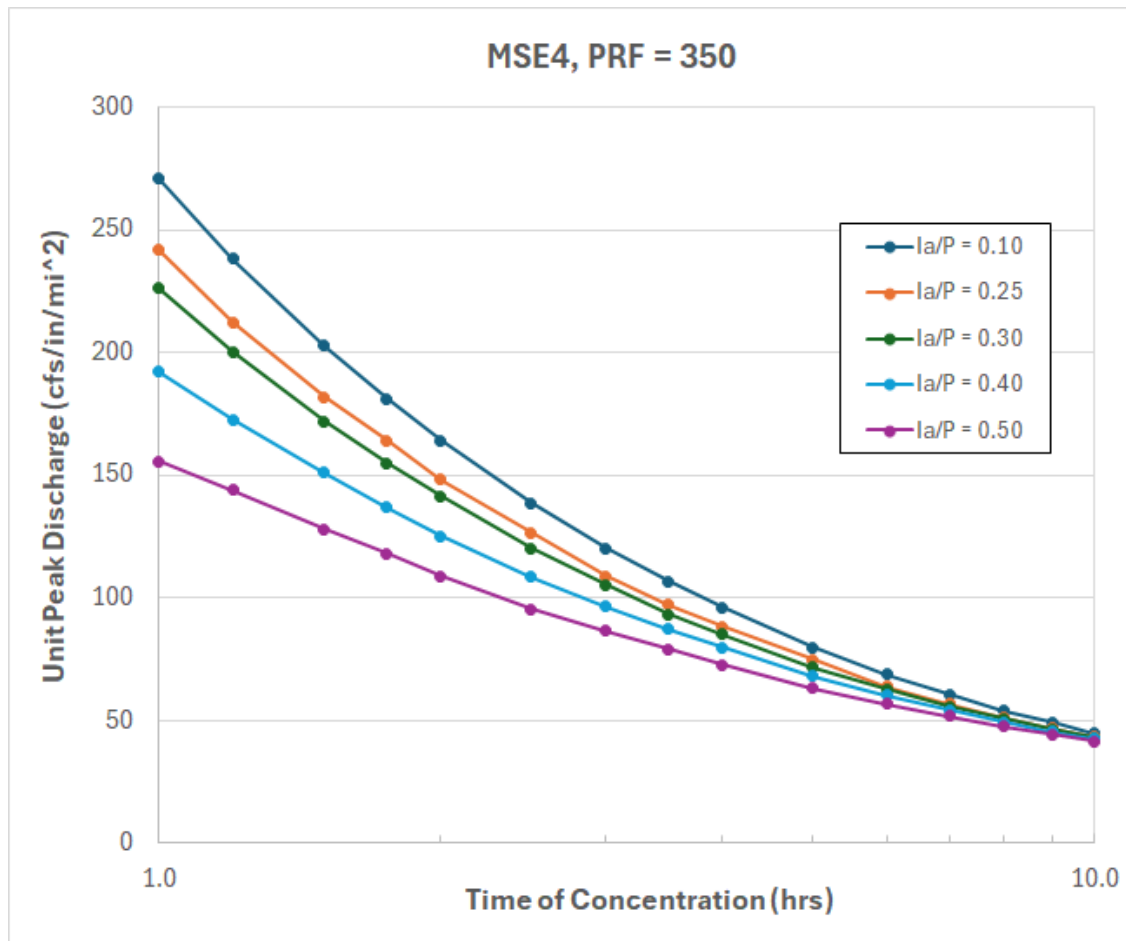


Figure 6.3. Unit peak discharge curves for MSE4, PRF = 350.

Table 6.1. NRCS rainfall distributions for Michigan counties.

County	Rainfall Distribution	County	Rainfall Distribution	County	Rainfall Distribution
Alcona	MSE3	Gratiot	MSE4	Missaukee	MSE3
Alger	MSE3	Hillsdale	MSE3	Monroe	MSE3
Allegan	MSE3	Houghton	MSE4	Montcalm	MSE3
Alpena	MSE3	Huron	MSE3	Montmorency	MSE4
Antrim	MSE3	Ingham	MSE3	Muskegon	MSE4
Arenac	MSE3	Ionia	MSE3	Newaygo	MSE4
Baraga	MSE4	Iosco	MSE3	Oakland	MSE3
Barry	MSE3	Iron	MSE4	Oceana	MSE4
Bay	MSE3	Isabella	MSE3	Ogemaw	MSE3
Benzie	MSE3	Jackson	MSE3	Ontonagon	MSE4
Berrien	MSE3	Kalamazoo	MSE3	Osceola	MSE3
Branch	MSE3	Kalkaska	MSE3	Oscoda	MSE3
Calhoun	MSE3	Kent	MSE4	Otsego	MSE3
Cass	MSE3	Keweenaw	MSE4	Ottawa	MSE4
Charlevoix	MSE3	Lake	MSE3	Presque Isle	MSE4
Cheboygan	MSE4	Lapeer	MSE3	Roscommon	MSE3
Chippewa	MSE3	Leelanau	MSE3	Saginaw	MSE3
Clare	MSE3	Lenawee	MSE3	Sanilac	MSE3
Clinton	MSE3	Livingston	MSE3	Schoolcraft	MSE3
Crawford	MSE3	Luce	MSE3	Shiawassee	MSE3
Delta	MSE3	Mackinac	MSE3	St. Clair	MSE3
Dickinson	MSE4	Macomb	MSE3	St. Joseph	MSE3
Eaton	MSE3	Manistee	MSE3	Tuscola	MSE3
Emmet	MSE3	Marquette	MSE4	Van Buren	MSE3
Genesee	MSE3	Mason	MSE4	Washtenaw	MSE3
Gladwin	MSE3	Mecosta	MSE3	Wayne	MSE3
Gogebic	MSE4	Menominee	MSE4	Wexford	MSE3
Grand Traverse	MSE3	Midland	MSE3		

Table 6.2. Unit hydrograph analysis results by watershed

<i>Watershed</i>	<i>N_events</i>	<i>PRF</i>	<i>ABS(%Err Vol)</i>	<i>ABS(%Err Qp)</i>	<i>ABS(%Err Tr)</i>
S.B. Raisin River 04175748	1	250	14.5	16.4	3.4
		300	16.0	17.8	5.2
		350	18.7	17.8	6.9
		400	20.6	18.4	6.9
		484	22.8	22.8	5.2
M.B. Clinton River 04164800	11	250	22.9	13.3	23.6
		300	21.4	13.1	19.9
		350	20.4	12.6	12.6
		400	19.7	12.1	9.4
		484	18.4	11.2	7.0
U. River Rouge at Farm. 04166300	4	250	8.6	9.6	29.4
		300	8.0	6.8	32.1
		350	9.5	4.0	31.7
		400	10.9	4.8	34.2
		484	13.3	6.5	32.5
Plum Brook at Utica 04163400	5	250	2.0	6.6	5.6
		300	3.1	6.1	8.8
		350	4.6	7.9	9.7
		400	7.4	10.2	13.3
		484	12.5	13.4	18.1
River Rouge at Birmingham 04166000	1	250	0.1	15.6	4.2
		300	3.7	11.5	4.2
		350	7.1	7.3	0.0
		400	11.1	3.7	0.0
		484	16.9	2.6	4.2
Sloan Creek 04112000	4	250	6.6	8.5	5.6
		300	9.2	10.8	5.0
		350	12.1	13.3	4.3
		400	14.2	15.9	5.6
		484	18.1	20.2	6.1
Dickinson Creek 041035285	1	250	18.8	9.5	5.6
		300	23.2	12.9	5.6
		350	27.8	15.6	11.1
		400	32.5	16.2	11.1
		484	37.1	22.5	11.1
Dowagiac Creek 04101590	2	250	11.3	6.8	40.8
		300	16.0	9.1	47.6
		350	20.0	11.8	50.2
		400	24.6	14.9	54.4
		484	31.0	20.6	55.5
Augusta Creek 04105700	4	250	11.2	5.8	48.3
		300	16.9	4.8	46.0
		350	20.3	7.3	48.5
		400	24.1	8.2	52.9
		484	30.0	12.1	51.7

Table 6.2 (Continued). Unit hydrograph analysis results by watershed

<i>Watershed</i>	<i>N_events</i>	<i>PRF</i>	<i>ABS(%Err Vol)</i>	<i>ABS(%Err Qp)</i>	<i>ABS(%Err Tr)</i>
Portage Creek 04106500	3	250	36.0	16.8	50.0
		300	42.4	13.3	50.0
		350	46.8	10.1	50.0
		400	50.4	7.9	50.0
		484	54.5	5.8	41.7
Pigeon River @ 120th Ave 04108862	2	250	2.9	6.0	0.0
		300	4.9	5.7	0.8
		350	7.9	8.5	2.4
		400	11.2	11.1	3.2
		484	15.3	16.7	4.8
Ecorse River 04168580	6	250	5.1	4.9	41.6
		300	6.5	4.5	49.7
		350	10.6	6.6	54.4
		400	14.7	8.3	61.0
		484	19.2	13.7	62.7
Spring Creek 0409754132	1	250	0.4	7.5	12.5
		300	2.7	3.8	8.3
		350	7.3	1.1	4.2
		400	9.9	2.5	0.0
		484	16.1	7.8	8.3
Pilgrim River 4043016	5	250	11.1	16.8	17.3
		300	9.7	14.3	14.6
		350	8.3	11.8	14.5
		400	7.4	9.3	12.8
		484	9.2	6.5	10.6
Coles Creek 04043021	1	250	16.3	3.4	9.1
		300	14.5	5.1	27.3
		350	17.8	2.3	9.1
		400	22.3	0.4	9.1
		484	24.1	6.1	18.2
Trap Rock River 04043050	4	250	9.6	11.2	7.9
		300	8.4	9.4	10.9
		350	7.4	9.1	7.8
		400	7.2	10.2	7.8
		484	8.6	11.0	9.9
Gratiot River 04040260	2	250	5.5	6.4	16.1
		300	3.4	3.3	16.7
		350	4.0	3.2	16.1
		400	8.5	5.0	17.2
		484	13.9	11.3	18.3
E. Br. Salmon Trout R. 04043244	5	250	12.3	5.7	11.8
		300	13.4	4.7	14.0
		350	15.5	4.9	11.8
		400	18.5	7.4	10.8
		484	21.5	11.7	10.3

Table 6.2 (Continued). Unit hydrograph analysis results by watershed

<i>Watershed</i>	<i>N_events</i>	<i>PRF</i>	<i>ABS(%Err Vol)</i>	<i>ABS(%Err Qp)</i>	<i>ABS(%Err Tr)</i>
Salmon Trout River	2	250	5.6	13.6	0.0
04043238		300	10.7	10.3	5.6
		350	15.9	6.9	11.3
		400	20.6	7.1	14.4
		484	33.1	11.2	22.5
M. Br. Escanaba	1	250	12.5	-7.3	13.6
04057800		300	8.6	-4.1	13.6
		350	5.5	-1.1	13.6
		400	2.6	2.0	13.6
		484	-1.5	7.3	15.9
Black River nr Garnet	1	250	6.8	4.1	20.5
04046000		300	9.0	8.1	22.7
		350	11.6	11.4	25.0
		400	13.8	15.1	29.5
		484	19.1	19.9	34.1

Table 6.3. Watershed characteristics related to time of concentration.

USGS#	SITE NAME	RCN_NLCDMTRI	Tc (hrs)	LFP_SLOPE (ft per mile)	LFP_Length (miles)	L/S ^{0.5}
04065600	Pine Creek	55.4	8.79	30.6	7.43	1.34
04106320	W Fork Portage Creek	60.8	21.30	16.7	5.51	1.35
04106400	W Fork Portage Creek	65.4	8.19	16.7	5.51	1.35
04111500	Deer Creek	68.7	14.29	8.3	7.42	2.58
04113090	Carrier Creek	74.7	25.6	15.0	4.07	1.05
04117000	Quaker Brook	73.6	7.56	25.1	5.06	1.01
04122100	Bear Creek	70.8	19.26	8.2	8.49	2.96
04144180	Jones Creek	80.9	11.95	12.6	5.19	1.46
04148144	Chipmunk Creek	78.3	9.54	8.5	3.59	1.23
04112000	Sloan Creek	79.9	12.62	9.2	6.18	2.04
04148160	Gilkey Creek	80.0	12.84	12.5	7.02	1.99
04148200	Swartz Creek	69.2	11.4	15.1	6.95	1.79
04148610	Cole Creek	81.3	12.05	9.7	6.32	2.03
04148640	Armstrong Creek	77.0	16.8	13.5	7.14	1.95
04148740	Central Stadler Drain	78.5	18.7	12.3	9.23	2.63
04148900	Silver Creek	73.3	13.4	19.4	3.84	0.87
04149300	Mistequay Creek	81.9	20.3	6.5	7.39	2.89
04160570	N Br Belle River	64.1	14.04	7.0	6.86	2.59
04174518	Malletts Creek	80.7	9.3	24.2	7.41	1.51
04001000	Washington Creek	76.8	8.41	47.1	7.71	1.12
04043238	Salmon Trout River	46.6	10.22	64.2	5.92	0.74
04043244	E. Br. Salmon Trout R.	57.6	5.6	75.9	6.57	0.75
04044200	Carp Creek	69.0	16	15.3	7.45	1.91
04058300	Warner Creek	34.6	25.42	9.5	9.17	2.97
04138600	Gamble Creek	56.4	5.8	67.4	5.13	0.62
04138700	Bixby Creek	71.9	1.71	122.4	2.54	0.23
04138900	Wilkins Creek	54.7	6.74	56.7	6.48	0.86
04139900	Ammond Creek	81.5	2.8	58.9	3.04	0.40
04140200	Klacking Creek	58.2	4.9	93.9	5.22	0.54
04141000	S. Branch Shepards Cr.	81.5	2.065	62.6	2.31	0.29

Table 6.4. Unit peak discharge equation coefficients by rainfall distribution and PRF.

MSE3, PRF 300				MSE3, PRF 350		
I_a/P	C1	C2	C3	C1	C2	C3
0.1	2.4196	-0.7585	-0.0579	2.4719	-0.7434	-0.0649
0.25	2.3730	-0.7482	-0.0336	2.4256	-0.7395	-0.0357
0.3	2.3483	-0.7261	-0.0340	2.3993	-0.7175	-0.0351
0.4	2.2875	-0.6510	-0.0541	2.3358	-0.6422	-0.0555
0.5	2.2176	-0.5788	-0.0656	2.2578	-0.5575	-0.0729
T_c > 15 hrs	2.5569	-0.9402	--	2.6010	-0.9264	--
MSE4, PRF 300				MSE4, PRF 350		
I_a/P	C1	C2	C3	C1	C2	C3
0.1	2.3842	-0.7302	-0.0596	2.4346	-0.7143	-0.0665
0.25	2.3353	-0.7213	-0.0335	2.3863	-0.7138	-0.0357
0.3	2.3077	-0.6995	-0.0301	2.3582	-0.6958	-0.0290
0.4	2.2419	-0.6313	-0.0369	2.2854	-0.6089	-0.0502
0.5	2.1586	-0.5299	-0.0637	2.1974	-0.5183	-0.0632
T_c > 15 hrs	2.5466	-0.9341	--	2.5874	-0.9183	--

Table 6.5. USGS streamflow gaging stations used in the regional regression analysis. Stations with increasing [++] or decreasing [--] trends in peak annual discharges are indicated, based on the Mann-Kendall tests with $p < 0.01$. Increasing (+) and decreasing (-) trends with $p < 0.05$ are also indicated.

USGS ID	Station Name	Region	DA (mi ²)	N (yrs)	Trend
04001000	WASHINGTON CREEK AT WINDIGO, MI	1	13.66	39	(-)
04031000	BLACK RIVER NEAR BESSEMER, MI	1	199.62	50	
04031500	PRESQUE ISLE RIVER AT MARENISCO, MI	1	172.53	38	
04032000	PRESQUE ISLE RIVER NEAR TULA, MI	1	264.29	46	
04033000	MIDDLE BRANCH ONTONAGON RIVER NR PAULDING, MI	1	162.98	75	
04035000	EAST BRANCH ONTONAGON RIVER NEAR MASS, MI	1	273.14	37	
04039500	SOUTH BRANCH ONTONAGON RIVER AT EWEN, MI	1	348.34	46	
04040500	STURGEON RIVER NEAR SIDNAW, MI	1	168.69	83	(-)
04041000	PERCH RIVER AT STATE HWY-28 NEAR SIDNAW, MI	1	63.23	38	
04042300	STURGEON RIVER NEAR PELKIE, MI	1	500.93	11	
04042500	OTTER RIVER NR ELO, MI	1	161.24	37	
04043050	TRAP ROCK RIVER NEAR LAKE LINDEN, MI	1	29.57	56	
04043150	SILVER RIVER NEAR L'ANSE, MI	1	65.23	20	
04043238	SALMON TROUT RIVER NEAR BIG BAY, MI	1	7.47	18	[--]
04043244	EAST BRANCH SALMON TROUT RIVER NEAR DODGE CITY, MI	1	10.17	17	
04043275	YELLOW DOG RIVER NEAR BIG BAY, MI	1	31.01	12	
04044200	CARP CREEK AT HIGHWAY 41A AT ISHPERING, MI	1	16.68	21	
04044813	TWO HEARTED RIVER NEAR PARADISE, MI	1	206.27	41	(-)
04045500	TAHQUAMENON RIVER NEAR PARADISE, MI	1	758.65	69	
04045538	W BRANCH WAISKA RIVER AT TILSON RD NR BRIMLEY, MI	1	33.61	41	[--]
04045559	EAST BRANCH WAISKA RIVER NEAR BRIMLEY, MI	1	28.49	19	
04046000	BLACK RIVER NEAR GARNET, MI	1	33.45	71	
04049500	MANISTIQUE RIVER AT GERMFASK, MI	1	9.37	45	
04054500	DUCK CREEK NEAR BLANEY, MI	1	58.95	17	
04055000	MANISTIQUE RIVER AT COOKSON BRIDGE NR BLANEY, MI	1	709.05	42	
04056000	WEST BRANCH MANISTIQUE RIVER NR MANISTIQUE, MI	1	330.78	19	
04056500	MANISTIQUE RIVER NEAR MANISTIQUE, MI	1	1126.52	85	
04057510	STURGEON RIVER NEAR NAHMA JUNCTION, MI	1	180.53	54	
04057800	MIDDLE BRANCH ESCANABA RIVER AT HUMBOLDT, MI	1	45.71	63	(-)
04057900	BLACK RIVER AT COUNTY ROAD NEAR REPUBLIC, MI	1	34.52	29	
04058300	WARNER CREEK AT CO RD MK NR PALMER, MI	1	15.77	16	
04058500	EAST BRANCH ESCANABA RIVER AT GWINN, MI	1	125.05	26	
04059400	TENMILE CREEK AT PERRONVILLE, MI	1	43.50	41	
04059500	FORD RIVER NEAR HYDE, MI	1	443.65	68	
04060500	IRON RIVER AT CASPIAN, MI	1	92.90	51	
04060993	BRULE RIVER AT US HIGHWAY 2 NEAR FLORENCE, WI	1	378.41	80	
04062200	PESHEKEE RIVER NEAR CHAMPION, MI	1	131.77	32	
04062300	MICHIGAMME RIVER AT REPUBLIC, MI	1	238.11	30	

Table 6.5 (Cont.). USGS streamflow gaging stations used in the regional regression analysis.

USGS ID	Station Name	Region	DA (mi ²)	N (yrs)	Trend
04065000	MENOMINEE RIVER NEAR IRON MOUNTAIN, MI	1	2461.51	12	
04065300	WEST BRANCH STURGEON RIVER NEAR RANDVILLE, MI	1	53.76	23	
04065393	E B STURGEON RIVER BELOW SKUNK C NR FELCH, MI	1	61.52	11	
04065500	STURGEON RIVER NEAR FOSTER CITY, MI	1	235.44	26	
04127917	PINE RIVER NEAR RUDYARD, MI	1	200.25	50	
04096015	GALIEN RIVER NEAR SAWYER, MI	2	80.72	27	
04096272	BEEBE CREEK AT MOORE ROAD NEAR HILLSDALE, MI	2	42.70	17	
04096340	ST. JOSEPH RIVER AT CLARENDON, MI	2	144.90	17	
04096400	ST. JOSEPH RIVER NEAR BURLINGTON, MI	2	194.69	29	(+)
04096405	ST. JOSEPH RIVER AT BURLINGTON, MI	2	198.49	60	
04096515	SOUTH BRANCH HOG CREEK NEAR ALLEN, MI	2	48.48	53	
04096600	COLDWATER RIVER NEAR HODUNK, MI	2	286.89	27	[++]
04096900	NOTTAWA CREEK NEAR ATHENS, MI	2	150.69	31	
04097060	LITTLE PORTAGE CREEK AT 38TH ST NEAR FULTON, MI	2	27.94	11	
04097170	PORTAGE RIVER AT W AVENUE NEAR VICKSBURG, MI	2	66.31	52	
04097370	FLOWERFIELD CREEK AT FLOWERFIELD, MI	2	35.11	16	
04097500	ST. JOSEPH RIVER AT THREE RIVERS, MI	2	1235.45	60	[++]
04097540	PRAIRIE RIVER NEAR NOTTAWA, MI	2	105.77	60	
04098500	FAWN RIVER NEAR WHITE PIGEON, MI	2	203.12	25	[++]
04098980	MILL CREEK AT QUAKER STREET NEAR MOTTVILLE, MI	2	44.70	10	
04100500	ELKHART RIVER AT GOSHEN, IN	2	594.19	95	
04101500	ST. JOSEPH RIVER AT NILES, MI	2	3714.08	92	[++]
04101535	DOWAGIAC RIVER AT STATE HWY 51 NR DOWAGIAC, MI	2	74.30	10	
04101800	DOWAGIAC RIVER AT SUMNERVILLE, MI	2	251.59	62	[++]
04102500	PAW PAW RIVER AT RIVERSIDE, MI	2	389.93	71	[++]
04102700	SOUTH BRANCH BLACK RIVER NEAR BANGOR, MI	2	83.40	56	
04102776	MIDDLE BRANCH BLACK RIVER NEAR SOUTH HAVEN, MI	2	83.03	28	
04103010	KALAMAZOO RIVER NEAR MARENGO, MI	2	268.95	25	
04104945	WANADOGA CREEK NEAR BATTLE CREEK, MI	2	48.32	28	
04105000	BATTLE CREEK AT BATTLE CREEK, MI	2	275.51	90	(+)
04105500	KALAMAZOO RIVER NEAR BATTLE CREEK, MI	2	820.57	85	
04105700	AUGUSTA CREEK NEAR AUGUSTA, MI	2	37.19	58	[++]
04105800	GULL CREEK AT 37TH STREET NEAR GALESBURG, MI	2	35.71	10	(+)
04106300	PORTAGE CREEK NEAR KALAMAZOO, MI	2	20.38	44	
04106400	WEST FORK PORTAGE CREEK AT KALAMAZOO, MI	2	23.30	63	[++]
04108600	RABBIT RIVER NEAR HOPKINS, MI	2	64.13	57	[++]
04108645	RABBIT RIVER AT STATE HIGHWAY 40 AT HAMILTON, MI	2	270.30	44	
04108660	KALAMAZOO RIVER AT NEW RICHMOND, MI	2	1977.52	21	
04108800	MACATAWA RIVER AT STATE ROAD NEAR ZEELAND, MI	2	66.68	62	
04109000	GRAND RIVER AT JACKSON, MI	2	171.96	87	
04109500	PORTAGE RIVER AT PORTAGE LAKE RD NR MUNITH, MI	2	54.50	12	(-)
04110000	ORCHARD CREEK AT STATE HWY-106 NEAR MUNITH, MI	2	47.03	12	

Table 6.5 (Cont.). USGS streamflow gaging stations used in the regional regression analysis.

USGS ID	Station Name	Region	DA (mi ²)	N (yrs)	Trend
04111000	GRAND RIVER NEAR EATON RAPIDS, MI	2	693.36	59	
04111379	RED CEDAR RIVER NEAR WILLIAMSTON, MI	2	162.83	35	
04111500	DEER CREEK NEAR DANSVILLE, MI	2	16.26	57	
04112000	SLOAN CREEK NEAR WILLIAMSTON, MI	2	10.47	68	
04112500	RED CEDAR RIVER AT EAST LANSING, MI	2	342.66	114	(-)
04112700	SYCAMORE CREEK AT HARPER ROAD NEAR MASON, MI	2	35.74	39	
04112850	SYCAMORE CREEK AT HOLT ROAD NEAR HOLT, MI	2	79.87	15	
04113090	CARRIER CREEK AT ST. JOE HWY NR GRAND LEDGE, MI	2	6.15	20	
04114000	GRAND RIVER AT PORTLAND, MI	2	1397.11	63	(+)
04114498	LOOKING GLASS RIVER NEAR EAGLE, MI	2	283.35	73	
04115000	MAPLE RIVER AT MAPLE RAPIDS, MI	2	419.76	77	
04115265	FISH CREEK NEAR CRYSTAL, MI	2	37.16	35	
04116000	GRAND RIVER AT IONIA, MI	2	2871.83	74	
04117000	QUAKER BROOK NEAR NASHVILLE, MI	2	7.81	60	
04117500	THORNAPPLE RIVER NEAR HASTINGS, MI	2	408.11	78	
04119000	GRAND RIVER AT GRAND RAPIDS, MI	2	4900.88	122	
04119055	PLASTER CREEK AT 28TH STREET AT GRAND RAPIDS, MI	2	45.95	48	
04119160	BUCK CREEK AT WILSON AVENUE AT GRANDVILLE, MI	2	50.77	44	(+)
04120295	BLACK CREEK NEAR MUSKEGON, MI	3	42.74	15	
04121300	CLAM RIVER AT VOGEL CENTER, MI	3	239.38	56	
04121500	MUSKEGON RIVER AT EVART, MI	3	1430.34	89	
04121900	LITTLE MUSKEGON RIVER NEAR MORLEY, MI	3	135.37	30	
04121944	LITTLE MUSKEGON RIVER NEAR OAK GROVE, MI	3	362.95	27	[++]
04122100	BEAR CREEK NEAR MUSKEGON, MI	3	16.70	57	(-)
04122200	WHITE RIVER NEAR WHITEHALL, MI	3	404.64	65	
04122223	PENTWATER RIVER NEAR HART, MI	3	74.64	10	(+)
04122230	NORTH BRANCH PENTWATER RIVER NR PENTWATER, MI	3	41.39	47	
04122500	PERE MARQUETTE RIVER AT SCOTTVILLE, MI	3	689.91	83	[++]
04123000	BIG SABLE RIVER NEAR FREESOIL, MI	3	109.35	33	
04123500	MANISTEE RIVER NEAR GRAYLING, MI	3	132.23	42	
04124000	MANISTEE RIVER NEAR SHERMAN, MI	3	864.94	102	
04124500	EAST BRANCH PINE RIVER NEAR TUSTIN, MI	3	61.18	66	
04125000	PINE RIVER NEAR LEROY, MI	3	128.99	11	
04125500	PINE RIVER NEAR HOXEYVILLE, MI	3	252.30	30	
04126200	LITTLE MANISTEE RIVER NEAR FREESOIL, MI	3	184.04	26	
04126600	BETSIE RIVER AT US HIGHWAY 31 NEAR BENZONIA, MI	3	167.99	47	
04126740	PLATTE RIVER AT HONOR, MI	3	125.77	32	
04126970	BOARDMAN R ABOVE BROWN BRIDGE ROAD NR MAYFIELD, MI	3	123.63	25	
04127800	JORDAN RIVER NEAR EAST JORDAN, MI	3	67.29	56	
04127850	BOYNE RIVER AT DAM ROAD NEAR BOYNE CITY, MI	3	64.20	16	

Table 6.5 (Cont.). USGS streamflow gaging stations used in the regional regression analysis.

USGS ID	Station Name	Region	DA (mi ²)	N (yrs)	Trend
04127997	STURGEON RIVER AT WOLVERINE, MI	3	188.21	80	
04128500	INDIAN RIVER AT INDIAN RIVER, MI	3	386.50	41	
04129500	PIGEON RIVER AT AFTON, MI	3	143.39	39	
04130000	CHEBOYGAN RIVER NEAR CHEBOYGAN, MI	3	875.51	40	
04131000	RAINY RIVER NEAR ONAWAY, MI	3	84.69	11	
04131500	RAINY RIVER NEAR OCQUEOC, MI	3	96.42	30	
04132500	THUNDER BAY RIVER NEAR HILLMAN, MI	3	221.01	37	
04134000	NORTH BRANCH THUNDER BAY RIVER NR BOLTON, MI	3	173.45	35	
04135500	AU SABLE RIVER AT GRAYLING, MI	3	96.73	52	
04135700	SOUTH BRANCH AU SABLE RIVER NEAR LUZERNE, MI	3	394.11	55	
04136000	AU SABLE RIVER NEAR RED OAK, MI	3	1109.92	33	
04137000	AU SABLE RIVER AT BAMFIELD, MI	3	1599.00	11	(+)
04138000	EAST BRANCH AU GRES RIVER NEAR MCIVOR, MI	3	89.91	32	
04138500	AU GRES RIVER AT COX ROAD NEAR NATIONAL CITY, MI	3	150.75	31	
04138600	GAMBLE CREEK AT LUPTON ROAD AT LUPTON, MI	3	9.62	23	
04138700	BIXBY CREEK NEAR ROSE CITY, MI	3	2.62	27	
04138900	WILKINS CREEK NEAR ROSE CITY, MI	3	9.69	26	
04139000	HOUGHTON CREEK NEAR LUPTON, MI	3	29.76	39	
04139900	AMMOND CREEK NEAR SELKIRK, MI	3	3.12	12	
04140000	PRIOR CREEK AT PETERS ROAD NEAR SELKIRK, MI	3	20.99	28	
04140200	KLACKING CREEK AT CAMPBELL ROAD NEAR SELKIRK, MI	3	7.10	38	
04140500	RIFLE RIVER AT STATE ROAD AT SELKIRK, MI	3	116.42	60	
04141000	SOUTH BRANCH SHEPARDS CREEK NEAR SELKIRK, MI	3	1.14	36	
04141500	WEST BRANCH RIFLE RIVER NEAR SELKIRK, MI	3	65.07	12	
04142000	RIFLE RIVER NEAR STERLING, MI	3	333.05	86	
04143500	NORTH BRANCH KAWKAWLIN RIVER NR KAWKAWLIN, MI	4	101.96	32	
04143900	SHIAWASSEE RIVER AT LINDEN, MI	4	81.88	30	
04144180	JONES CREEK AT BALDWIN RD NR GAINES, MI	4	8.27	14	
04144220	JONES CREEK AT GRAND BLANC RD NR DUFFIELD, MI	4	22.37	14	
04144500	SHIAWASSEE RIVER AT OWOSSO, MI	4	530.85	92	
04145000	SHIAWASSEE RIVER NEAR FERGUS, MI	4	622.93	61	
04145500	BAD RIVER AT HEMLOCK ROAD NEAR BRANT, MI	4	89.39	18	
04146000	FARMERS CREEK NEAR LAPEER, MI	4	51.00	90	
04146063	SOUTH BRANCH FLINT RIVER NEAR COLUMBIAVILLE, MI	4	215.64	43	
04146450	NORTH BRANCH FLINT RIVER NEAR COLUMBIAVILLE, MI	4	224.38	21	
04147990	BUTTERNUT CREEK AT FRANCES ROAD NR GENESEE, MI	4	34.93	14	
04148000	FLINT RIVER AT GENESEE ROAD AT GENESEE, MI	4	594.34	22	[++]
04148120	KEARSLEY CREEK AT JORDAN ROAD NEAR ATLAS, MI	4	56.99	14	
04148139	BLACK CREEK AT IRISH ROAD NEAR DAVISON, MI	4	25.10	14	
04148140	KEARSLEY CREEK NEAR DAVISON, MI	4	101.34	57	

Table 6.5 (Cont.). USGS streamflow gaging stations used in the regional regression analysis.

USGS ID	Station Name	Region	DA (mi ²)	N (yrs)	Trend
04148144	CHIPMUNK CREEK AT NORTH GENESEE RD NR GENESEE, MI	4	5.92	14	
04148160	GILKEY CREEK NEAR FLINT, MI	4	7.12	14	
04148200	SWARTZ CREEK AT ELLIOT ROAD NEAR HOLLY, MI	4	11.80	29	
04148255	SWARTZ CREEK AT BALDWIN RD NR GRAND BLANC, MI	4	35.66	14	
04148270	WEST BRANCH SWARTZ CREEK NR SWARTZ CREEK, MI	4	39.92	14	
04148295	SWARTZ CREEK AT CLAUDE AVENUE AT FLINT, MI	4	114.00	46	
04148410	THREAD CREEK AT BALDWIN ROAD NR GOODRICH, MI	4	28.61	14	
04148440	THREAD CREEK NEAR FLINT, MI	4	54.87	46	
04148500	FLINT RIVER NEAR FLINT, MI	4	960.22	90	
04148610	COLE CREEK AT POTTER ROAD NEAR FLUSHING, MI	4	8.37	19	
04148640	ARMSTRONG CREEK AT MORRISH ROAD NEAR MONTROSE, MI	4	11.36	19	
04148720	BRENT RUN AT MORRISH ROAD NEAR MONTROSE, MI	4	21.34	14	
04148740	CENTRAL STADLER DRAIN AT WILSON RD NR MONTROSE, MI	4	13.92	14	
04148800	PINE RUN AT ELMS ROAD NEAR MONTROSE, MI	4	28.20	14	
04148900	SILVER CREEK AT WEIR ROAD NEAR CLIO, MI	4	4.01	14	
04149000	FLINT RIVER NEAR FOSTERS, MI	4	1154.50	30	
04149300	MISTEGUAY CREEK AT DUFFIELD RD NR FLUSHING, MI	4	17.50	14	
04150500	CASS RIVER AT CASS CITY, MI	4	359.54	60	
04150800	CASS RIVER AT WAHJAMEGA, MI	4	642.66	37	
04151500	CASS RIVER AT FRANKENMUTH, MI	4	839.18	83	
04152238	SOUTH BRANCH TOBACCO RIVER NEAR BEAVERTON, MI	4	152.41	36	(+)
04153500	SALT RIVER NEAR NORTH BRADLEY, MI	4	144.65	50	
04154000	CHIPPEWA RIVER NEAR MOUNT PLEASANT, MI	4	409.74	90	
04155500	PINE RIVER NEAR MIDLAND, MI	4	408.24	76	
04156000	TITTABAWASSEE RIVER AT MIDLAND, MI	4	2371.55	113	(+)
04157005	SAGINAW RIVER AT HOLLAND AVENUE AT SAGINAW, MI	4	5990.52	90	
04157500	STATE DRAIN (SEBEWAING RIVER) NR SEBEWAING, MI	4	64.09	15	
04158000	COLUMBIA DRAIN AT GETTEL ROAD NR SEBEWAING, MI	4	33.21	18	
04158500	PIGEON RIVER NEAR OWENDALE, MI	4	58.02	30	
04159010	PIGEON RIVER NEAR CASEVILLE, MI	4	66.75	12	
04159492	BLACK RIVER NEAR JEDDO, MI	5	463.72	79	
04159900	MILL CREEK NEAR AVOCA, MI	5	168.55	51	
04160000	MILL CREEK NEAR ABBOTSFORD, MI	5	183.86	17	
04160050	BLACK RIVER NEAR PORT HURON, MI	5	683.63	11	
04160350	PINE RIVER AT GRATIOT ROAD NEAR RATTLE RUN, MI	5	135.57	40	
04160570	NORTH BRANCH BELLE RIVER AT M-21 AT IMLAY CITY, MI	5	16.54	36	
04160600	BELLE RIVER AT MEMPHIS, MI	5	150.52	60	
04160800	SASHABAW CREEK NEAR DRAYTON PLAINS, MI	5	21.23	55	

Table 6.5 (Cont.). USGS streamflow gaging stations used in the regional regression analysis.

USGS ID	Station Name	Region	DA (mi ²)	N (yrs)	Trend
04161000	CLINTON RIVER AT AUBURN HILLS, MI	5	123.23	60	[++]
04161500	PAINT CREEK NEAR LAKE ORION, MI	5	40.42	36	
04161540	PAINT CREEK AT ROCHESTER, MI	5	72.12	61	(+)
04161580	STONY CREEK NEAR ROMEO, MI	5	24.10	49	
04161760	WEST BRANCH STONY CREEK NEAR WASHINGTON, MI	5	24.45	45	
04161820	CLINTON RIVER AT STERLING HEIGHTS, MI	5	309.98	27	
04163400	PLUM BROOK AT UTICA, MI	5	16.29	56	
04163500	PLUM BROOK NEAR UTICA, MI	5	23.49	13	
04164010	NORTH BRANCH CLINTON RIVER AT ALMONT, MI	5	9.51	55	
04164050	N BRANCH CLINTON R AT 33 MILE RD NR ROMEO, MI	5	50.07	55	
04164100	EAST POND CREEK AT ROMEO, MI	5	21.33	64	
04164200	COON CREEK AT NORTH AVENUE NEAR ARMADA, MI	5	9.63	55	
04164250	TUPPER BROOK AT RAY CENTER, MI	5	8.65	22	
04164350	HIGHBANK CREEK AT 32 MILE ROAD NEAR ARMADA, MI	5	15.11	47	[++]
04164360	E BRANCH COON C AT 29-MILE RD NR NEW HAVEN, MI	5	36.21	48	
04164500	NORTH BRANCH CLINTON RIVER NR MT CLEMENS, MI	5	198.29	75	
04164600	MIDDLE BR CLINTON R AT SCHOENHERR RD NR MACOMB, MI	5	22.370	54	(+)
04164800	MIDDLE BRANCH CLINTON RIVER AT MACOMB, MI	5	41.12	41	[++]
04165500	CLINTON RIVER AT MORAVIAN DR AT MT CLEMENS, MI	5	735.44	88	
04166000	RIVER ROUGE AT BIRMINGHAM, MI	5	36.70	70	[++]
04166100	RIVER ROUGE AT SOUTHFIELD, MI	5	86.89	62	
04166300	UPPER RIVER ROUGE AT FARMINGTON, MI	5	17.57	62	(+)
04166500	RIVER ROUGE AT DETROIT, MI	5	185.67	92	(+)
04167000	MIDDLE RIVER ROUGE NEAR GARDEN CITY, MI	5	98.50	77	
04168000	LOWER RIVER ROUGE AT INKSTER, MI	5	84.17	69	
04168580	ECORSE RIVER AT DEARBORN HEIGHTS, MI	5	11.81	20	
04168800	HURON RIVER NEAR ANDERSONVILLE, MI	5	13.68	19	
04171500	SOUTH ORE CREEK AT HAMBURG RD NR BRIGHTON, MI	5	32.66	17	
04172000	HURON RIVER NEAR HAMBURG, MI	5	319.66	71	(+)
04173000	HURON RIVER NEAR DEXTER, MI	5	537.37	34	
04173250	MILL CREEK NEAR LIMA CENTER, MI	5	48.95	20	
04173500	MILL CREEK NEAR DEXTER, MI	5	130.82	59	
04174518	MALLETTS CREEK AT ANN ARBOR, MI	5	10.35	26	
04175340	STONY CREEK AT TUTTLE HILL RD AT OAKVILLE, MI	5	69.33	13	(+)
04175600	RIVER RAISIN NEAR MANCHESTER, MI	5	131.93	50	
04175700	RIVER RAISIN NEAR TECUMSEH, MI	5	269.72	24	
04175960	S BR RIVER RAISIN AT HOWELL HWY NR ADRIAN, MI	5	165.42	13	
04176400	SALINE RIVER NEAR SALINE, MI	5	94.35	57	
04176500	RIVER RAISIN NEAR MONROE, MI	5	1040.99	85	(+)
04176605	OTTER CREEK AT LA SALLE, MI	5	63.62	26	
04184500	BEAN CREEK AT POWERS, OH	5	205.58	64	(+)

Table 6.6. Precipitation scaling factors for Michigan climatic zones from the CMIP Climate Model Processing Tool (RCP 4.5, Historical period 1950-2005, Future period 2041-2070).

Zone 1	bcc-csm1	ccsm4.6	cesm1-cams5	miroc5	Mean
2-yr	1.04	1.10	1.06	1.04	1.06
5-yr	1.09	1.19	1.13	1.10	1.13
10-y	1.12	1.24	1.16	1.13	1.16
25-yr	1.15	1.28	1.19	1.15	1.19
50-y	1.16	1.31	1.21	1.17	1.21
100-yr	1.18	1.33	1.22	1.18	1.23
500-yr	1.20	1.36	1.25	1.20	1.25
Zone 2					
2-yr	1.00	1.08	1.09	1.17	1.09
5-yr	0.99	1.16	1.16	1.25	1.14
10-y	0.99	1.20	1.20	1.28	1.17
25-yr	0.99	1.24	1.23	1.32	1.19
50-y	0.99	1.26	1.25	1.34	1.21
100-yr	0.99	1.28	1.27	1.35	1.22
500-yr	0.98	1.32	1.30	1.38	1.25
Zone 3					
2-yr	1.14	1.15	1.06	1.15	1.12
5-yr	1.14	1.22	1.07	1.13	1.14
10-y	1.13	1.24	1.08	1.12	1.15
25-yr	1.13	1.27	1.08	1.12	1.15
50-y	1.13	1.28	1.09	1.11	1.15
100-yr	1.13	1.30	1.09	1.11	1.16
500-yr	1.13	1.32	1.09	1.10	1.16
Zone 4					
2-yr	1.13	1.09	1.15	1.11	1.12
5-yr	1.12	1.06	1.15	1.09	1.11
10-y	1.12	1.05	1.15	1.08	1.10
25-yr	1.12	1.04	1.14	1.07	1.09
50-y	1.12	1.03	1.14	1.06	1.09
100-yr	1.12	1.02	1.14	1.06	1.08
500-yr	1.11	1.01	1.14	1.05	1.08
Zone 5					
2-yr	1.00	1.16	0.98	1.05	1.05
5-yr	1.16	1.19	0.92	1.02	1.07
10-y	1.23	1.19	0.90	1.00	1.08
25-yr	1.28	1.20	0.88	0.99	1.09
50-y	1.32	1.20	0.86	0.99	1.09
100-yr	1.34	1.21	0.86	0.98	1.10
500-yr	1.38	1.21	0.84	0.97	1.10

Table 6.6 (Continued). Precipitation scaling factors for Michigan climatic zones from the CMIP Climate Model Processing Tool (RCP 4.5, Historical period 1950-2005, Future period 2041-2070).

Zone 6	bcc-csm1	ccsm4.6	cesm1-cams5	miroc5	Mean
2-yr	1.03	1.21	1.12	0.95	1.08
5-yr	1.14	1.41	1.07	0.73	1.09
10-y	1.18	1.48	1.05	0.66	1.09
25-yr	1.21	1.54	1.04	0.61	1.10
50-y	1.22	1.57	1.04	0.58	1.10
100-yr	1.24	1.59	1.03	0.56	1.10
500-yr	1.25	1.63	1.02	0.52	1.11
Zone 7					
2-yr	1.04	1.17	1.18	0.99	1.09
5-yr	0.90	1.27	1.05	0.91	1.03
10-y	0.85	1.31	1.00	0.89	1.01
25-yr	0.81	1.34	0.96	0.87	0.99
50-y	0.78	1.35	0.94	0.86	0.98
100-yr	0.76	1.37	0.93	0.85	0.98
500-yr	0.73	1.39	0.90	0.84	0.96
Zone 8					
2-yr	1.03	1.04	1.12	0.96	1.04
5-yr	0.99	1.03	1.20	0.94	1.04
10-y	0.98	1.02	1.24	0.93	1.04
25-yr	0.96	1.02	1.28	0.92	1.04
50-y	0.95	1.02	1.30	0.91	1.04
100-yr	0.95	1.02	1.31	0.90	1.05
500-yr	0.93	1.01	1.34	0.90	1.05
Zone 9					
2-yr	1.06	0.96	1.10	1.03	1.04
5-yr	1.08	0.99	1.16	1.00	1.06
10-y	1.09	1.00	1.19	0.98	1.07
25-yr	1.10	1.01	1.22	0.97	1.08
50-y	1.11	1.02	1.23	0.96	1.08
100-yr	1.12	1.03	1.25	0.95	1.09
500-yr	1.13	1.04	1.27	0.94	1.09
Zone 10					
2-yr	1.09	0.91	1.15	0.98	1.03
5-yr	1.17	0.93	1.18	0.94	1.06
10-y	1.21	0.93	1.20	0.92	1.07
25-yr	1.25	0.94	1.22	0.90	1.08
50-y	1.27	0.94	1.22	0.89	1.08
100-yr	1.29	0.94	1.23	0.89	1.09
500-yr	1.32	0.95	1.25	0.87	1.10

Appendix B: MTU Toolbox Overview

This appendix includes the following:

- *Brief Descriptions of each tool in the MTU Toolbox*
- *Overview of functions in each tool and what each function does*
- *RCN Tool:*
 - *Information on workflows supported under tool*
 - *Where the data relevant to the tool is saved on Projectwise*
 - *How the Directory process works in this tool*
 - *LULC layers supported under this tool*
 - *Important columns in inputs for tool function*

MTU Hydro Toolbox

Hydro-enforcement

Code Overview

- Function
- Input
- Output



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Technological
University



Function:

Hydrodem

- Create list of test datasets based on bypass flags
- Create **Watershed Buffer** around **Watershed** at distance **Buffer Around Watershed** and convert to raster
- Rasterize **Stream feature class**
- If **Elevation Grid** does not exist, run **agree** to create it
- Rasterize **Watershed Buffer** again to create ridge raster
- Expand ridge raster to create ridge mask
- Add **Outwall Height** to **Elevation Grid** according to ridge mask
- Load drainplug raster
- Compute Euclidean distance for bowl lines and polygons
- Compute Inwall Buffer from **Inwall buffer distance** and Inwall
- Add **Inwall Height** to DEM according to Inwall Buffer
- Set extent and mask environment variables to ridge mask
- **substitute exact floating point values from original DEM for areas where it was not changed, to create finalized Enforced DEM**

Agree

- set extent, cellSize, and snapRaster environment variables based on the **DEM**
- compute the smooth drop/raise grid from stream raster, **DEM**, and **Agree Smooth**
- compute **Euclidean distance** raster from smooth grid
- compute **Euclidean Allocation** from smooth grid
- compute buffer grid from **Euclidean distance**, **DEM**, and **Agree Buffer**
- compute **Buffer distance** raster from buffer grid
- compute **Buffer Allocation** from buffer grid
- compute smooth modified elevation grid from other outputs
- compute sharp drop/raise grid from streams, smooth modified elevation, and **Agree Sharp**
- compute **Elevation Grid** from smooth modified elevation and sharp drop/raise grid

Tool Inputs

- **Buffer Around Watershed:** Creates a buffer around the Watershed File. This will clip your input DEM to the buffer distance around said watershed. Suggested values are: Small watersheds = 150m, Medium watersheds = 1500m, Large watersheds = 3000m.
- **Inwall Buffer distance:** Assigns elevation to the cells inside the buffer so that there is a straight line path from the vector line to the original elevation outside the buffer
- **Inwall Height:** Builds the height of the wall created around the buffer - prevents outside watersheds from interfering with the result. Wall is two pixels thick-inside.
- **Outwall Height:** Builds the height of the wall created around the buffer - prevents outside watersheds from interfering with the result. Wall is two pixels thick-outside.
- **Agree Buffer:** Buffer distance around agree function (stream dropping function).
- **Agree Smooth:** Used to build a smooth modified elevation grid.
- **Agree Sharp:** Controls how much the cells corresponding to the stream feature class are dropped/raised after the smooth modified elevation grid is completed. 'Digs a trench' if negative, 'builds a wall' if positive.
- **Bowling Depth:** Generates the input datasets from hydrography features for enforcing a gradient.

This tool artificially lowers the surface elevation of the water system within a watershed. This is done through: 1) dropping the elevation of the cells corresponding to the stream feature class by a certain amount, 2) buffering the stream line, 3) assigning elevation to the cells inside the buffer.

MTU Hydro Toolbox

Watershed Delineation

Code Overview



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- Function
- Input
- Output

No Functions are used in this tool

Full Delineation Tool Process:

- Set **Source Area** and **Snap Distance** to defaults if no valid value was entered
- Fix slash directions in **Output Directory** path
- Fill the **DEM**
- Generate **Flow Direction** from the filled DEM
- Generate **Flow Length** and **Flow Accumulation** from the **Flow Direction**
- Generate raster equal to 1 where flow accumulation is greater than **Source Area** threshold
- Run StreamLink tool on the modified flow accumulation and the **Flow Direction**
- Run Watershed tool on the **Flow Direction** and stream link
- Copy the **Pour Points** into a shapefile (**Pour Copy**)
- If there are **Additional Pour Points**, copy them into a shapefile and append to **Pour Copy**
- Add "VALUE" field to **Pour Copy** and set its values to 1 + the FID for each row
- If user has entered **Identifying Field Name for Pour Points** that matches a field in **Pour Copy**, get list of names from this field, otherwise use VALUE
- Run SnapPourPoint tool on **Pour Copy**, **Flow Accumulation**, and **Snap Distance**, creating **Snap Raster**
- For each pour point, run SnapPourPoint (using **Flow Accumulation** and **Snap Distance**), then run Watershed on **Flow Direction** and the individual snapped pour point, then convert the resulting raster to polygon, delete the raster, add 'area_acre' and 'flow_in_mi' fields to the **Preliminary Watershed**, and generate **Zonal Statistics Tables** for DEM and Flow Length
- If necessary, append all subwatersheds to a single **Watershed** file

Watershed delineation is the process of creating a boundary around the upslope area that contributes flow to a common outlet.

This tool uses a (potentially hydroenforced) DEM and pour points to automatically delineate a watershed. It works by computing the flow direction and snapped pour point in order to determine the contributing area of the watershed.

Tool Inputs

- **Identifying Field Name for Pour Points:** Column name from the Pour Points Feature Class, IDs pour points.
- **Watershed Title:** Title of the Delineation output
- **Source Area:** In meters, the potential contributing area above the watershed.
- **Snap Distance:** In meters, the maximum distance to search for a stream cell of higher accumulated flow. If there is not a stream nearby with a lower source area, or if the pour point is snapping to the wrong stream, move the pour point to the desired stream. **If you are not getting an output for the watershed that you are trying to delineate, reduce the size of this tool and use a flow accumulation raster to specify your pour point location.**

MTU Hydro Toolbox

RCN Tool Overview



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Workflows supported under this tool:

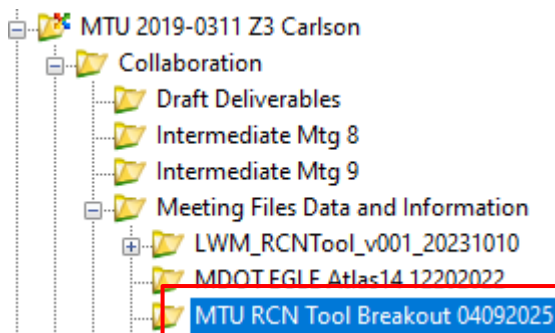
Single Watershed

- Multiple-polygon watersheds
- Multiple-polygon watersheds in multiple counties
- Single polygon watersheds in multiple counties
- Single polygon watersheds

Multiple Watersheds

- A selection of polygons within a larger shapefile
- A shapefile with multiple disconnected watershed polygons
- Disconnected watershed polygons in different counties
- *Warning: the tool will take longer to run when more polygons are fed to it*

Where is data for this tool saved on Projectwise?



Landuse spatial layers:

- NLCD 2021
- NLCDMTRI 2021, and
- MIRIS 1978 are in "LULC_FullLayers"

Final Toolbox, workflow document, and Tables are in "Download This for RCN Walkthrough"

MTU Hydro Toolbox

RCN Tool Overview



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How does the Directory work in this tool?

Area of Interest (AOI) | Soil Map | Soil Data Explorer | **Download Soils Data** | Shopping Cart (Free)

Download Soils Data for...

Your AOI (SSURGO)

Soil Survey Area (SSURGO)

General Information

Link: Description of Soil Survey Geographic (SSURGO) Database

Download Contents: Tabular data, spatial data (if available), template database (if selected), and FGDC metadata

Spatial Data Format: ESRI Shapefile, Geographic WGS84

Options

State: Michigan

County (optional): Eaton

Only show Soil Survey Areas updated since: [] [Update] [Clear]

Sort by: Area Symbol

Include Template Database: ☒

Soil Survey Area (SSURGO) Download Links

Name	Area Symbol	Data Availability	Version	Template Database	Download Size	Download Link
Eaton County, Michigan	MI045	Tabular and Spatial, complete	Survey Area: Version 21, Aug 26, 2024 Tabular: Version 21, Aug 26, 2024 Spatial: Version 10, Aug 25, 2022	soildb_MI_2003 Access 2003 Version 36	28.6 MB	wss_SSA_MI045_soildb_MI_2003_[2024-08-26].zip

- Counties
- Landusespatiallayer
- MIRIS Tables
- NLCD
- NLCDMTRITables
- Outputfolder
- Watershed
- wss_SSA_MI045_soildb_MI_2003_[2024-08-26]**
- wss_SSA_MI045_soildb_MI_2003_[2024-08-26].zip

The folder used for the “Directory” input must contain all soils data. The code uses the soil spatial layer (either the MUPolygon or the updated county soil data from SSURGO) to find the appropriate county specific soils table.

Layout | Current view | Show/Hide

es > AllDatafrom091124MDOTMeeting > wss_SSA_MI041_soildb_MI_2003_[2023-09-01] > MI041 > tabular

Name	Date modified	Type	Size
muaggatt.txt	8/28/2024 11:51 AM	Text Document	38 KB
muareao.txt	9/19/2023 3:10 AM	Text Document	25 KB
mucrpyd.txt	9/19/2023 3:10 AM	Text Document	17 KB
mutext.txt	9/19/2023 3:10 AM	Text Document	0 KB
sacatlog.txt	9/19/2023 3:10 AM	Text Document	47 KB
sainterp.txt	9/19/2023 3:10 AM	Text Document	1,719 KB
schema.ini	5/9/2024 9:30 AM	Configuration sett...	1 KB
sdvalgorithm.txt	9/19/2023 3:10 AM	Text Document	6 KB
sdvattribute.txt	9/19/2023 3:10 AM	Text Document	1,324 KB

- When the user downloads a county soil spatial layer from SSURGO, they should place the zipped and unzipped folder into the directory. Then the tool will be able to find the appropriate county specific soils table (labelled muaggatt)
- If the user is using the MUpolygon layer from EGLE, make sure that the County Specific Soil Tables created by EGLE are saved in the Directory.

While the soil files are the only layers that are required to be in the Directory, we recommend saving all necessary inputs in the Directory to for easier organization

MTU Hydro Toolbox

RCN Tool Overview

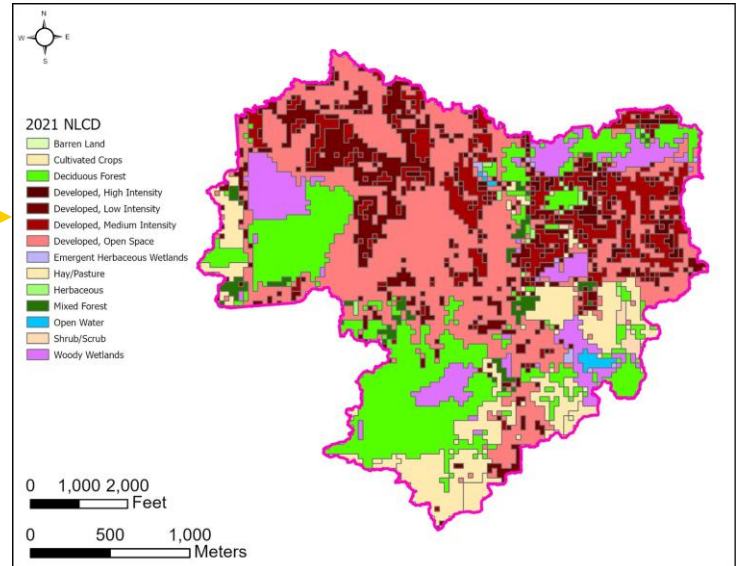


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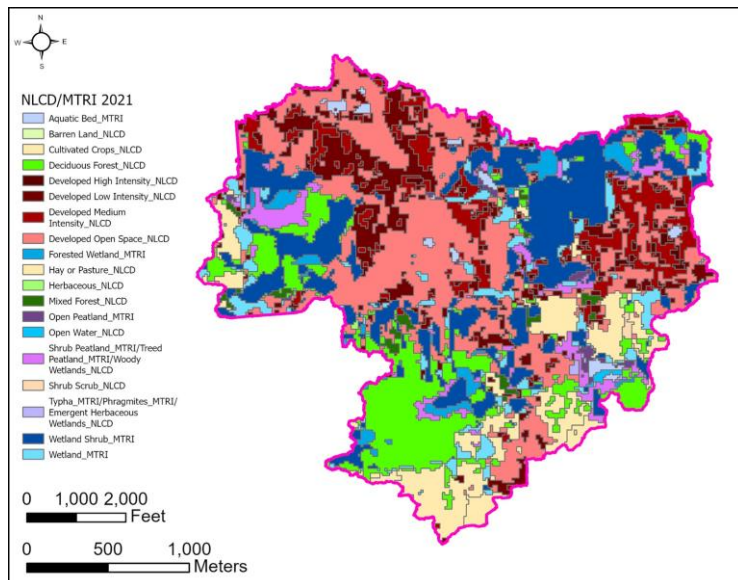


LULC layers supported under this tool:

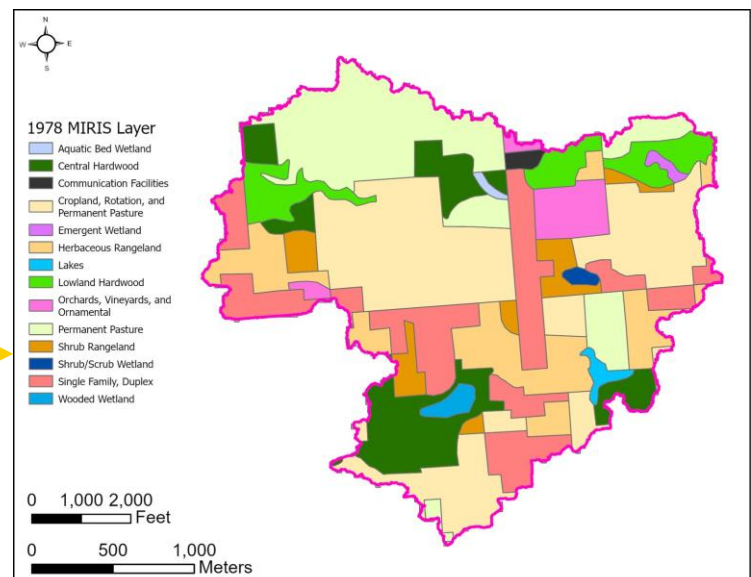
2021 NLCD



2021 NLCD/MTRI



1978 MIRIS



MTU Hydro Toolbox

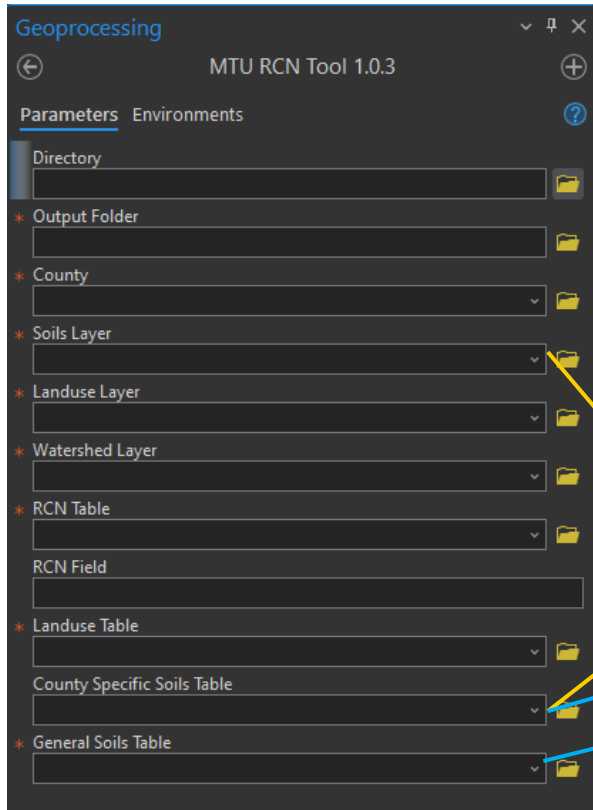
RCN Tool Overview



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Important Columns in inputs for tool function



Soils Spatial Layer joins:

“MUSYM: Joins to “ID” field in County Specific Soils Table

“hydgrp” in County Specific Soils Table joins to “soilclass” in General Soils Table

MUSYM	ID	hydgrp	SoilClass
12	12	B/D	B/D
27	27	A/D	A/D
BntadB	BntadB	D	D
10B	10B	C	C
10B	10B	C	C

Landuse Spatial Layer and Landuse Table joins by landuse/cover type:

NLCD 2021: “NLCD_Land_” joins to “NLCD_Descriptions”

NLCDMTRI2021: “ClassTitle:” joins to “updatedLCdescriptions:”

MIRIS1978: “LEVEL3” joins to “IGDS_TEXT”

ClassTitle	UpdatedLCD
Wetland_MTRI	Wetland_M...
Wetland Shrub_MTRI	Wetland Sh...
Shrub Peatland_MTRI/...	Shrub Peatl...
Cultivated Crops_NLCD	Cultivated...
Wetland_MTRI	Wetland_M...

NLCD/MTRI Join

LEVEL3	LABEL3	IGDS_TEXT
21	Cropland, Rotation, a...	21
113	Single Family, Duplex	113
24	Permanent Pasture	24
412	Central Hardwood	412
414	Lowland Hardwood	414
412	Central Hardwood	412
21	Cropland, Rotation, a...	21

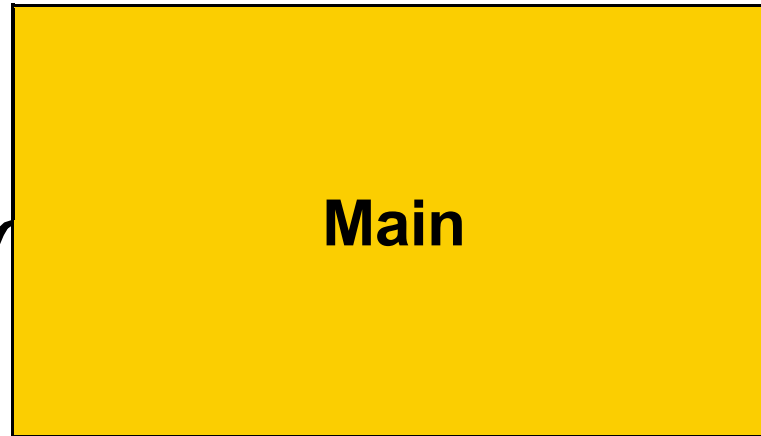
MIRIS Join

NLCD_Land_	NLCD_Descr
Hay/Pasture	Hay/Pasture
Deciduous Forest	Deciduous Forest
Woody Wetlands	Woody Wetlands
Cultivated Crops	Cultivated Crops
Hay/Pasture	Hay/Pasture
Developed, Low Inten...	Developed, Low Inten...
Developed, Low Inten...	Developed, Low Inten...

NLCD Join

- Function
- Input
- Output

Function:



- Creates list of all selected watersheds in Watershed input
- Sets up empty array for County Specific Soils table
- Calls watershed merging
- Calls select_rcnfield
- Calls ClippingSoils
- If user is using EGLE created County Specific Soils table, conducts join on it to Soils Layer and calls Fixcountyname
- If user is using gSSURGO-zip file Soils Layer and a blank County Specific Soils table input, it calls Countynamexip
- Creates CombinedCounties.csv with all County Specific Soils Tables necessary
- Appends list of relevant county
- Names selected watershed via ObjectID or FID and creates {row}.shp – watershed outline outputs
- Calls RCN



- If using an RCN table with multiple RCN value columns:
- Pulls column title written in GUI to be incorporated in calculations in RCN function



- If multiple polygons were input into the tool, this function will merge all of those polygons so there will be a combined polygon output



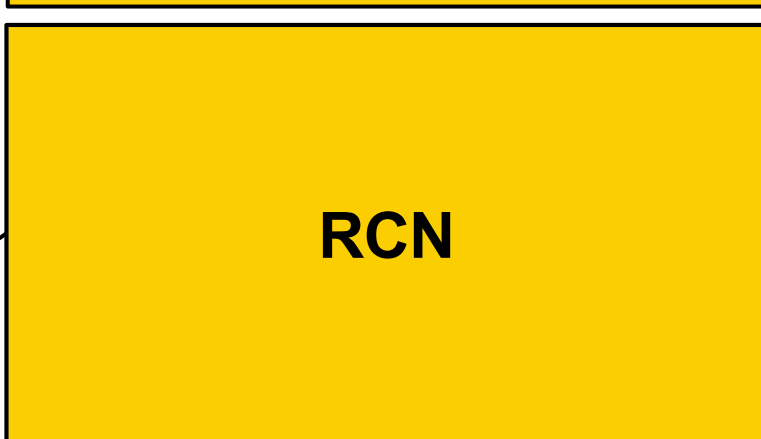
- Reprojects the Soils Layer to match the Landuse layer (which should be Georef)
- Clips reprojected Soils Layer, saved in Clippedsoil.shp



- Pulls Muaggatt out of zipped file from gSSURGO
- Converts it from a .txt to a .csv
- Adds CCODES column



- Replaces St. w/Saint, makes all county names lowercase in EGLE-created County Specific Soils Tables



- Checks Arcpro Version
- Calls Landusedecider
- Concatenates all soil tables into one
- Joins soil table to soils layer
- Checks MUSYM values that don't match and prints to user
- Joins landuse table to landuse layer based on landuse type
- Performs intersect between soil and landuse layers, creating landusesoilsinter
- Calculates sumclasval by adding class from landuse layer and value from soil layer, saved in sumclassval column
- Joins rcntable and landusesoilsinter together based on landuse type
- Adds 3 fields(sqmeter, a_rcn, rcn)
- Calculates geometry for sqmeter
- Calculates statistics from the landusesoilsinter and plugs them in statistics table
- Calculates statistics field (rcn) by dividing values in sum_a_rcn and sum_sqmeter
- Calculates rcn by dividing values in a_rcn by sqmile
- Adds files from output folder to map (RCN_completed.shp, statistics.txt)



- Determines which land use layer to use
 - IsMTRI, isMIRIS, isNLCD



MTU Hydro Toolbox

RCN Tool_MUPolygon

Overview



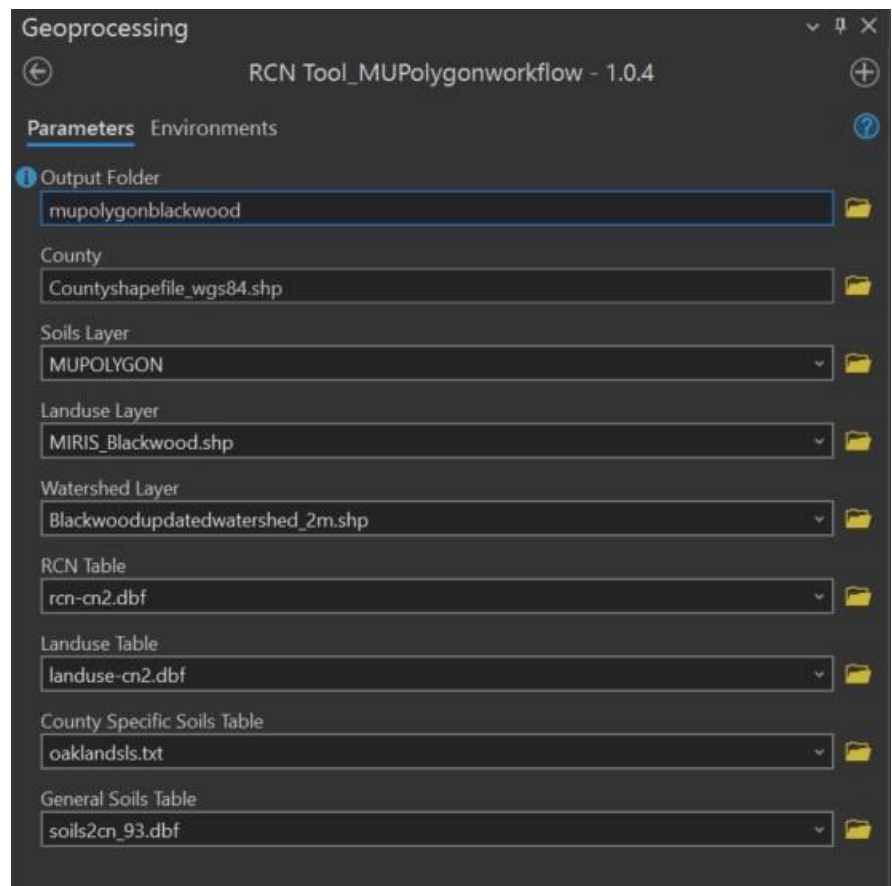
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What is RCN Tool MUPolygon?

RCN Tool MUPolygon is a much less sophisticated version of the RCN Tool. In order to incorporate updates such as solving the repeated soils issue, putting intermediate files into a delete-able folder, and re-attributing columns in the output (i.e. sumfield), the workflow that allowed for usage of the MUPolygon and the County Specific .txt files had to be removed from the original tool.

In order to allow for more testing to be done with the MUPolygon soil spatial later and the EGLE-generated .txt files, this functionality was preserved in the RCN Tool_MUPolygon workflow. This is a heavily simplified version of the RCN tool, with no directory functionality or ability to run updated soil datasets. This tool should only be run to compare the EGLE-generated MUPolygon and .txt file outputs to updated RCN Tool results.



Appendix C: MTU Toolbox Walkthrough

This appendix includes step by step instructions on how to run each tool in the MTU Toolbox, including descriptions of all inputs and outputs generated by each tool.



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Updating Michigan Hydrologic Calculation Procedures

Appendix C: MTU Hydro Toolbox Walkthrough

2019-031-Z3

MTU_Hydro_Tool_1.0.5

Hydroenforcement step by step

May 15 2025

Hydroenforcement Tool

General Overview of Tool

Hydroenforcement can be used on digital elevation models (DEMs), such as current generations of LiDAR-derived DEMs available from USGS and MSU to modify the elevation of impediments (i.e. culverts or bridge decks) to simulate continuous downslope flow (Poppenga 2014). This allows for a base layer for complex modeling of surface water flow.

This tool artificially lowers the surface elevation of the water system within a watershed. This is done through: 1) dropping the elevation of the cells corresponding to the stream feature class by a certain amount, 2) buffering the stream line, 3) assigning elevation to the cells inside the buffer.

This tool was built as a replacement for ArcHydro's 'Burn Stream Slope' tool in ArcMap, which allowed burning streams with slopes built based on elevation features in the stream feature class. This tool is meant to be implemented onto a DEM before running the watershed delineation tool, so it can be used as an input in said tool. The DEM produced by this tool should not be used in analysis post-watershed delineation, due to the artificial depth change created within the product.

Hydroenforcement Inputs

- **Output Directory:** Folder where output files will be saved
- **Watershed File:** Polygon feature class of the watershed being hydro-enforced. This can be any study area that you'd like to hydroenforce. For this beta we recommend using a watershed that had been derived in the EGLE 'Working' shapefile.
- **Input DEM:** Digital Elevation Model of the watershed, basis for hydro-enforced DEM.
- **Stream Feature Class:** Line feature class with stream/river data.

Hydroenforcement Parameter Definitions

All distances are the same units as the projection. (This example will be in NAD83 Michigan Georef)

- **DEM name (Optional):** Allows the user the ability to name the files, if there is no name input by the user, a default name will appear.
- **Buffer Around Watershed:** Creates a buffer around the Watershed File. This will clip your input DEM to the buffer distance around said watershed. Suggested values are: Small watersheds = 150m, Medium watersheds = 1500m, Large watersheds = 3000m.
- **Inwall Buffer distance:** Assigns elevation to the cells inside the buffer so that there is a straight line path from the vector line to the original elevation outside the buffer
- **Inwall Height:** Builds the height of the wall created around the buffer - prevents outside watersheds from interfering with the result. Wall is two pixels thick-inside.
- **Outwall Height:** Builds the height of the wall created around the buffer - prevents outside watersheds from interfering with the result. Wall is two pixels thick-outside.

- **Agree Buffer:** Buffer distance around agree function (stream dropping function).
- **Agree Smooth:** Used to build a smooth modified elevation grid.
- **Agree Sharp:** Controls how much the cells corresponding to the stream feature class are dropped/raised after the smooth modified elevation grid is completed. 'Digs a trench' if negative, 'builds a wall' if positive.
- **Bowling Depth:** Generates the input datasets from hydrography features for enforcing a gradient.

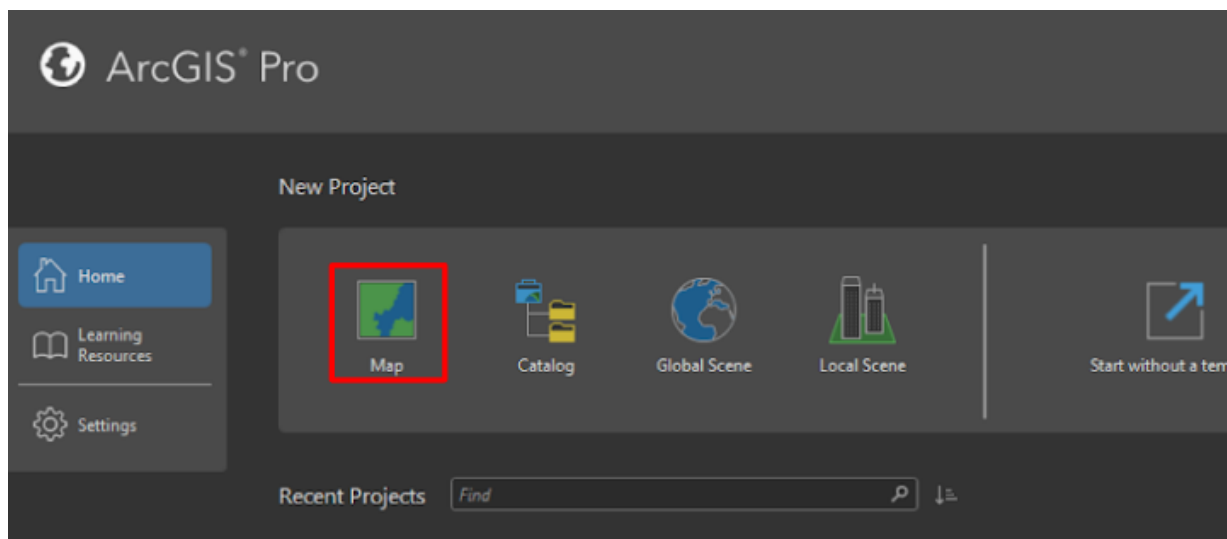
Hydroenforcement Outputs

- **Hucbuff.shp:** Buffer of watershed file input
- **Euclideanistance_(*Name chosen by runner*).tif:** Raster displaying watershed distance from the nearest source (stream feature).
- **Euclideanallocation_(*Name chosen by runner*).tif:** Raster storing elevation information of the closest stream feature cell.
- **Bufferdistance_(*Name chosen by runner*).tif:** Raster displaying buffer distance grids
- **BufferAllocation_(*Name chosen by runner*).tif:** Output of running euclidean distance and allocation grids – displaying nearest (stream feature) source based on Euclidean distance.
- **Elevationgrid_(*Name chosen by runner*).tif:** Output from creating smooth modified elevation grid
 - $\text{Float}(\text{vectallo} + (((\text{bufallo}) - (\text{vectallo})) / (\text{bufdist} + \text{vectdist})) * \text{vectdist})$
- **DEM_enforced_(*Name chosen by runner*).tif:** Final output, completed hydro-enforced raster layer.

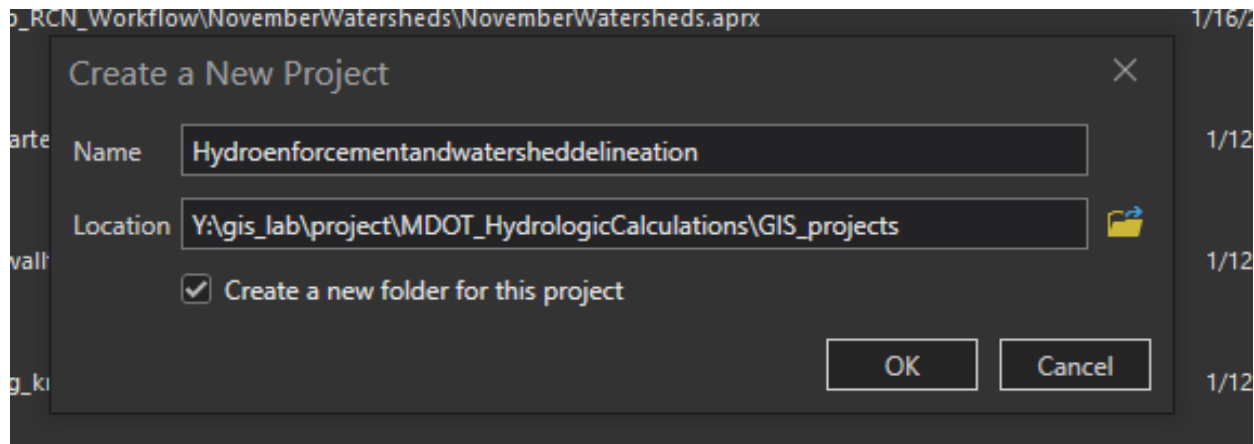
Step by Step Tutorial

Step 1: Open ArcPro and create a Project.

- Click 'map' under New Project

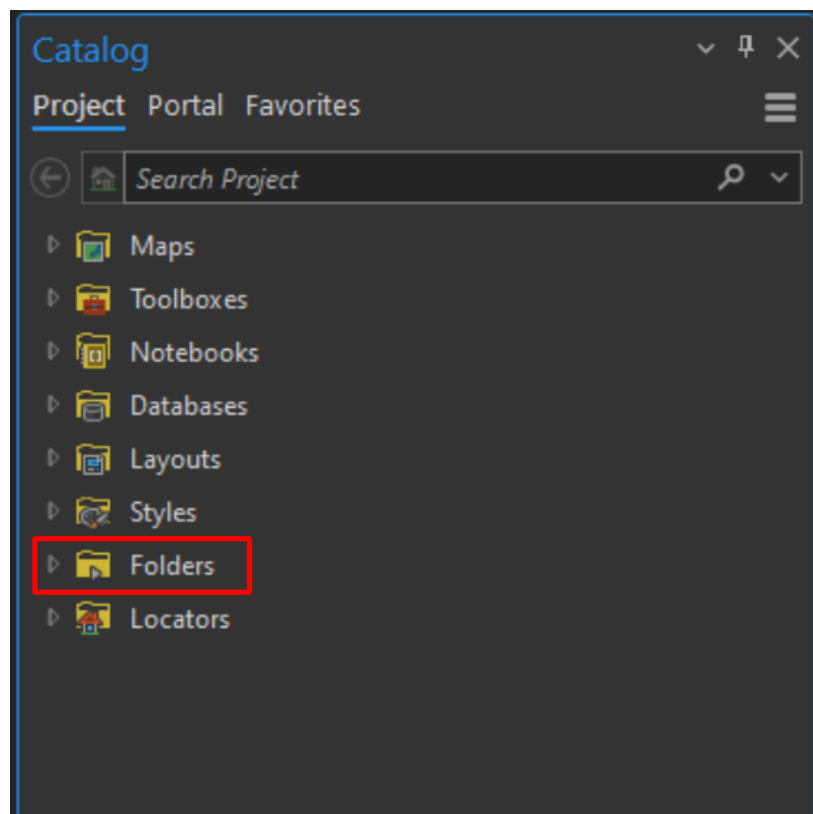


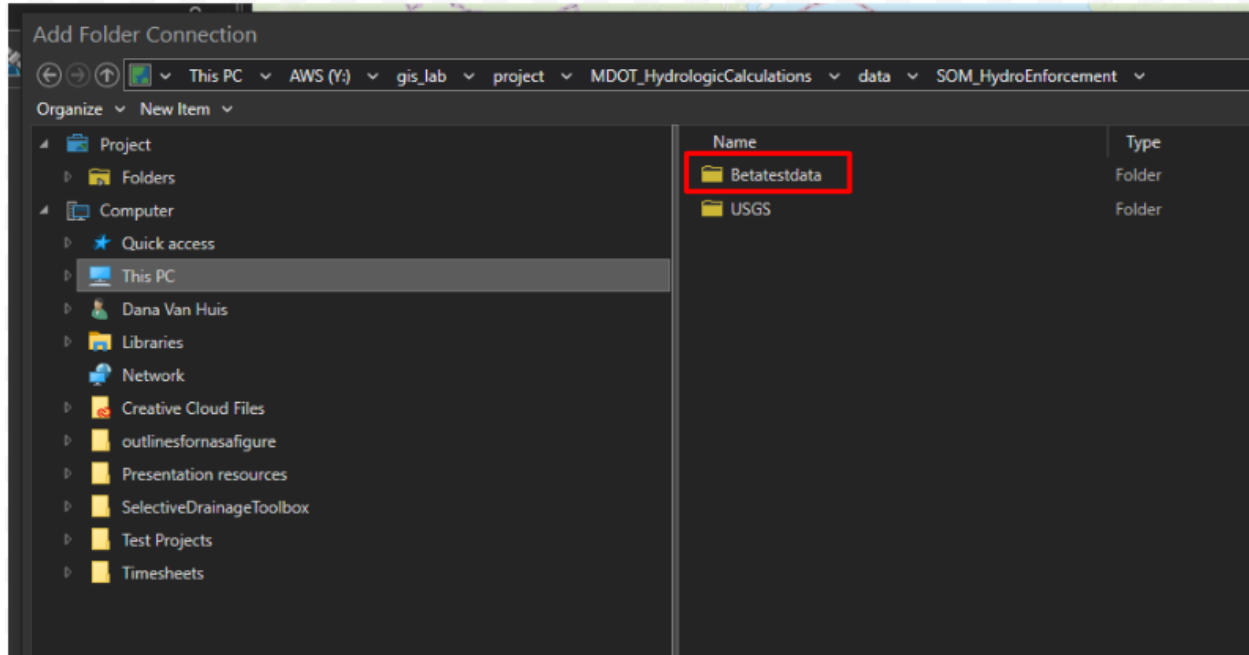
- Choose a location for your project and a file name



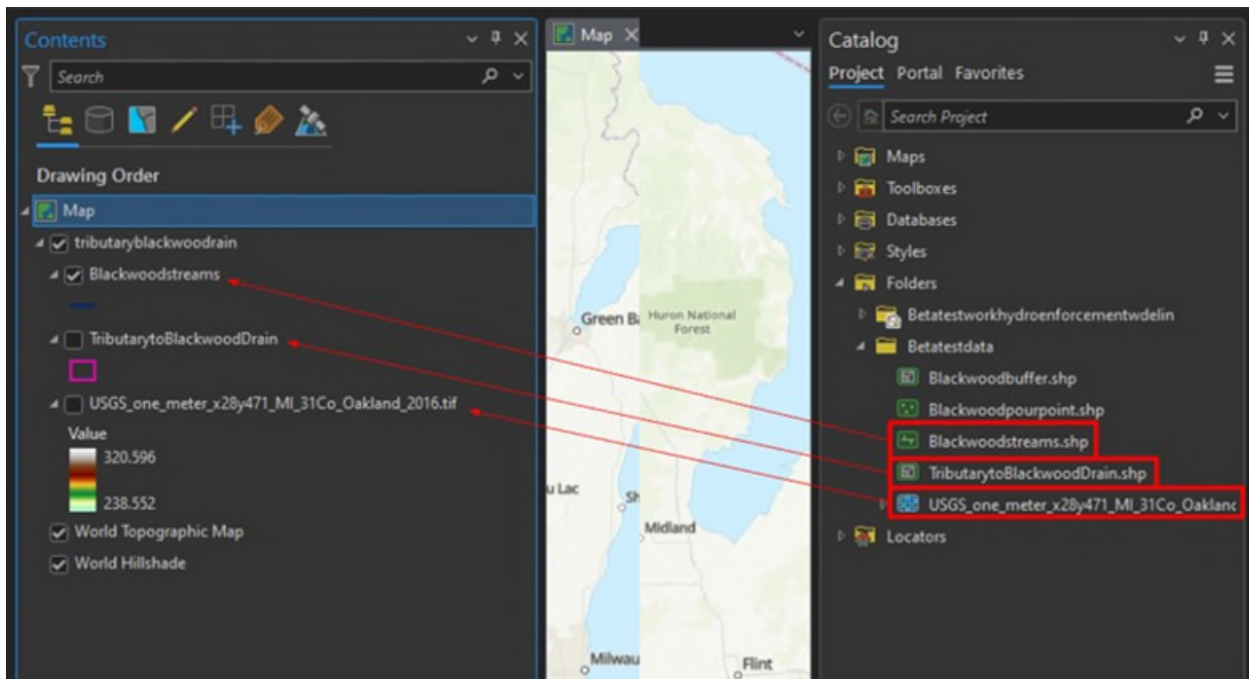
Step 2: Upload inputs into project

- Right click on 'folders' in the Catalog Pane and select 'Add Folder Connection'. Connect the folder that holds the inputs for the Hydroenforcement tool.



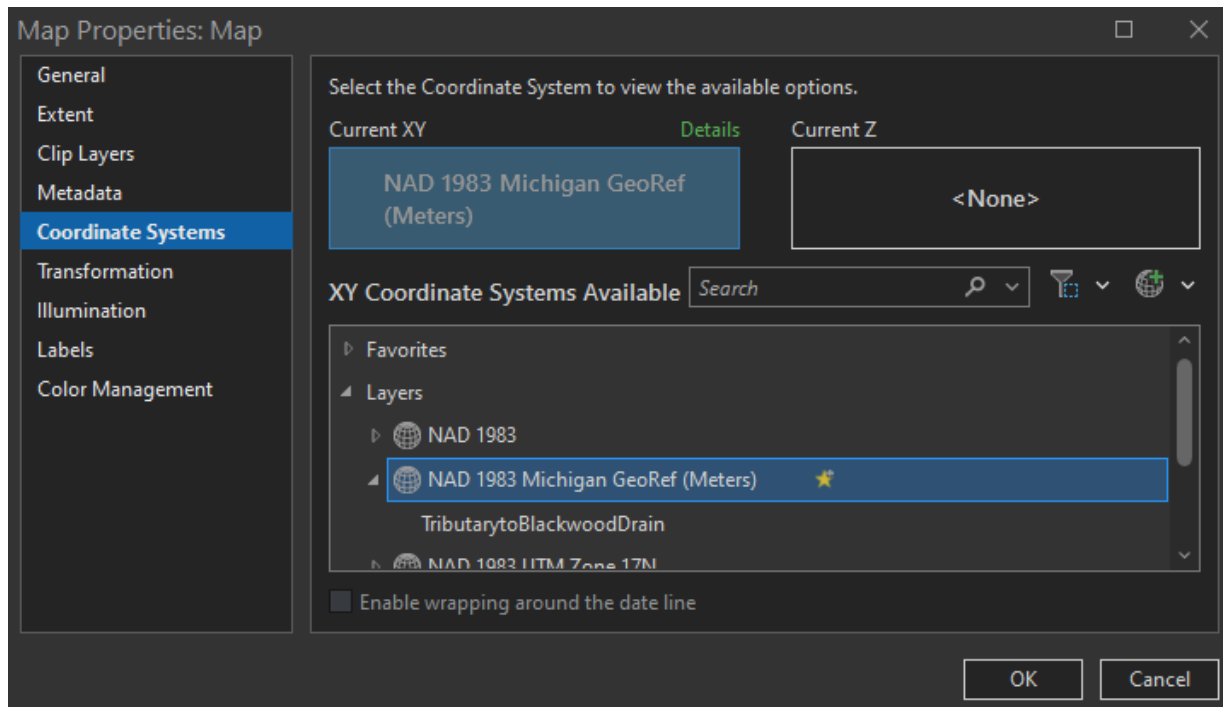


- Drag and drop necessary inputs into the 'Content's panel on the screen. For the hydroenforcement tool, necessary inputs include the streams layer, the watershed layer, and the DEM.

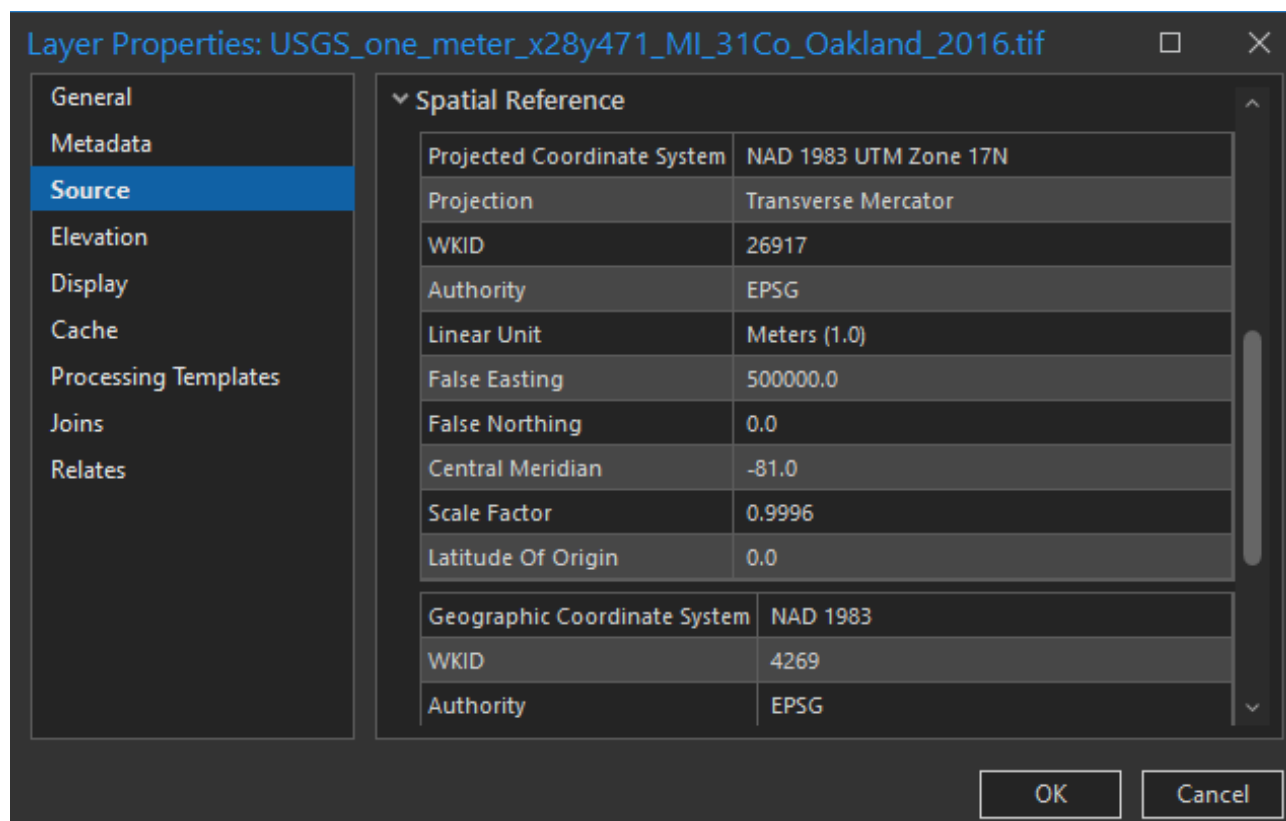


Step 3: Check projections

- Right click on the 'Map' icon in the Contents, and select Properties.
- Ensure that you're in the correct projection. For this example, we will be in NAD 1983 Michigan GeoRef.



- Check your DEM by right clicking on it in the Contents pane, and selecting Properties. The projection of each class can be found in the 'Source' pane, under 'Spatial Reference'.

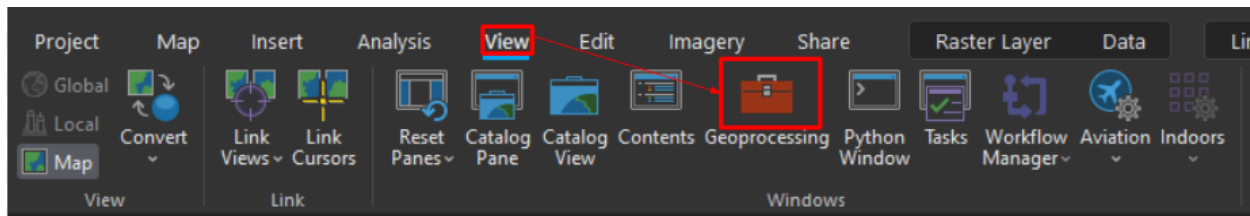


- If your DEM does not match your projects' Coordinate system, you can reproject it using Geoprocessing Tools. It is best to do this with a clipped version of your DEM to reduce time.

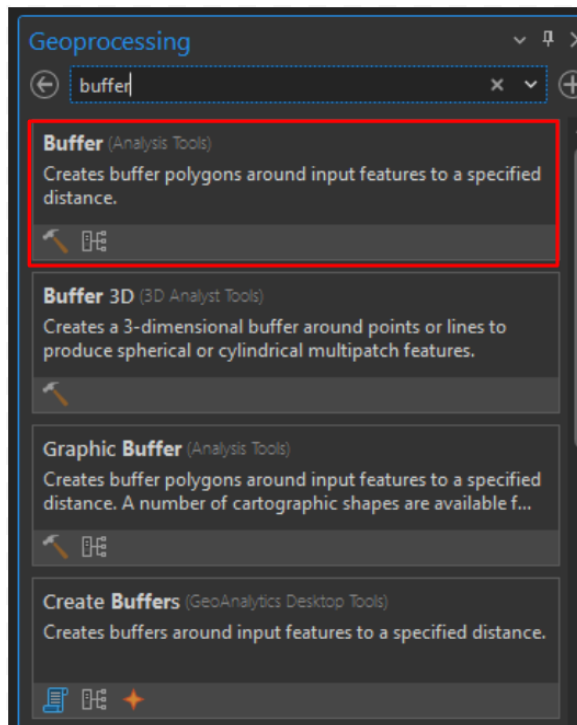
Step 4: Clip Raster

This step is only necessary if the DEM needs to be reprojected. If the DEM does not to be reprojected, move on to Step 6

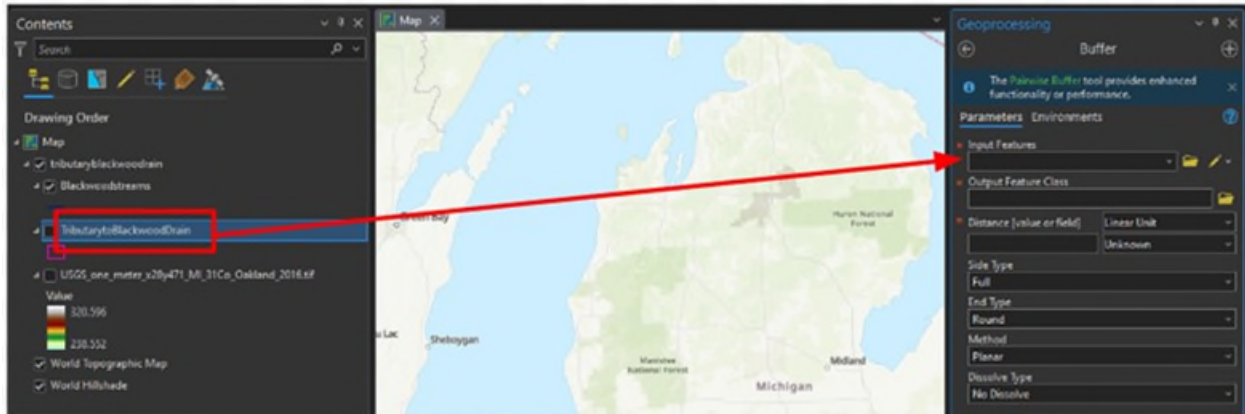
- To speed up processing time, we can Clip the raster to a buffer of the watershed.
- Go into the Geoprocessing tab by selecting 'View' from the list of commands at the top of the screen, and then select 'Geoprocessing'



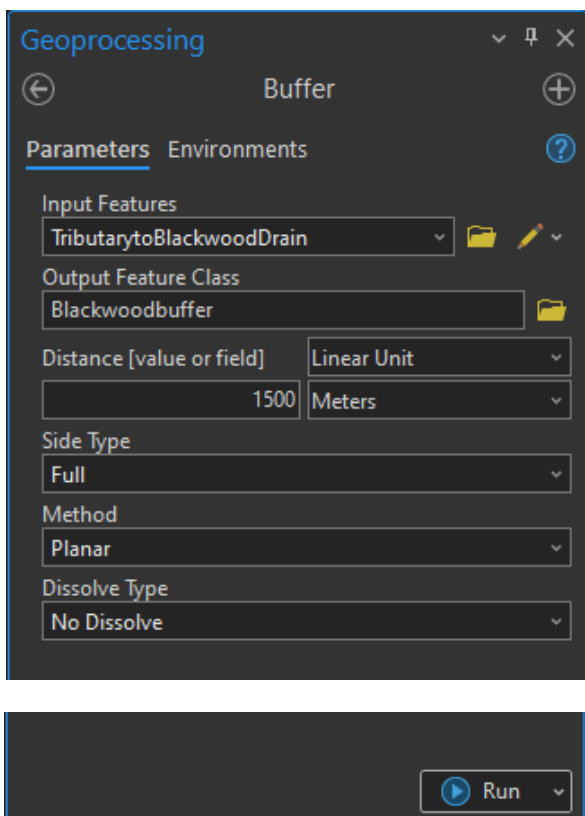
- Search for 'Buffer'



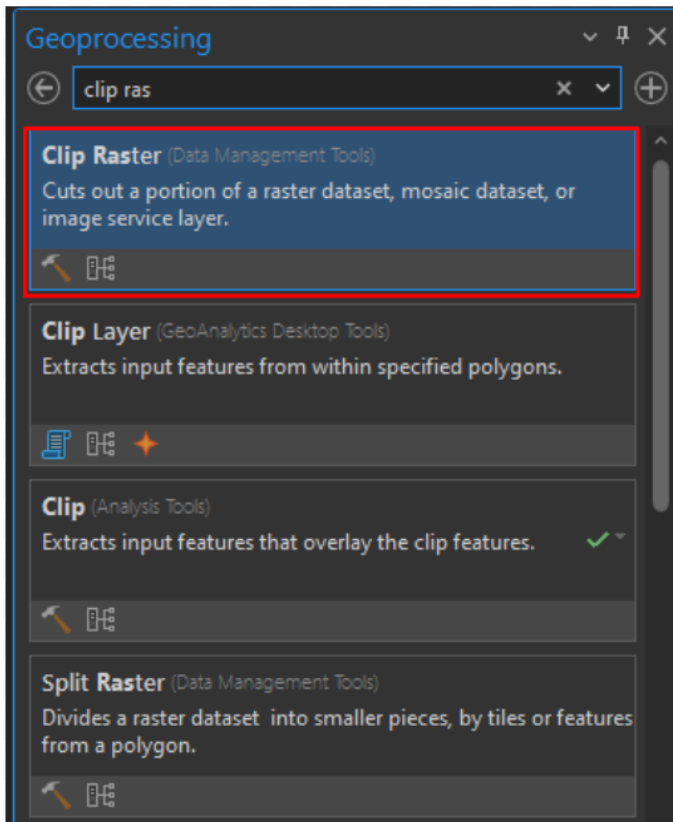
- Drag and drop your watershed feature class into the input feature column.



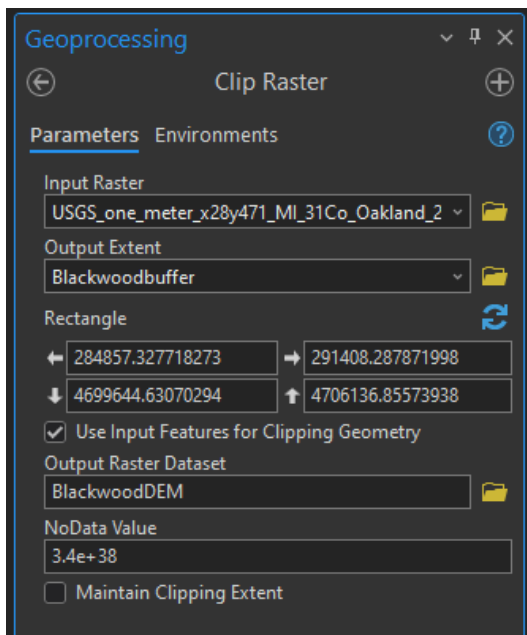
- Input other parameters. The size of your buffer will be dependent on the watershed that you're working on. As a default, we recommend 150m for a small watershed (5sqmi and below), 1500m for a medium (5-15sqmi) watershed, and 3000m for a large watershed (15sqmi and above). (These definitions came from analysis of the Working EGLE watershed and its standard watershed sizes.)



- Go back to the Geoprocessing pane and search for 'Clip Raster'

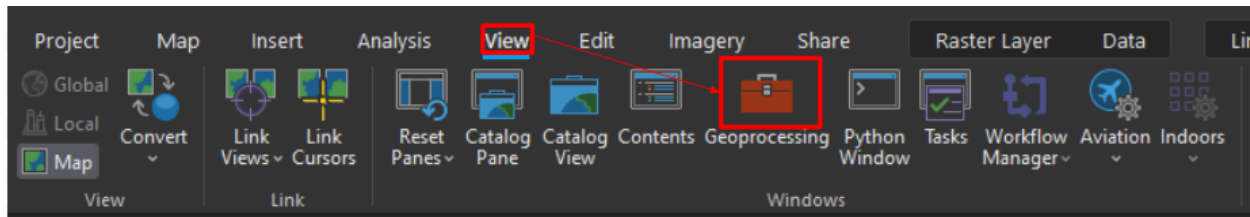


- Use your DEM as your input raster, and use your buffered watershed feature as your Output Extent, and hit Run.

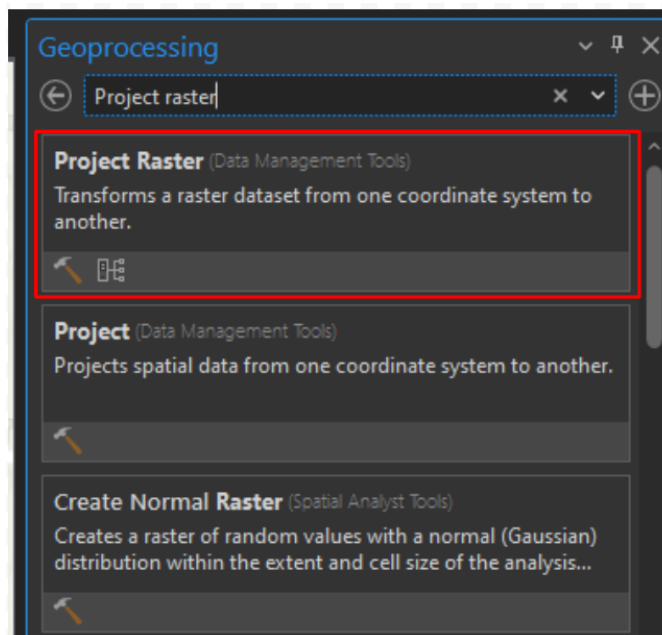


Step 5: Reproject Raster

- Go into the Geoprocessing tab by selecting 'View' from the list of commands at the top of the screen, and then select 'Geoprocessing'



- Search for 'Project Raster'



- Input necessary information into the tool, and hit 'Run'

Geoprocessing

Project Raster

Parameters Environments

Input Raster
BlackwoodDEM

Output Raster Dataset
BlackwoodDEM_Georef

Output Coordinate System
NAD_1983_Michigan_GeoRef_Meters

Geographic Transformation

Resampling Technique
Nearest neighbor

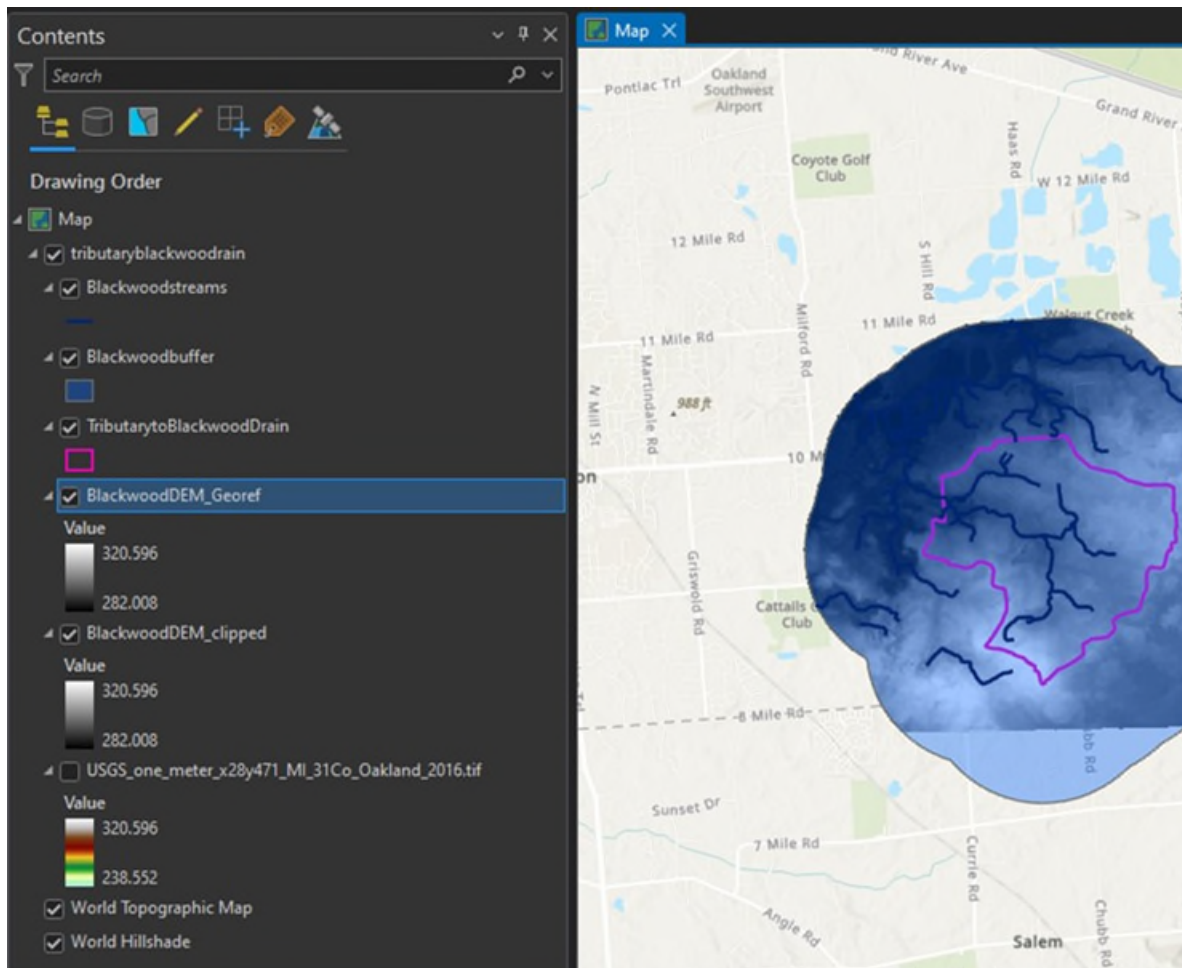
Output Cell Size

X 1 Y 1

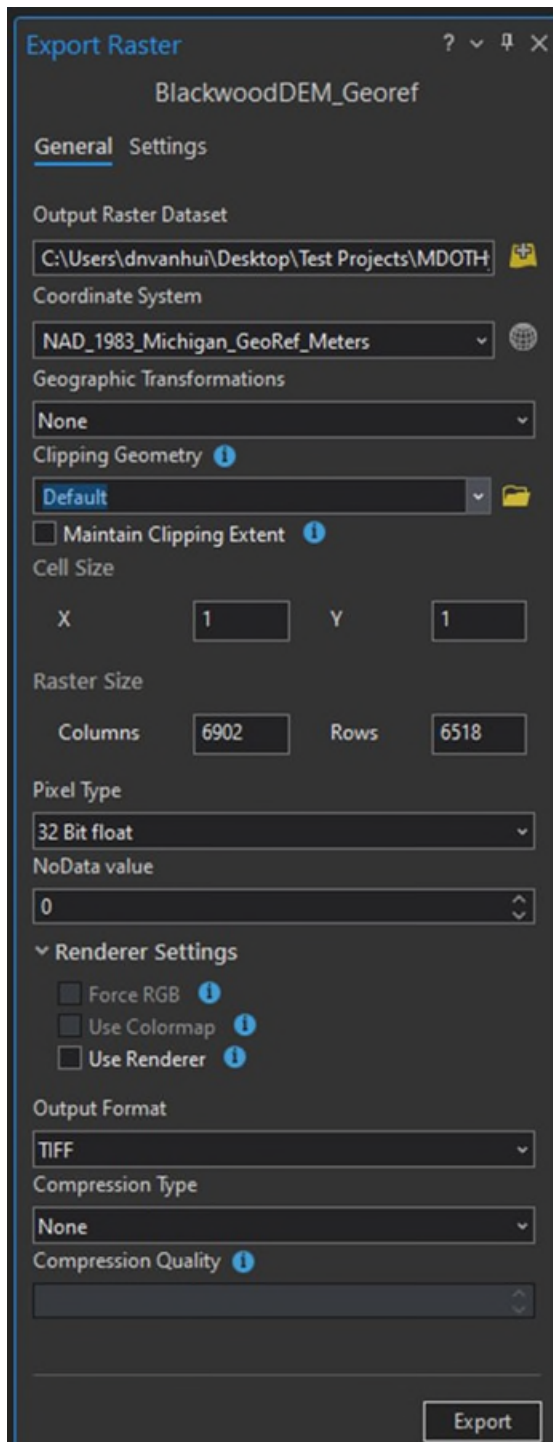
Registration Point
X Y

Run

- Your reprojected raster should show up in the project. Move them below the buffer, watershed, and streams layer.



Export the reprojected raster into your input folder by right clicking it and selecting 'Export Raster' under the 'Data' tab. Set your output raster dataset as the folder the rest of your inputs are saved in. Set your pixel type as the same pixel type as your DEM. This information can be found by right clicking the layer in the contents pane, selecting 'properties', and going to Raster information. Make sure that your cell size is maintained. And make sure that the output format is a TIFF file.



Export Raster

BlackwoodDEM_Georef

General Settings

Output Raster Dataset
C:\Users\dnvanhui\Desktop\Test Projects\MDOT\

Coordinate System
NAD_1983_Michigan_GeoRef_Meters

Geographic Transformations
None

Clipping Geometry
Default

☐ Maintain Clipping Extent

Cell Size
X: 1 Y: 1

Raster Size
Columns: 6902 Rows: 6518

Pixel Type
32 Bit float

NoData value
0

▼ **Renderer Settings**
☐ Force RGB
☐ Use Colormap
☐ Use Renderer

Output Format
TIFF

Compression Type
None

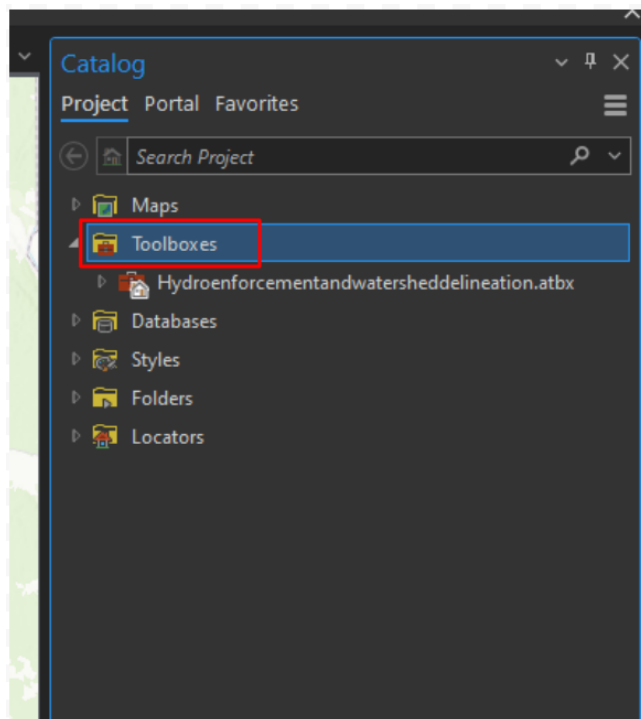
Compression Quality

Export

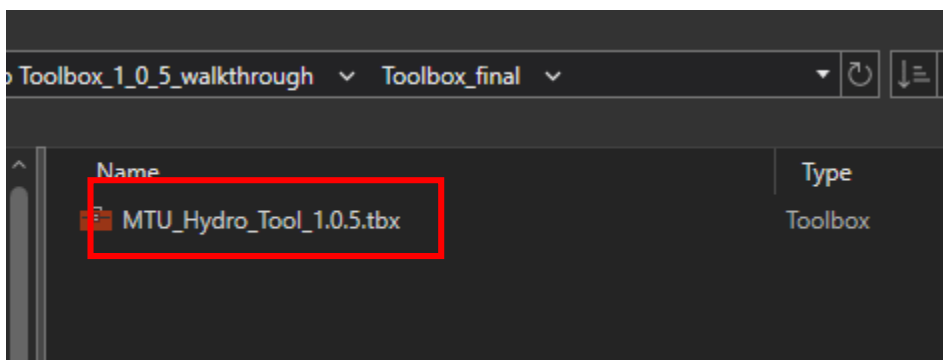
- This DEM is what we're going to use as our raster input for the Hydro-enforcement tool. Other raster files can be removed from the project at this point as they are no longer needed.

Step 6: Install tool

- Right click 'Toolboxes' in the Catalog Pane

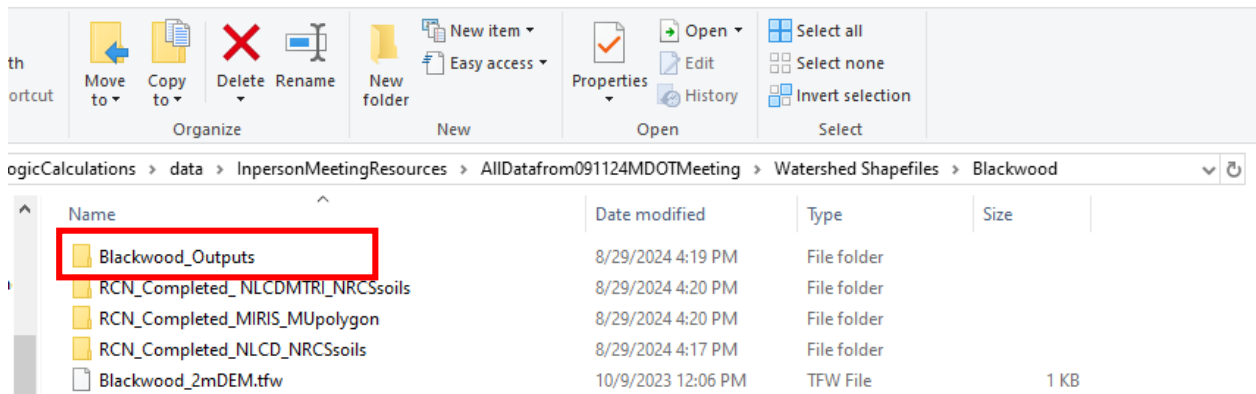


- Select 'Add Toolbox, and find where you have saved the MTU_Hydro_Tool. Select and click 'Ok'.

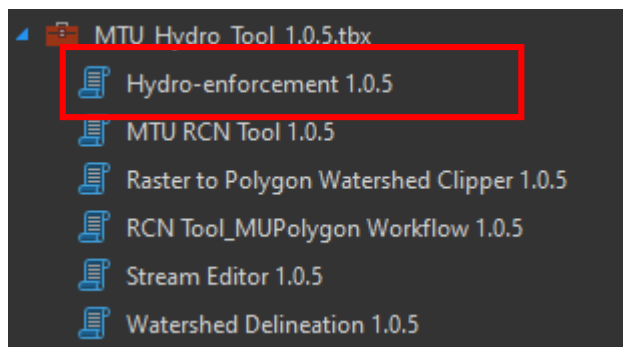


Step 7: Run tool

- Create an 'output' folder in your File Explorer, in order to save all products created by this tool



- Double click the 'Hydro-enforcement 1.0.5' tool in the MTU_Hydro_Tool_1.0.5.tbx



- Select the directory you just created as your 'output directory', then input your watershed feature class, DEM, and stream feature class by either clicking the arrow to select from available layers in the project, clicking the folder icon next to the input to find the feature class in the folder it's saved in, or by dragging and dropping the file from the Contents pane to the Tool pane. **Make sure that your watershed feature class includes the full area that you want to delineate.**

Geoprocessing ⌵ 📌 ✕

← Hydro-enforcement →

Parameters ? Environments

Output Directory
BlackwoodTributary_Hydroenforcement 📁

Watershed File
TributarytoBlackwoodDrain 📁

Input DEM
BlackwoodDEMgeoref.tif 📁

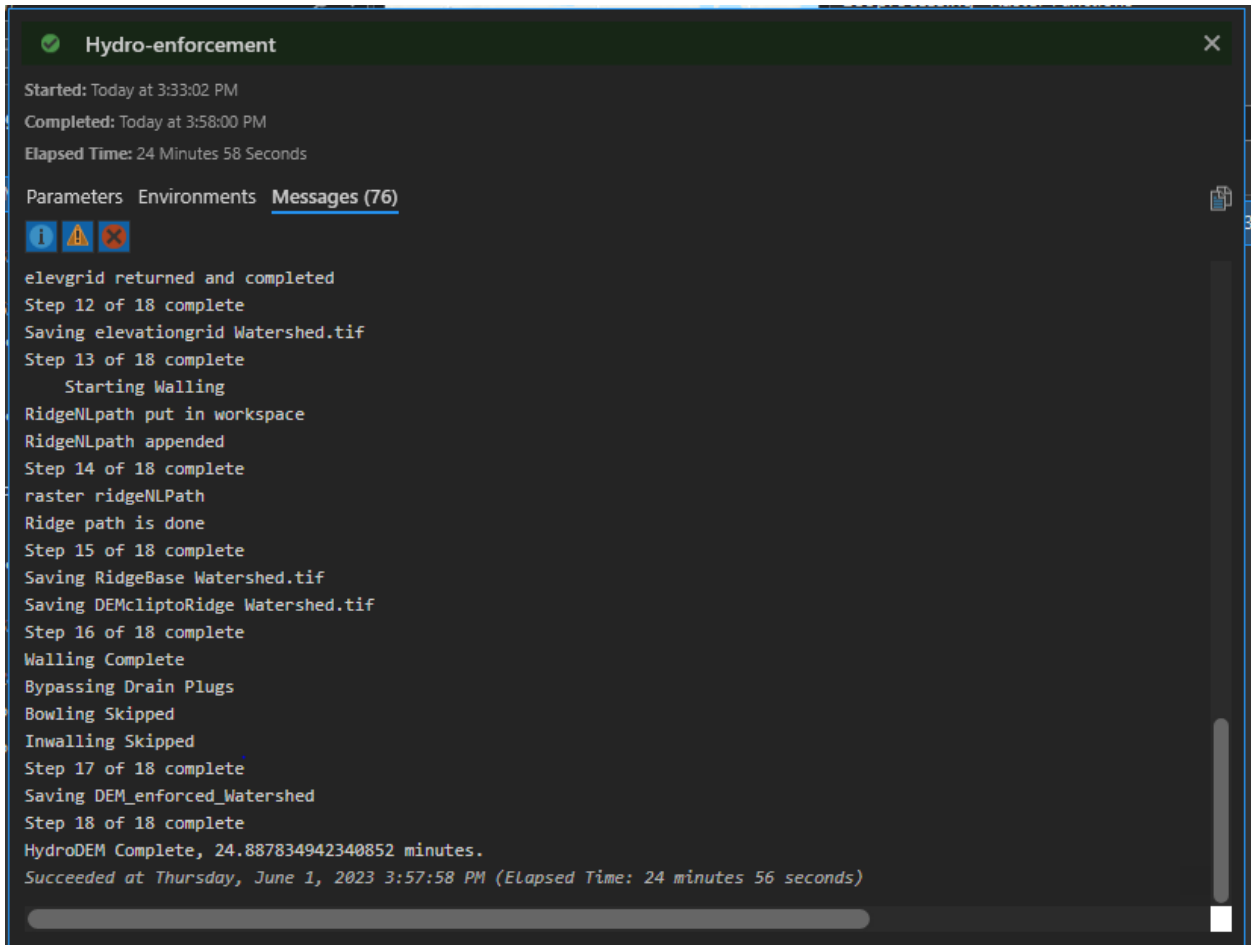
Stream feature class
Blackwoodstreams 📁

DEM name (optional)
Blackwoodtributary

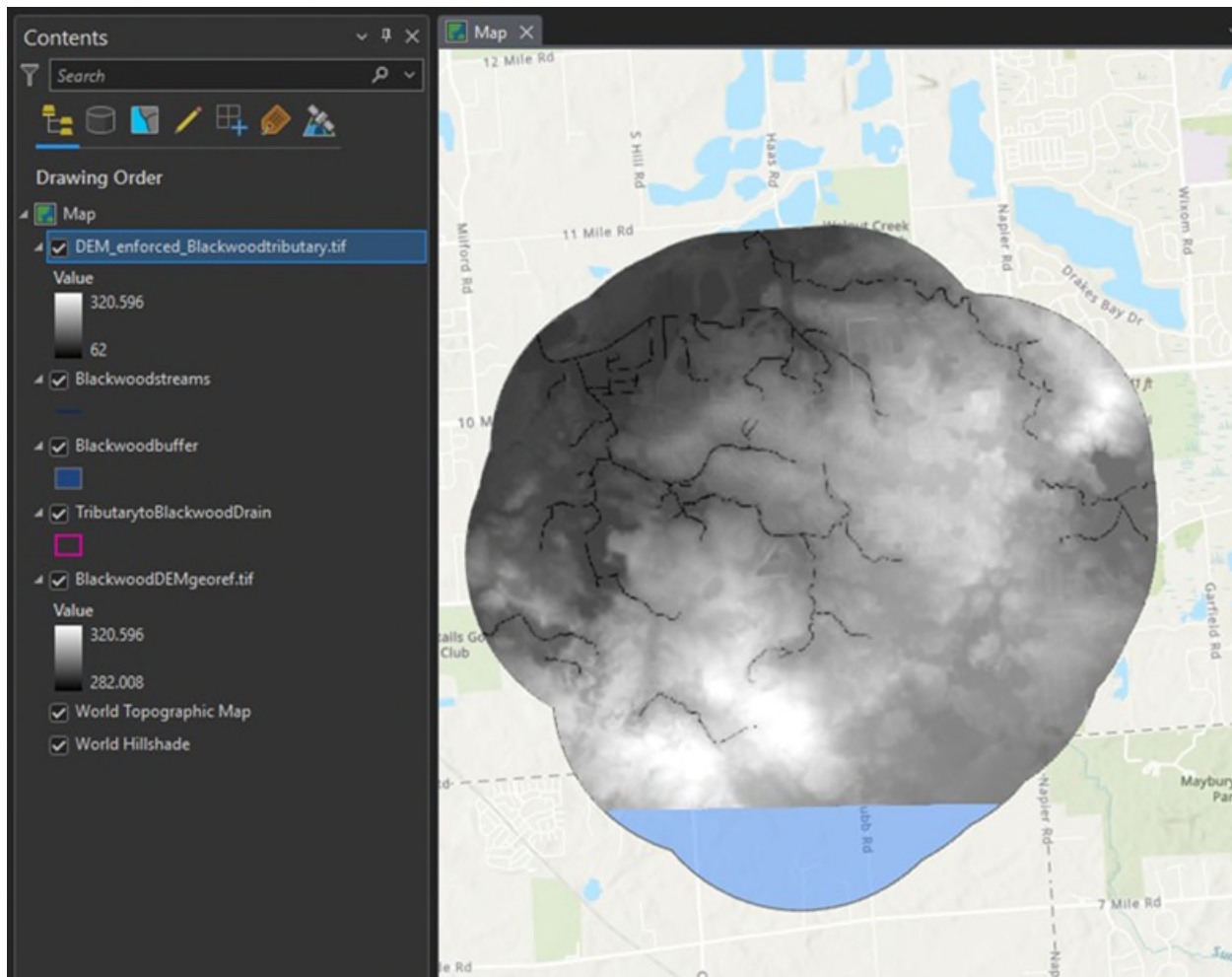
Buffer around Watershed	1500
Inwall Buffer Distance	15
Inwall Height	150
Outwall Height	300
Agree Buffer	6
Agree Smooth	-20
Agree Sharp	-200
Bowling Depth	2000

▶ Run ⌵

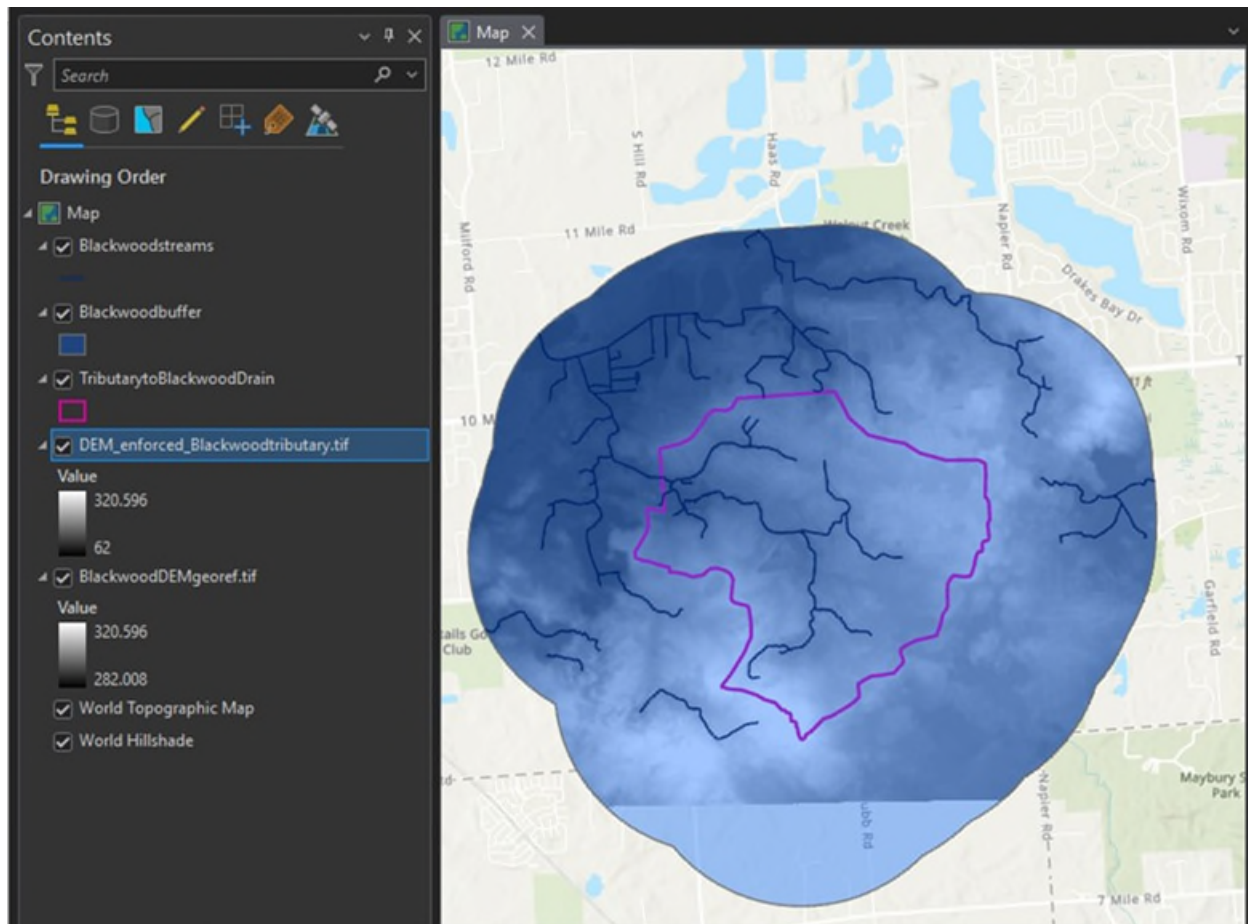
- Select 'View Details' as the tool is running if you'd like to see its progress. If the tool was successful, it should say 'Succeeded at... (time)'



- The final output should automatically populate into your map.

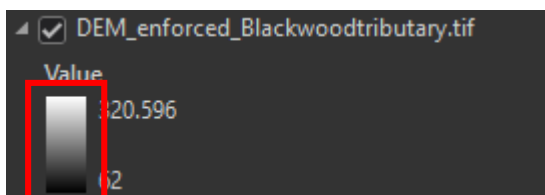


- Move the layer below the shapefiles in the project.

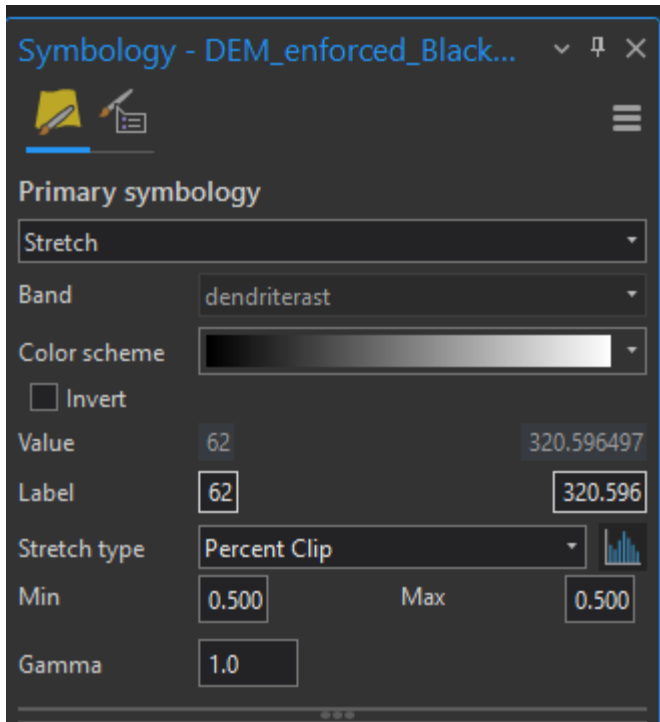


Step 8: Change Symbolology

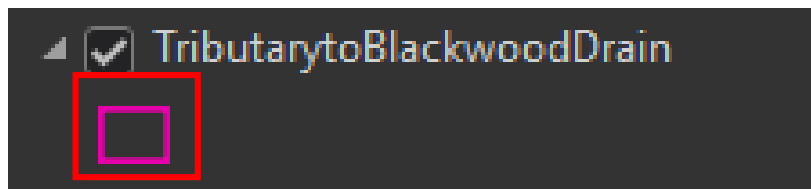
- Double click the white to black gradient below the layer's title in the Contents pane.



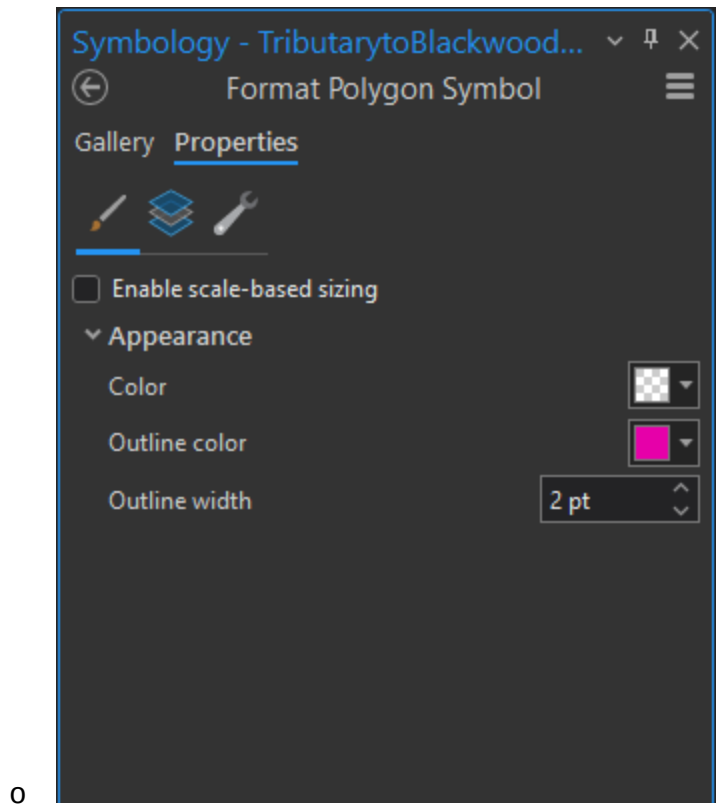
- The Symbolology pane will appear, and you can change the symbology to something that better displays the DEM. We suggest Elevation #1.



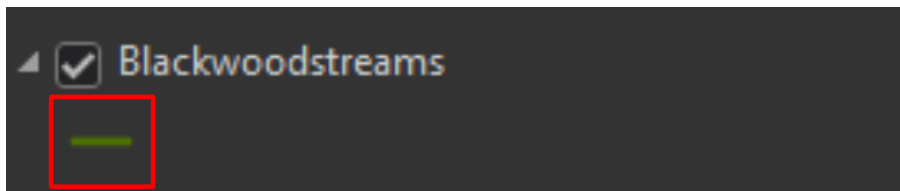
- Double click on the square underneath the Watershed layer title in the Contents pane.



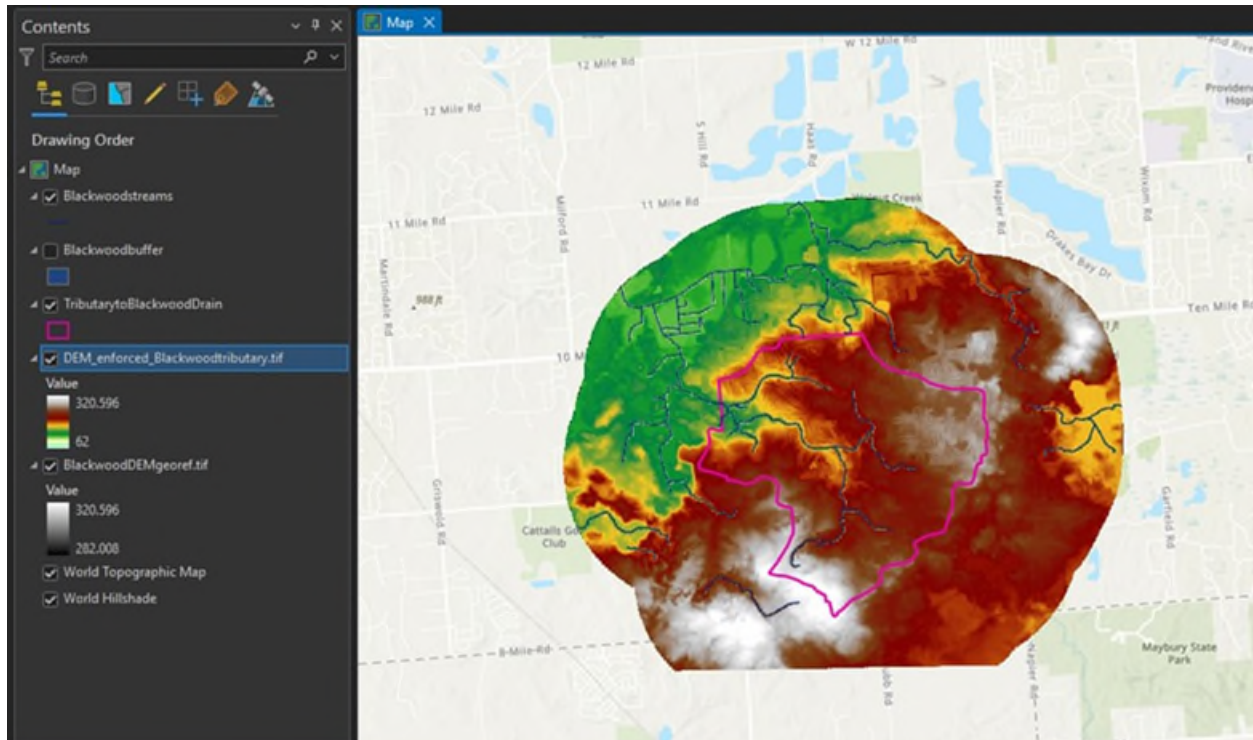
- o The Symbology pane will appear, and you can change the symbology to only display the Outline so you can better see the DEM



- Double click on the line underneath the Stream layer title in the Contents pane.



- o The Symbology pane will appear, and you can change the symbology to a dark blue so it is more visible
- You now have a hydroenforced DEM!



MTU_Hydro_Tool_1.0.5

Watershed Delineation step by step

May 15 2025

General Overview of the Watershed Delineation Tool

Watershed delineation is the process of creating a boundary around the upslope area that contributes flow to a common outlet.

This tool uses a (potentially hydroenforced) DEM and pour points to automatically delineate a watershed. It works by computing the flow direction and snapped pour point in order to determine the contributing area of the watershed.

Watershed Delineation Inputs

- **DEM:** DEM that is being used to delineate the watershed. If the hydro enforcement tool has been used, use the output DEM from that tool.
- **Pour Points:** Where water flows out of the watershed, point feature class. Has 'Point and Click' feature to create pour points within the tool. Can also hold a shapefile with previously existing pour point, but can't hold both file types at the same time.
- **Additional Pour Points:** Additional ability to add pour points if so desired. Will append all points to an output "pour_copy.shp" where all pour points are used. This parameter allows the user to delineate watersheds off of pour points created within the tool, and pour points that had been previously created.
- **Output Directory:** Folder where output files will be saved.

Watershed Delineation Parameter Definitions

- **Identifying Field Name for Pour Points:** Column name from the Pour Points Feature Class, IDs pour points.
- **Watershed Title:** Title of the Delineation output
- **Source Area:** In meters, the potential contributing area above the watershed.
- **Snap Distance:** In meters, the maximum distance to search for a stream cell of higher accumulated flow. If there is not a stream nearby with a lower source area, or if the pour point is snapping to the wrong stream, move the pour point to the desired stream. **If you are not getting an output for the watershed that you are trying to delineate, reduce the size of this tool and use a flow accumulation raster to specify your pour point location.**

Watershed Delineation Outputs

- **watershed.shp:** Final Output
- **wtr.shp and watershed_simpler:** Preliminary delineation outputs
- **Snap.tif:** Raster layer used to snap the pour point to the correct pixel to create an accurate watershed delineation. Will appear blank if brought into the project
- **Pour_copy.shp:** Pour point feature class created by tool.
- **output_flow_length.tif:** Displays distance of pixel from the stream layer

- **output_flow_direction.tif:** Displays flow direction in the watershed
- **flow_accumulation_complete.tif:** Displays flow accumulation in the watershed. The best way to symbolize this is to change the Primary Symbology to 'Classify', and convert the classes displayed to log form (.01, 1., 10., etc.).

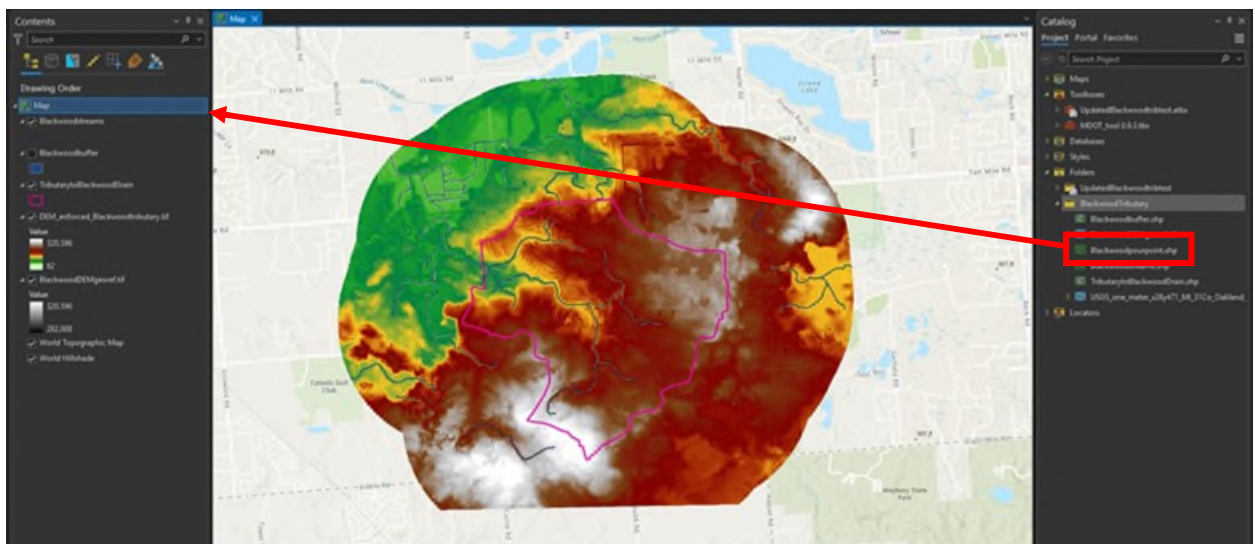
Step By Step Tutorial

- *This tutorial assumes that you've already gone through the steps found in the Hydroenforcement tool tutorial. If you have not done so already, go to the Hydroenforcement tool tutorial and run steps 1-6. Then return to this tutorial.*
- *This tool can also run on DEMs that have not been enforced or hydroenforced with a different methodology. If you are planning on running this tool on a DEM that has not been hydroenforced, consider running steps 1-5 of the hydroenforcement tutorial, then return to this tutorial.*

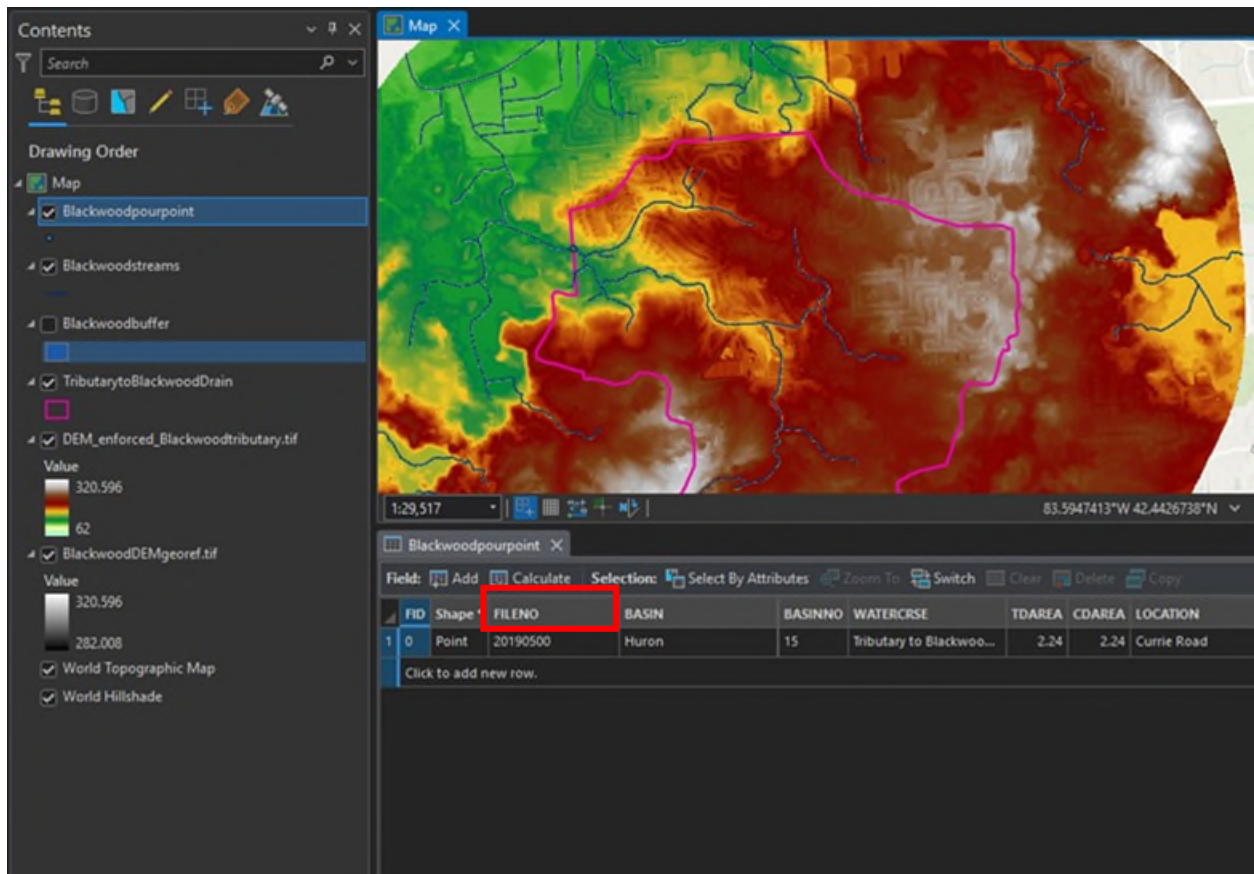
If you do not have a pour point layer, skip Step 1. (Step 2 will help you make a pour point.)

Step 1: Upload inputs into Project

- If you have a pour point file, go back into your input folder on the Catalog pane and drag over your pour point file



- Right click on your pour point in the Contents pane, and click on 'attribute table'. Find the distinct identifier column title.

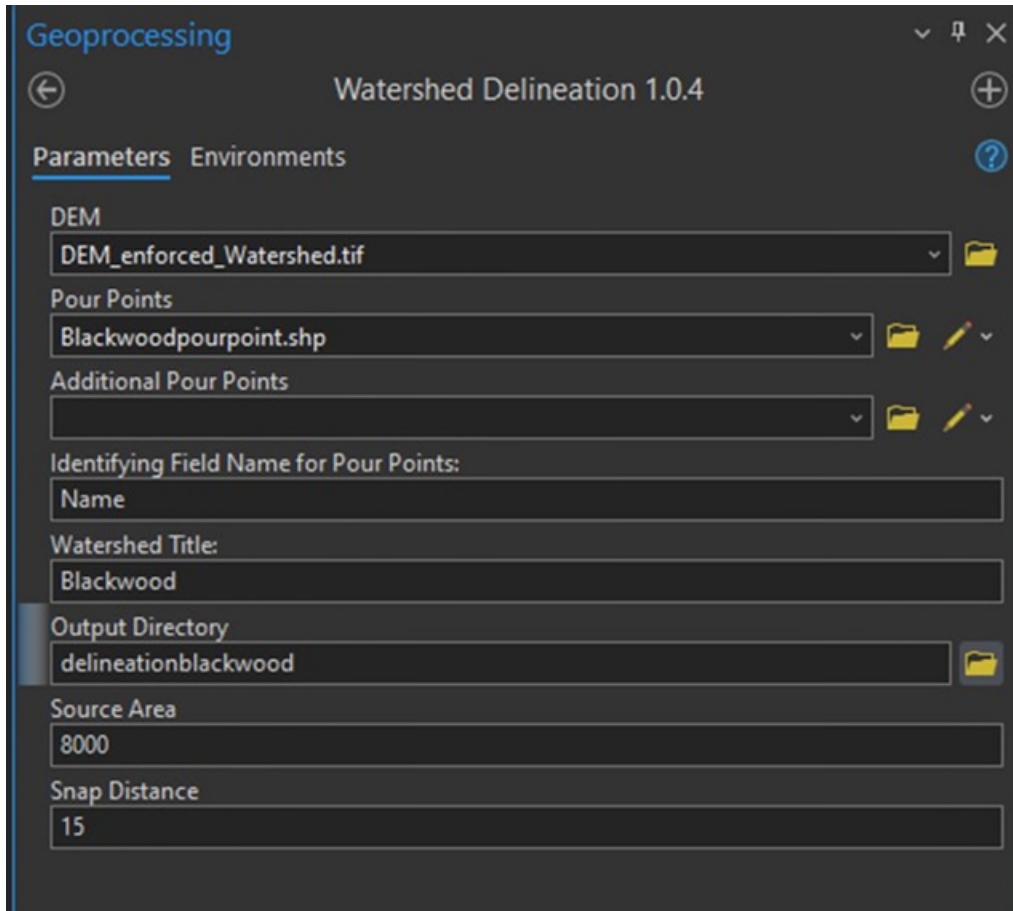
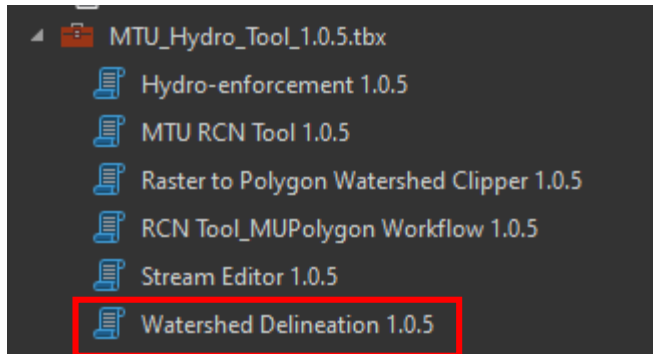


Step 2: Run Tool

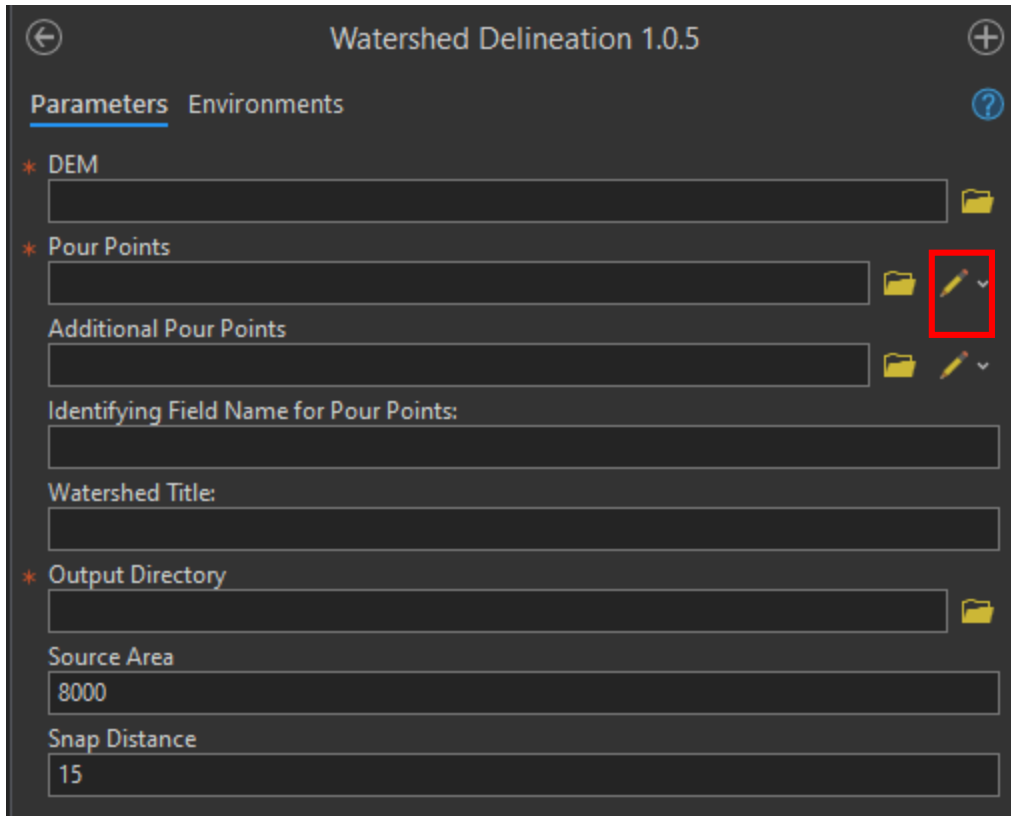
- Create an 'output' folder, to save all products created by this tool

Organize	New	Open	Select	
cCalculations > data > InpersonMeetingResources > AllDatafrom091124MDOTMeeting > Watershed Shapefiles > Blackwood				
Name	Date modified	Type	Size	
Blackwood_Outputs	8/29/2024 4:19 PM	File folder		
BlackwoodTributary_Delineation	8/29/2024 4:22 PM	File folder		
RCN_Completed_NLCDMTRI_NRCssoils	8/29/2024 4:20 PM	File folder		
RCN_Completed_MIRIS_MUpolygon	8/29/2024 4:20 PM	File folder		
RCN_Completed_NLCD_NRCssoils	8/29/2024 4:17 PM	File folder		
Blackwood_2mDEM.tfw	10/9/2023 12:06 PM	TFW File	1 KB	
Blackwood_2mDEM.tif	10/9/2023 12:06 PM	TIF File	228,568 KB	

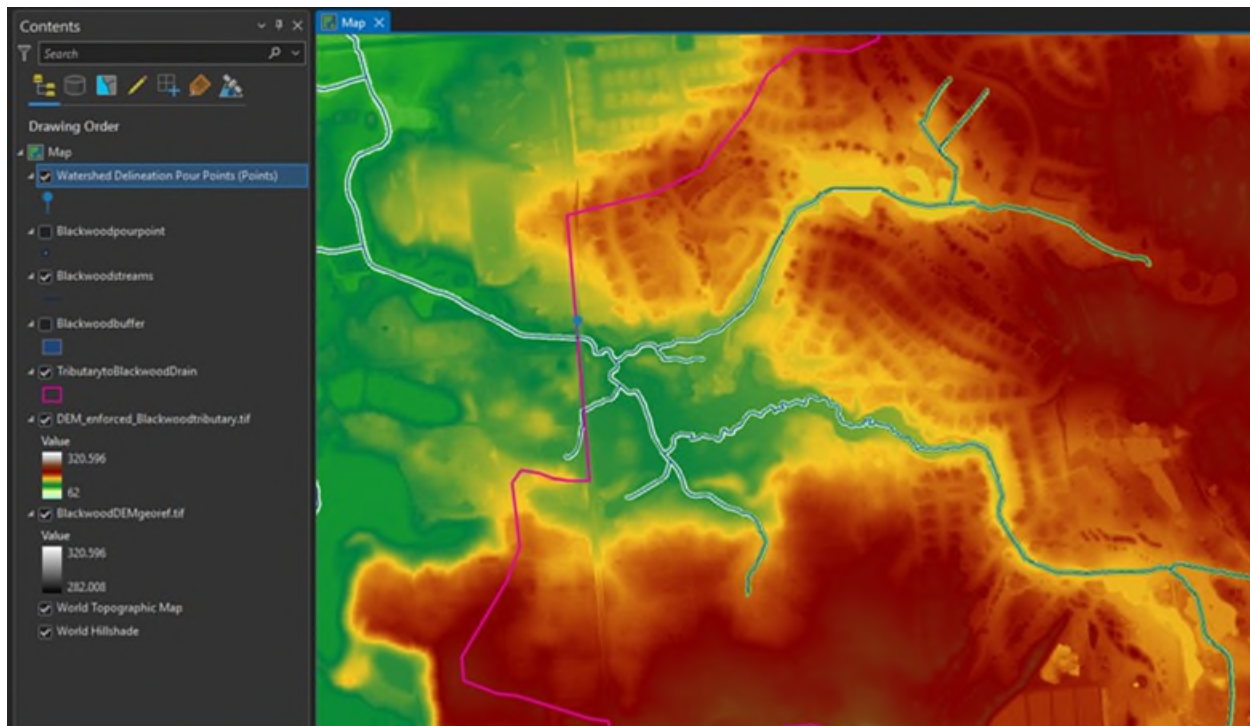
- Double click the 'Watershed Delineation' tool in the MDOT_Toolbox
- Select inputs. These should be the DEM (either hydro-enforced or not) and your pour point file. Use the distinct identifier column title in your pour point layer as the 'field name', so the tool can differentiate between pour points if your file contains multiple points. Determine whether or not you would like to use the default parameters or if your project requires different parameters.



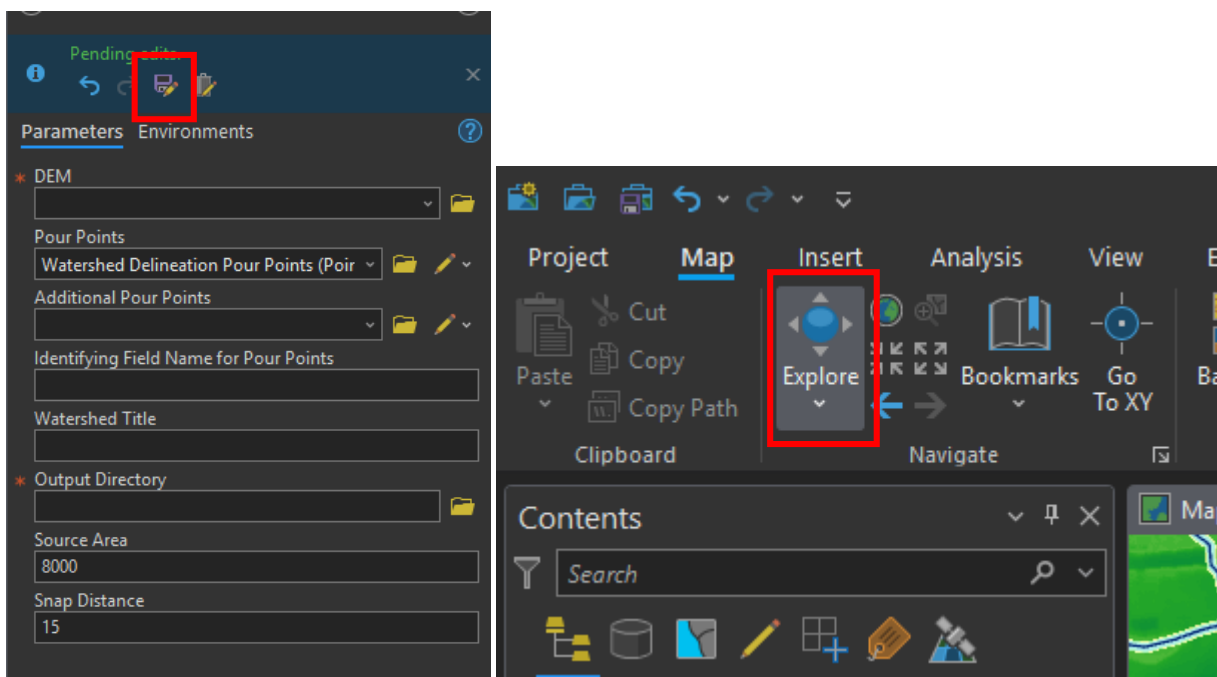
- If you don't have a pour point layer, select the pencil icon next to Pour Points.



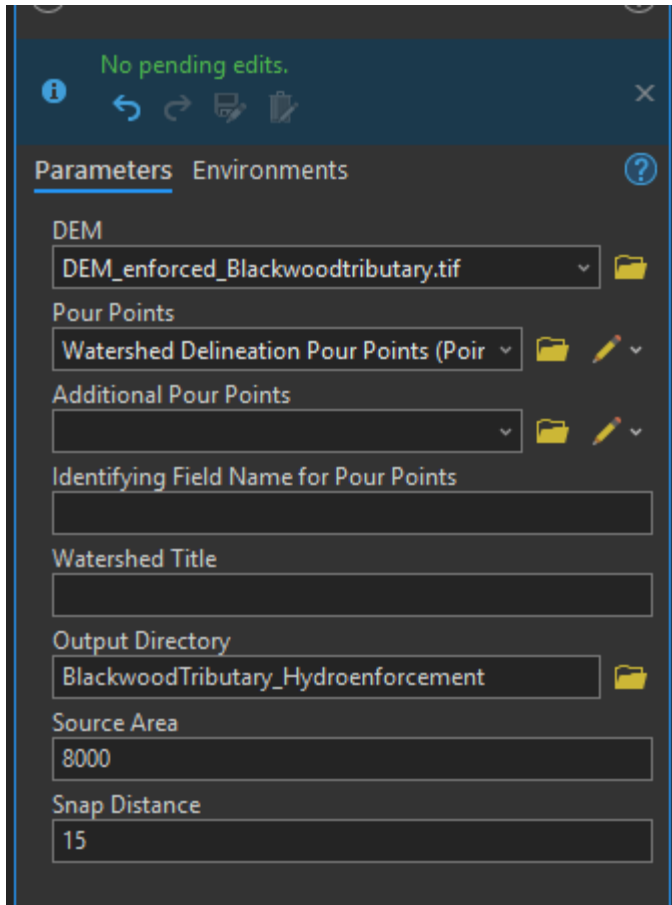
- This will create a new point layer titled “Watershed Delineation Pour Points (Points)”, and turn on Feature Editing mode. From here, you can place your pour points within the watersheds you’d like to delineate. **If you’ve already created a flow accumulation from a previous run of the tool in this area, use this as an additional source for building your pour points.**
- Place your pour point as close to the watershed’s pour point as possible. The Snapping tool built into the tool will make sure that it snaps to the correct cell.
- *If you are using the tool built for 3.1, you can use a pour point feature class that has already been built in the Pour Point command and use the point-and-click tool in the Additional Pour Point command, and the output will append both datasets. This functionality unfortunately does not exist in ArcGIS Pro 2.9.5.



- When finished, hit 'save' on the Pending Edits warning that pops up in the tool, and reselect 'Explore' in the 'Map' tab so you don't accidentally create more pour points.

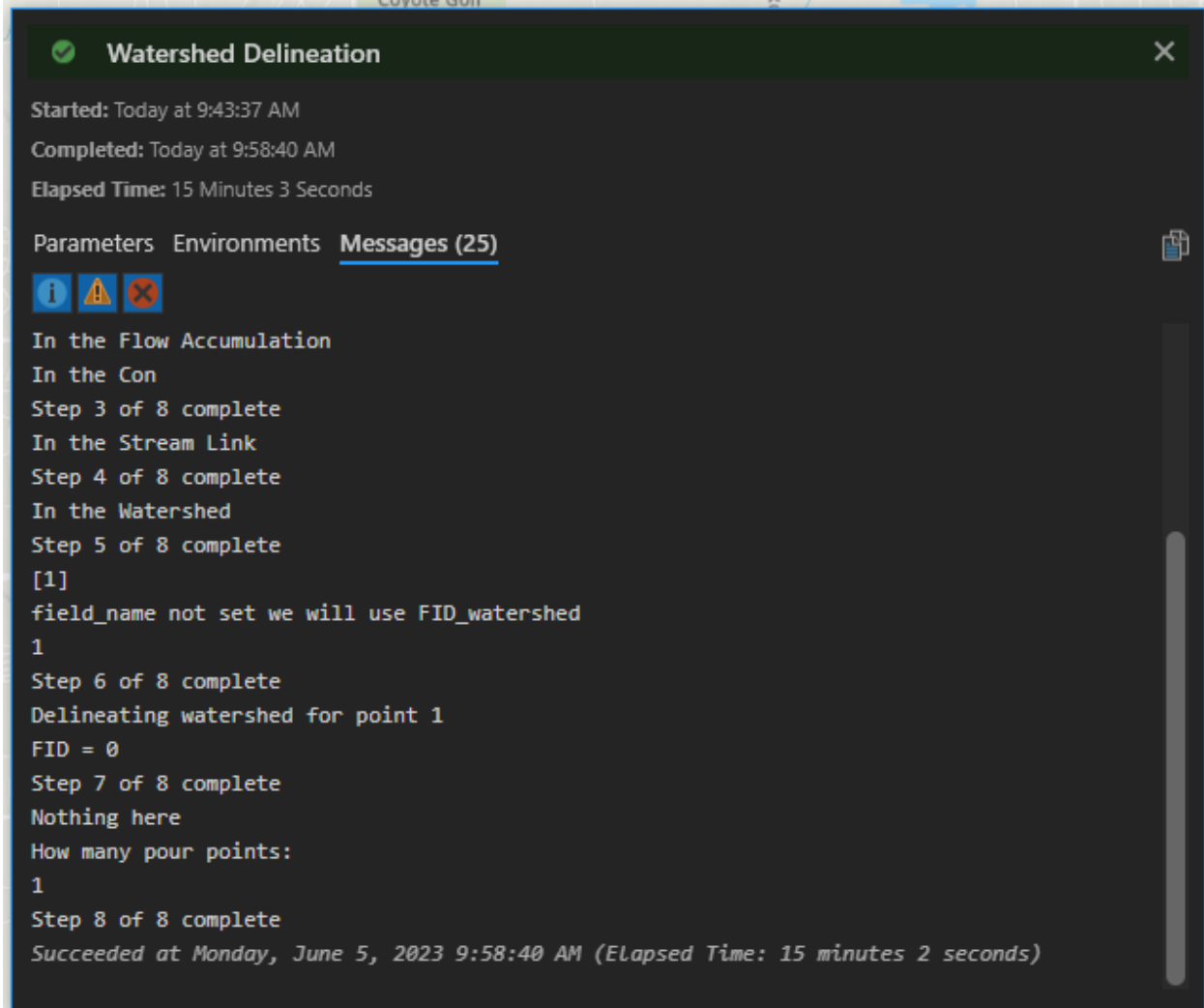


- Fill out the rest of the parameters in the tool, and hit 'Run'.

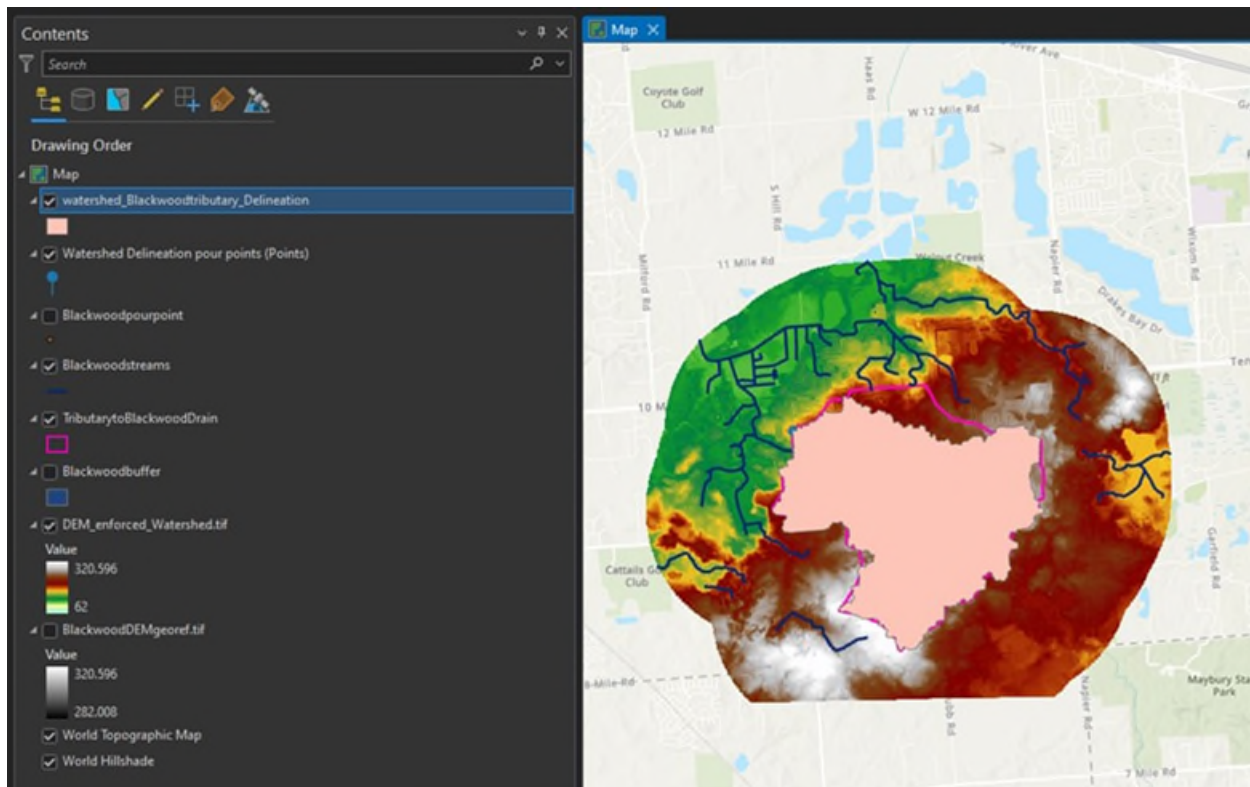


The screenshot shows the 'Parameters' tab of a software interface. At the top, a status bar indicates 'No pending edits.' with icons for undo, redo, save, and delete. Below this, the 'Parameters' section is active, showing various input fields and dropdown menus. The 'DEM' field is set to 'DEM_enforced_Blackwoodtributary.tif'. The 'Pour Points' field is set to 'Watershed Delineation Pour Points (Poir)'. The 'Additional Pour Points' field is empty. The 'Identifying Field Name for Pour Points' field is empty. The 'Watershed Title' field is empty. The 'Output Directory' field is set to 'BlackwoodTributary_Hydroenforcement'. The 'Source Area' field is set to '8000'. The 'Snap Distance' field is set to '15'.

- Select 'View Details' as the tool is running if you'd like to see its progress. If the tool was successful, it should say 'Succeeded at... (time)'.



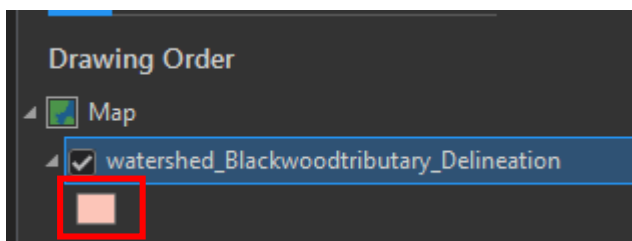
- The result should auto-populate into your map.

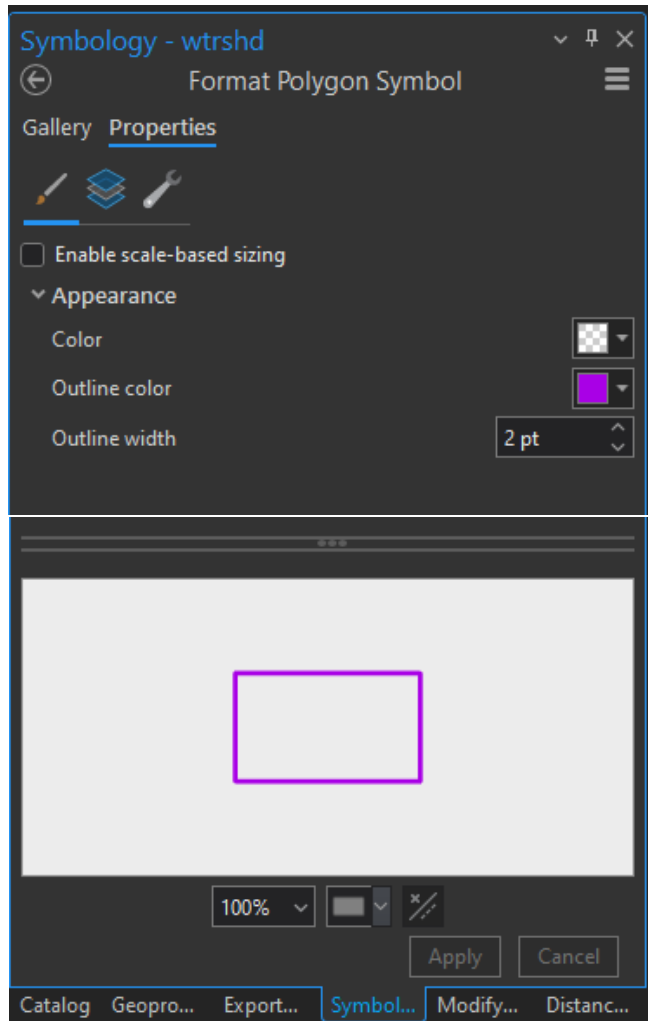


- You can also add the Flow Accumulation to the project by going into your output folder and dragging and dropping the 'flow_accumulation_complete.tif' into the project.

Step 3: Change Symbolology

- Double-click the square below the watershed layer. The Symbolology pane will appear, and you can change the symbolology to only display the Outline so you can better see the DEM





- Double click the gradient below the Flow Accumulation layer. The Symbology pane will pop up. Switch the 'Primary Symbology' from 'Stretch' to 'Classify'. Switch the color scheme from the default to 'Yellow-Green-Blue (Continuous)'. You can then convert the classes displayed in the flow accumulation to a log scale for the best visualization of flow. This is done by going into the 'upper value' menu in the symbology pane and manually changing the values. Be sure to keep the highest value the same. In order to best visualize the flow accumulation, you can remove the color from the pixels with a value less than 100 by double clicking on the color box in the 'color' column in the symbology pane. You will have to manually change the values in the symbolization tool.

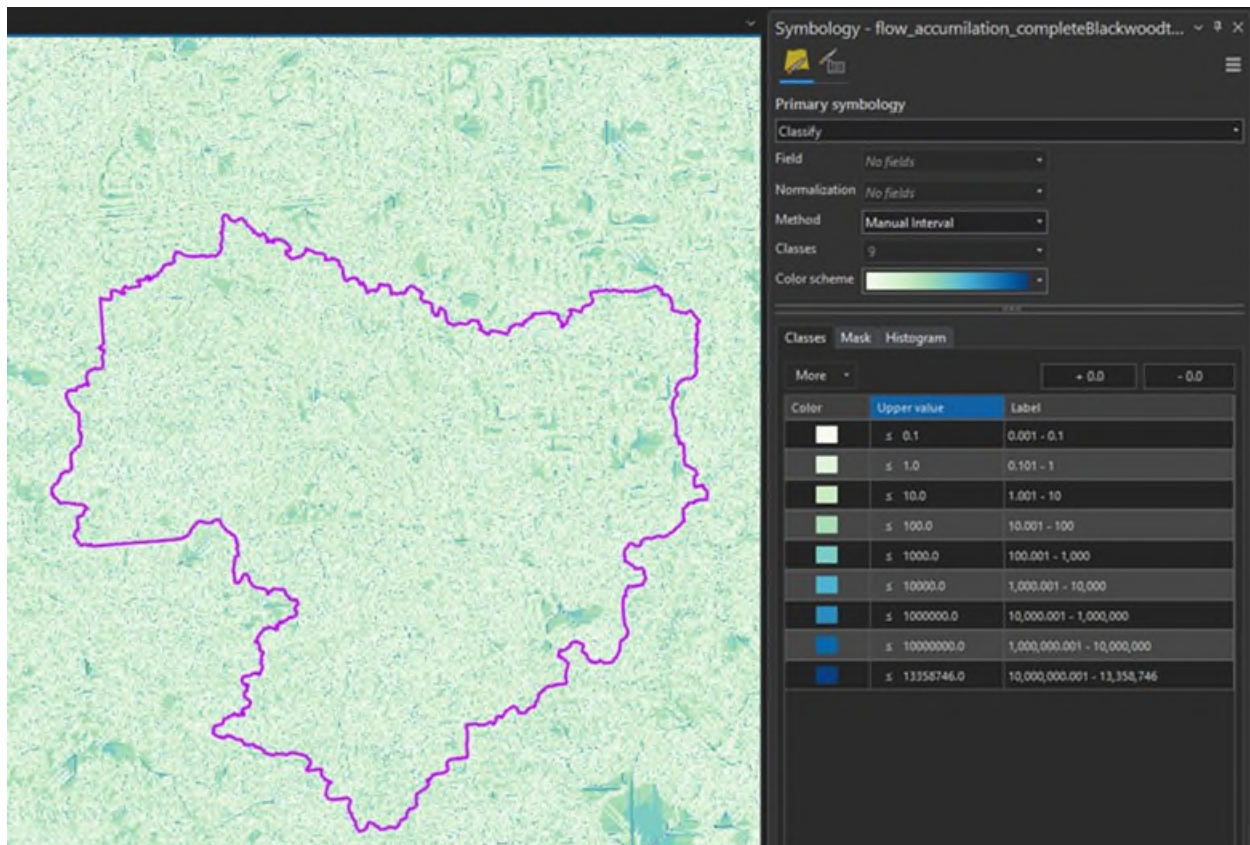
Classes Mask Histogram

More ▾

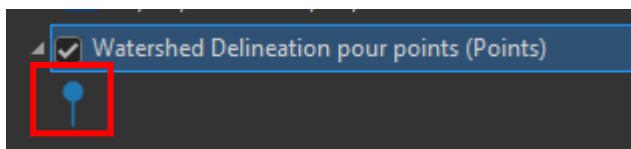
+ 0.0

- 0.0

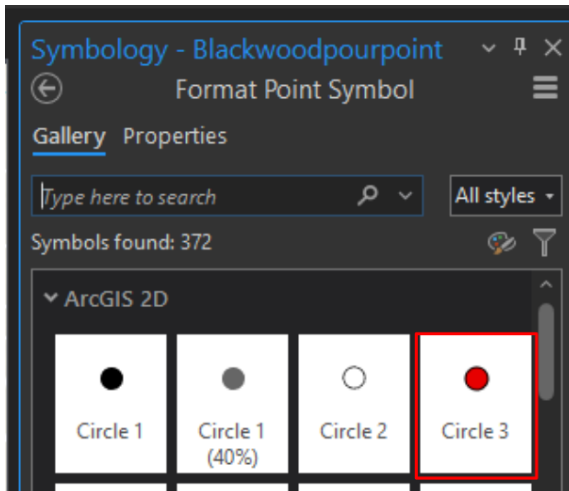
Color	Upper value	Label
	≤ 0.1	0.001 - 0.1
	≤ 1.0	0.101 - 1
	≤ 10.0	1.001 - 10
	≤ 100.0	10.001 - 100
	≤ 1000.0	100.001 - 1,000
	≤ 10000.0	1,000.001 - 10,000
	≤ 1000000.0	10,000.001 - 1,000,000
	≤ 10000000.0	1,000,000.001 - 10,000,000
	≤ 13358746.0	10,000,000.001 - 13,358,746



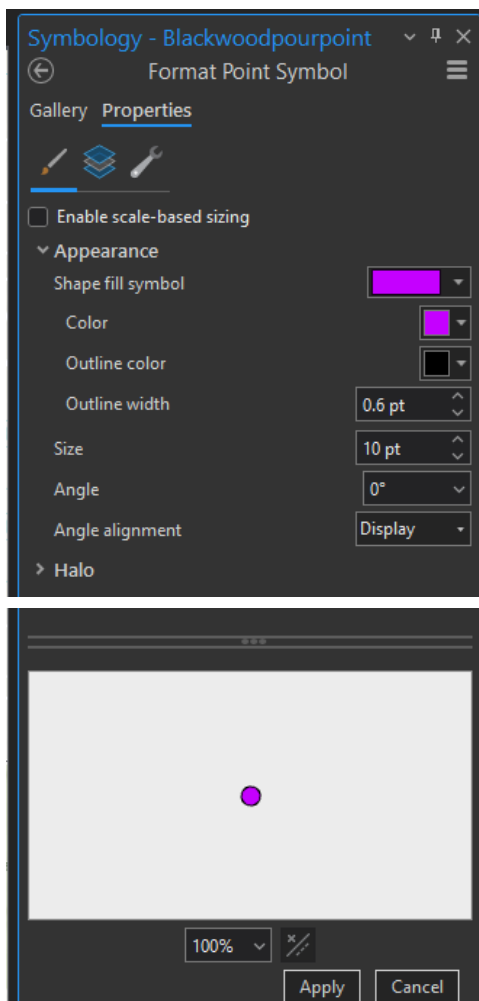
- Change the symbology of your pour point by double clicking on the point below the label title in the Contents pane



- In the 'Gallery' tab of the symbology menu, select 'Circle 3'



- In the 'Properties' tab of the symbology pane, change the color of the pour point to best reflect your watershed



- Make sure your layers are in the correct visibility order.

Contents

Search

Drawing Order

Map

☒ Watershed Delineation pour points (Points)

☒ Blackwoodstreams

☒ watershed_Blackwoodtributary_Delineation

☒ TributarytoBlackwoodDrain

☒ flow_accumulation_completeBlackwoodtributary_Delineation.tif

Value

0.001 - 0.1

0.101 - 1

1.001 - 10

10.001 - 100

100.001 - 1,000

1,000.001 - 10,000

10,000.001 - 1,000,000

1,000,000.001 - 10,000,000

10,000,000.001 - 13,358,746

☐ Blackwoodpourpoint

☐ Blackwoodbuffer

☐ DEM_enforced_Watershed.tif

Value

320.596

62

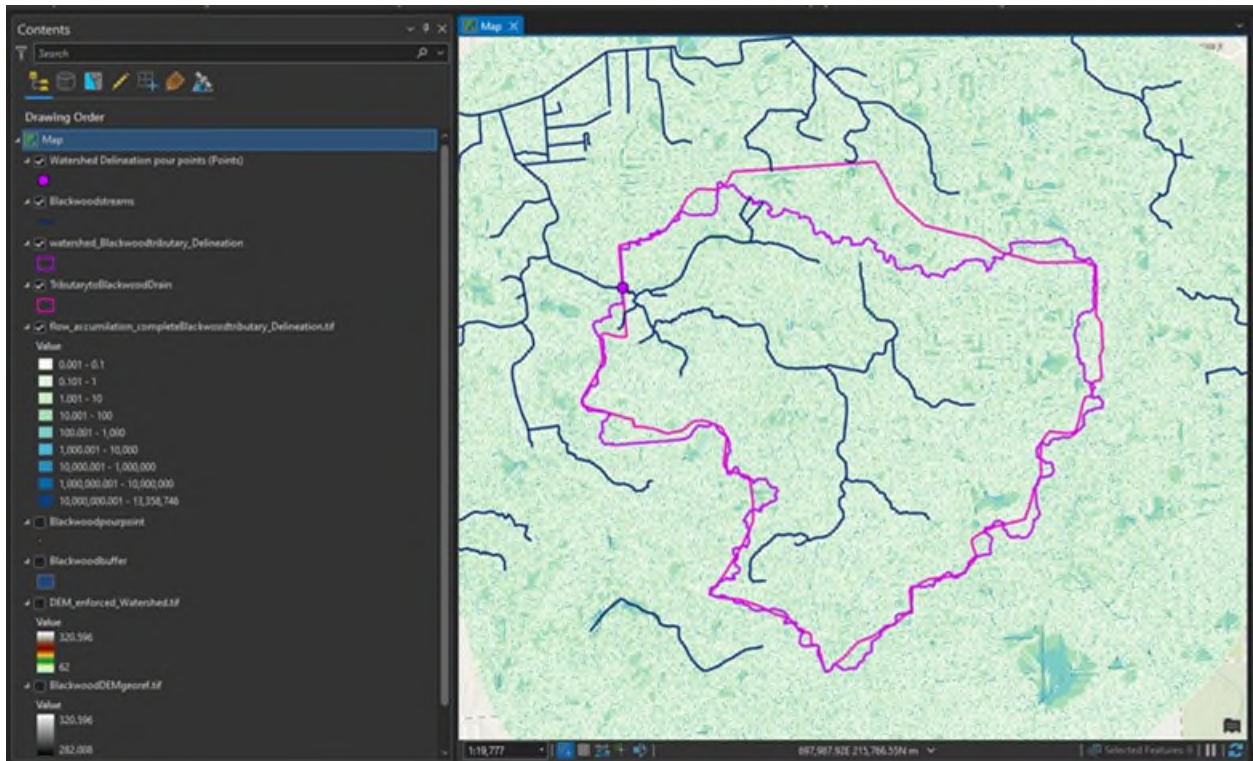
☐ BlackwoodDEMgeoref.tif

Value

320.596

282.008

- Congratulations! You've delineated your first hydro-enforced watershed!



References

This tool was originally developed by Mary Ellen Miller through Michigan Tech Research Institute to gather inputs for Curve Number hydrology models in ArcMap. It was then converted to be used in ArcPro by Mary Ellen Miller, Emily Teh, Dana Reduis, and Xanthe Thomas in July 2022. Mary Ellen Miller, Alexander Mueller, Nicholas Dobson, and Dana Redhuis at Michigan Tech Research Institute began building the version of the code seen in this tool in September 2022.

Wolock, D.M., 1993, Simulating the variable source area concept of streamflow generation with the watershed model TOPMODEL: U.S. Geological Survey Open File Report 93-4124, 33 p.

Running Tool on Multiple Areas at once

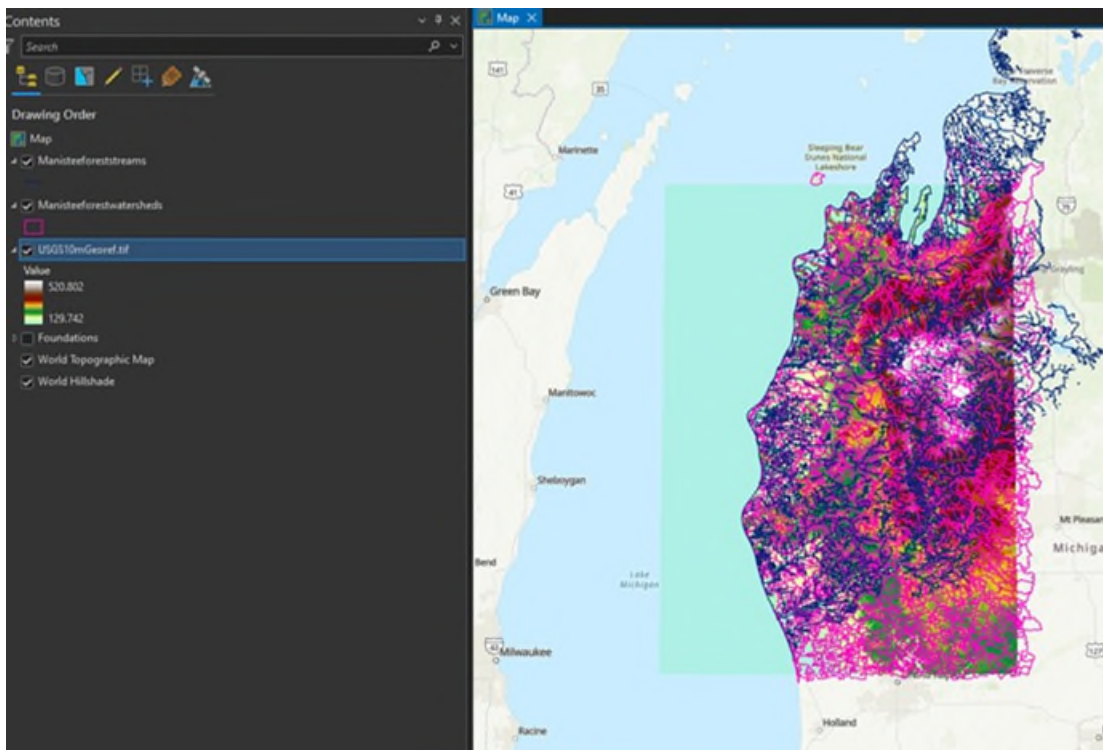
It is possible with this tool to hydro-enforce and delineate multiple watersheds at once. There are two ways to accomplish this task: (1) select multiple areas to hydro-enforce within your study area, or (2) batch processes, either by setting up processes in a queue or by scheduling processes. Option 1 ensures that **all outputs are in one DEM or feature class**, and option 2 creates **separate DEMs and feature classes**.

Selecting Multiple Areas to Run at Once

Hydro-enforcement

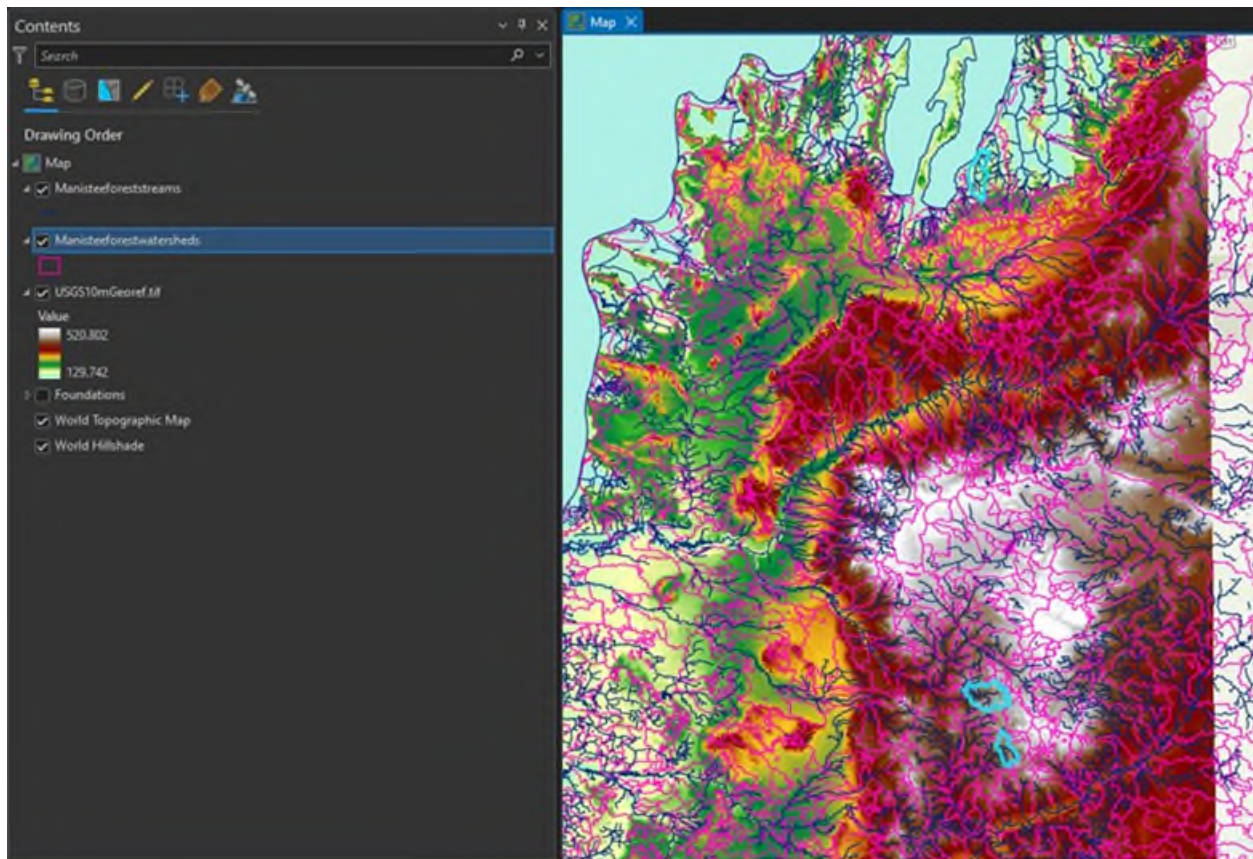
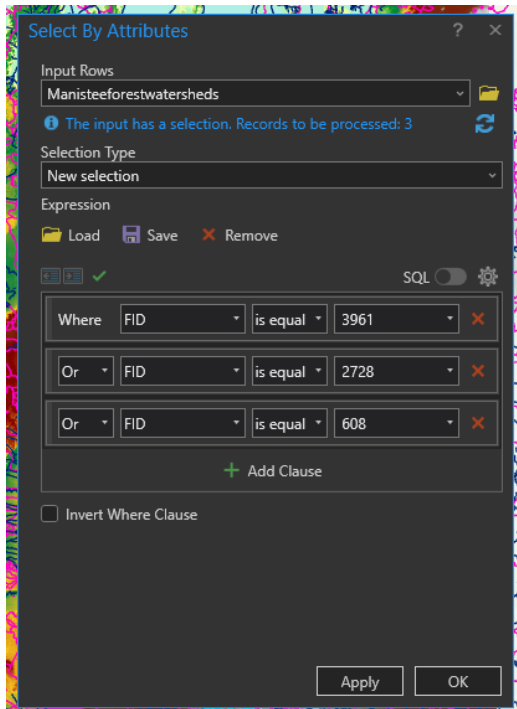
Step 1: Pull in Data

- Pull in your watershed layer, your DEM, and your streams layer, and symbolize appropriately.



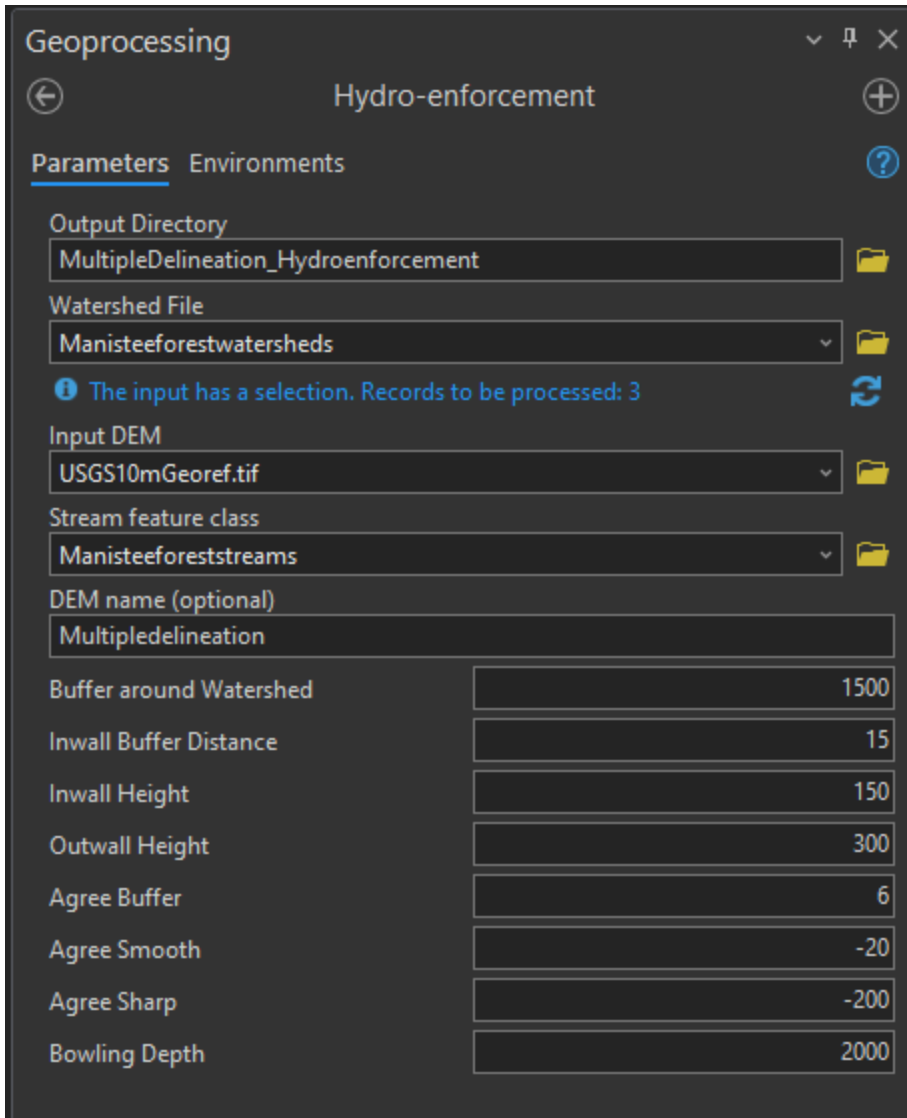
Step 2: Select Areas to Run

- Open Select by Attributes while having your watershed layer selected. Use Select by Attribute to select the watershed areas you'd like to hydro-enforce.



Step 3: Run Tool

- Go to the Hydro-enforcement tool and input your parameters. A warning will pop up under Watershed File, stating that “The input has a selection. Records to be Processed: #”. This is good, it means that the tool will only run on the watershed polygons that you selected.



Geoprocessing

Hydro-enforcement

Parameters Environments

Output Directory
MultipleDelineation_Hydroenforcement

Watershed File
Manisteeforestwatersheds

The input has a selection. Records to be processed: 3

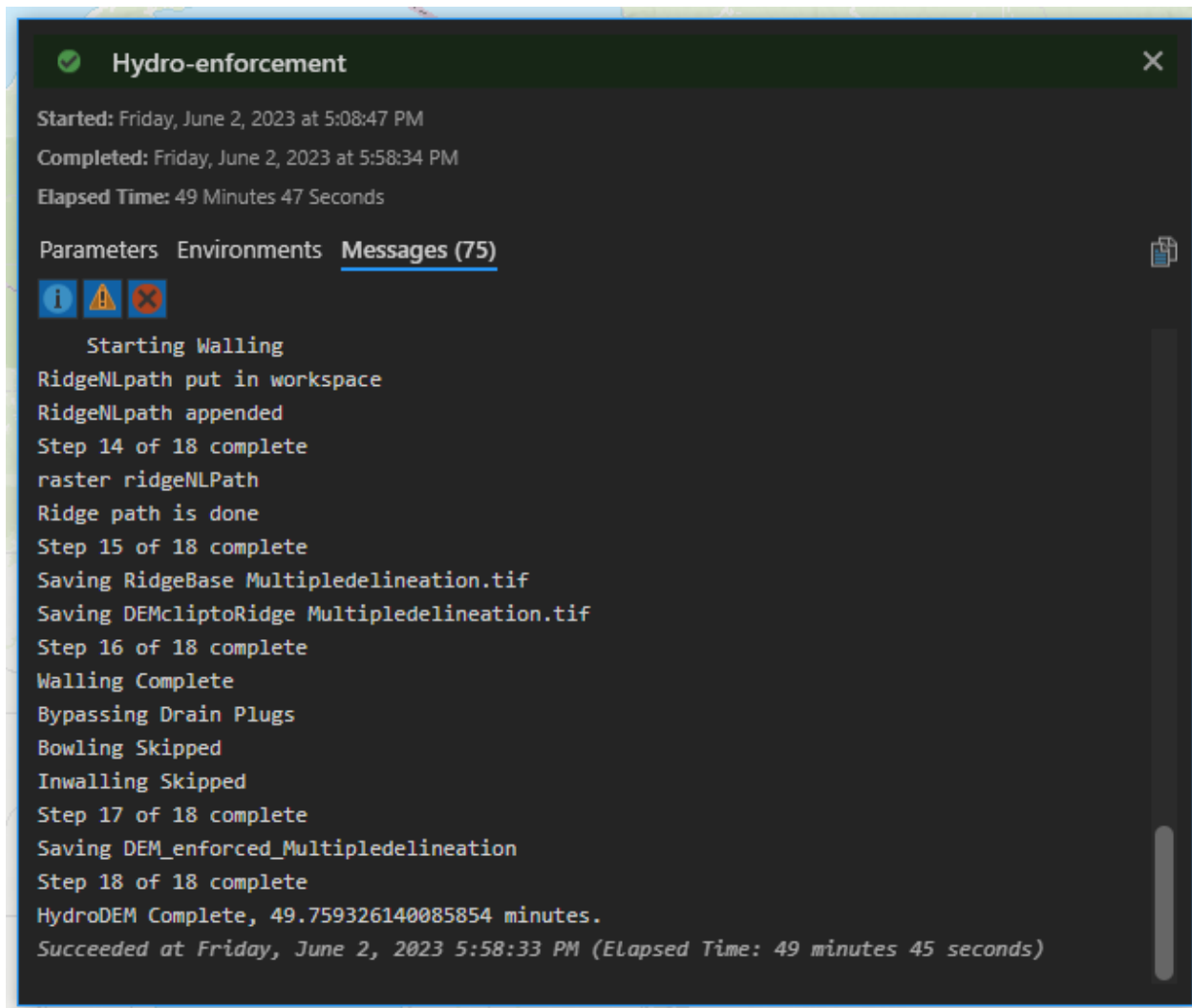
Input DEM
USGS10mGeoref.tif

Stream feature class
Manisteeforeststreams

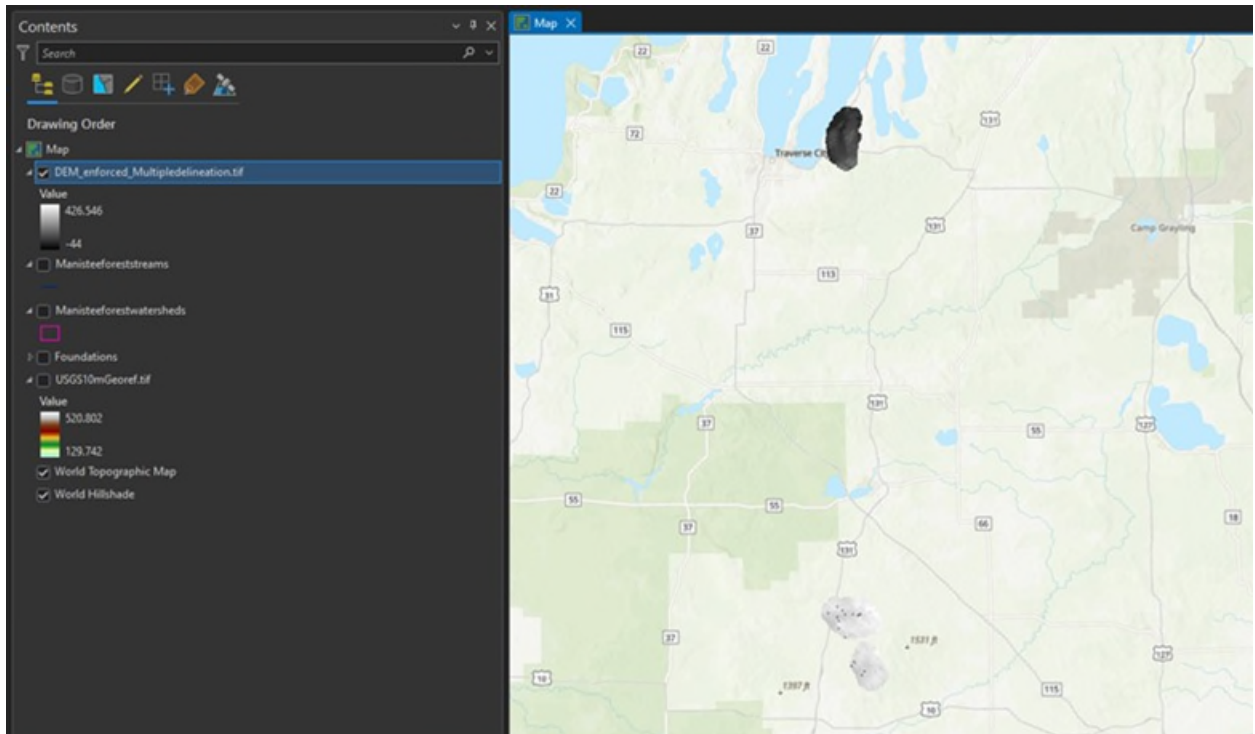
DEM name (optional)
Multipledelineation

Buffer around Watershed	1500
Inwall Buffer Distance	15
Inwall Height	150
Outwall Height	300
Agree Buffer	6
Agree Smooth	-20
Agree Sharp	-200
Bowling Depth	2000

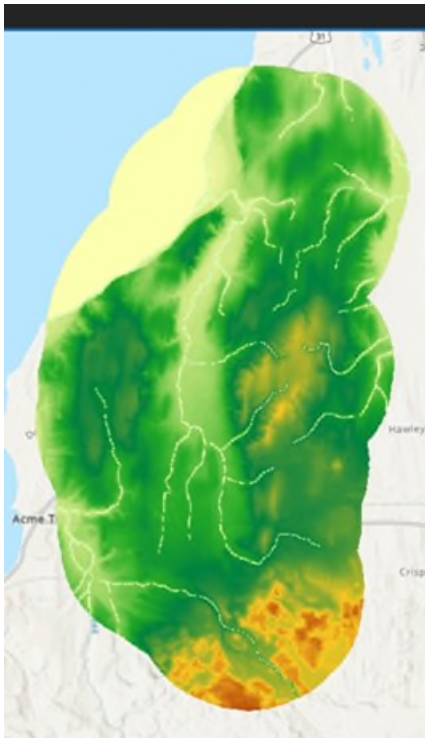
- Select ‘View Details’ as the tool is running if you’d like to see its progress. If the tool was successful, it should say ‘Succeeded at... (time)’.



- Your output should automatically appear in the map. For visibility's sake, turn off all other layers.



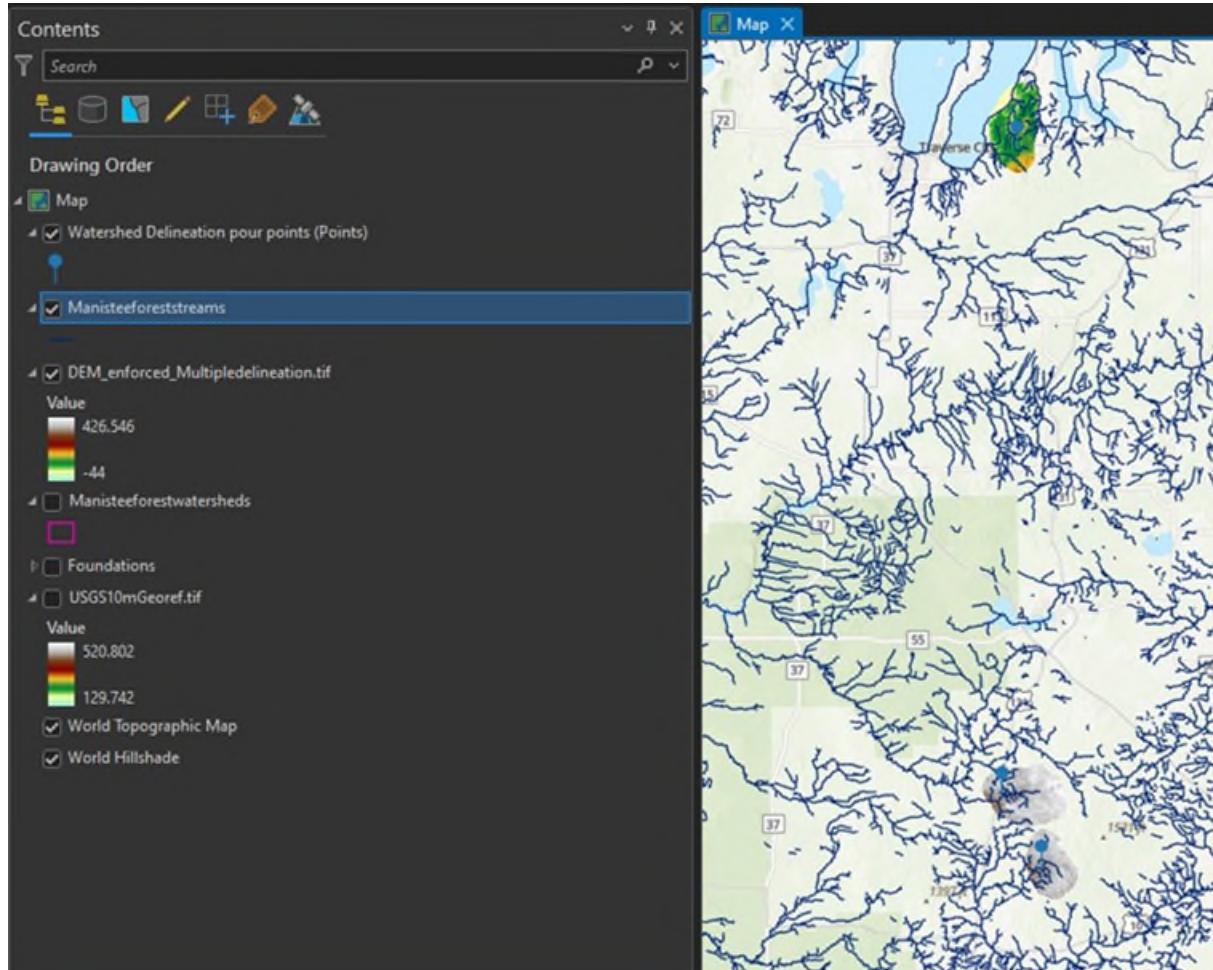
- Change symbology and check each DEM separately to ensure that the output is correct.



Watershed Delineation

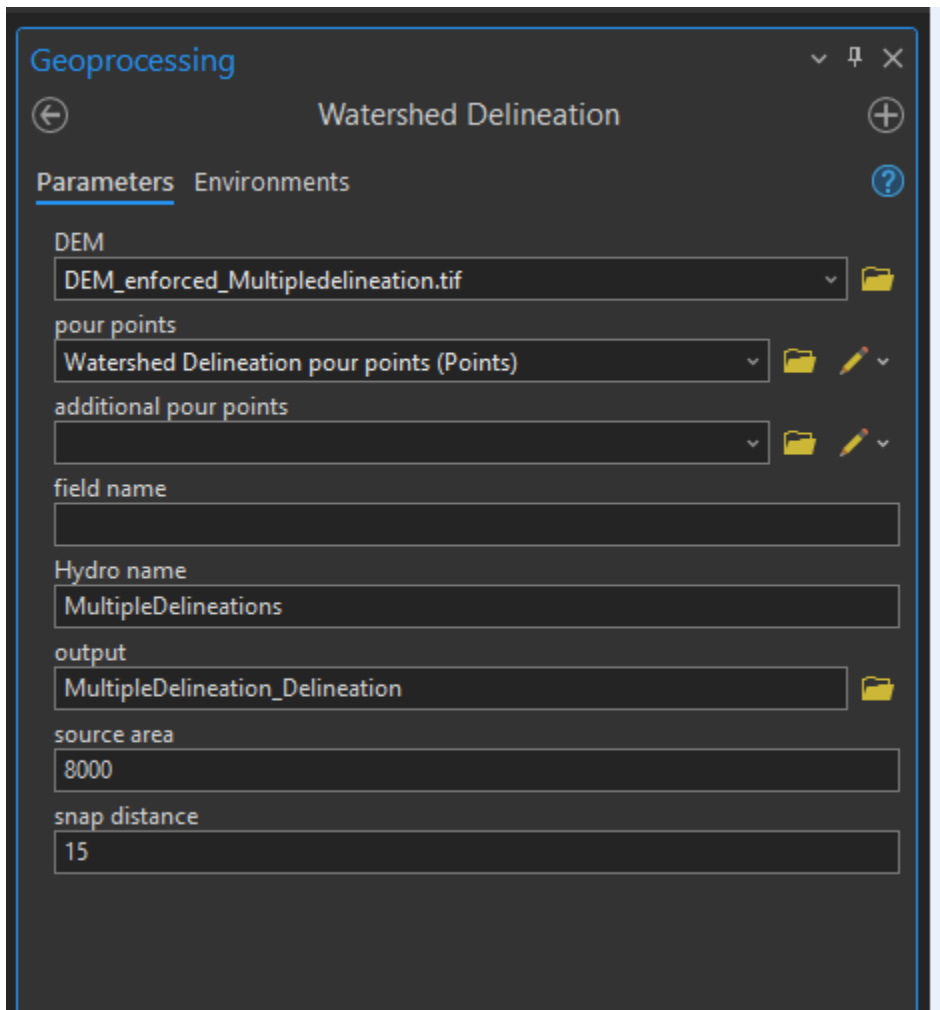
Step 1: Build Pour Points

- At this point all of your inputs should already be input in your project and symbolized appropriately. Open the Watershed Delineation Tool and begin selecting your pour points using the Streams Layer and the hydro-enforced DEM.

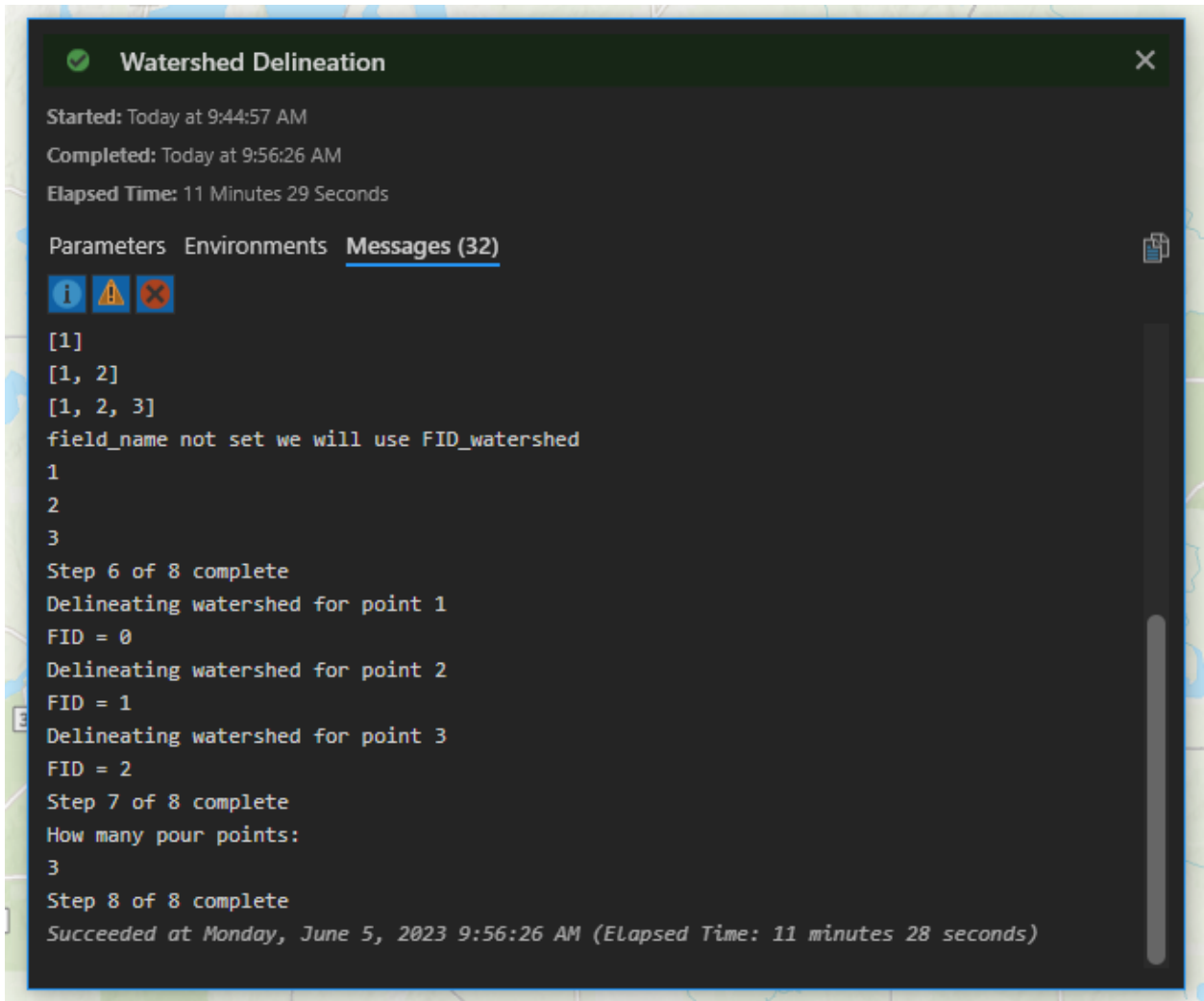


Step 2: Run Tool

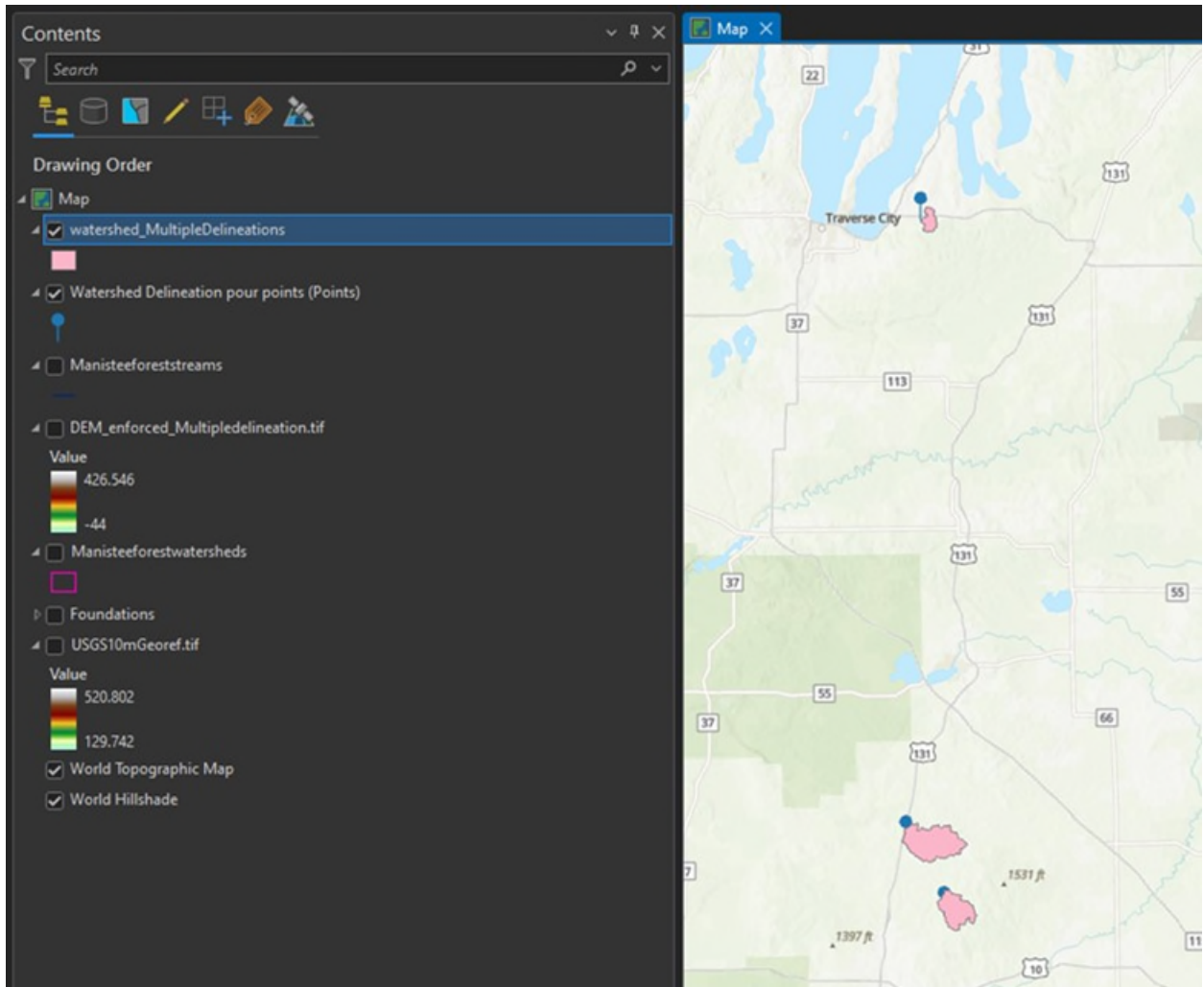
- Fill in all other inputs for the watershed delineation tool, and hit 'Run'.



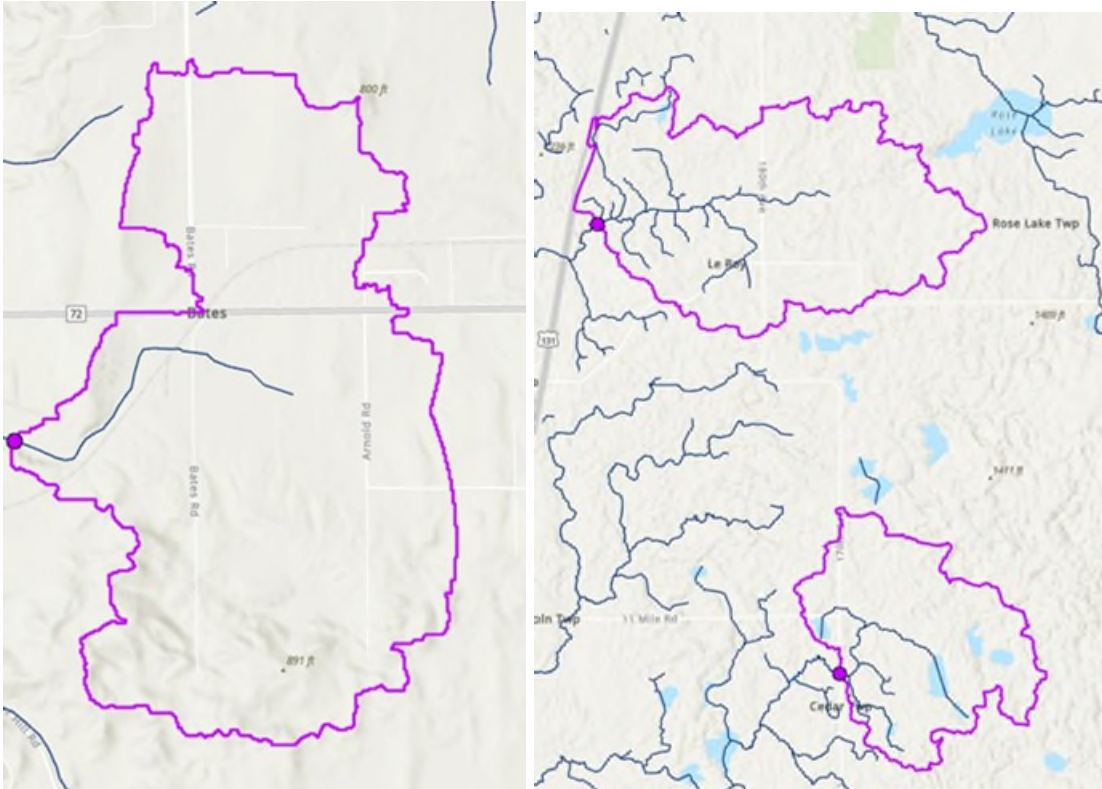
- Select 'View Details' as the tool is running if you'd like to see its progress. If the tool was successful, it should say 'Succeeded at... (time)'.



- Your output should automatically appear in the map. For visibility's sake, turn off all other layers.



- Change symbology and check each DEM separately to ensure that the output is correct.

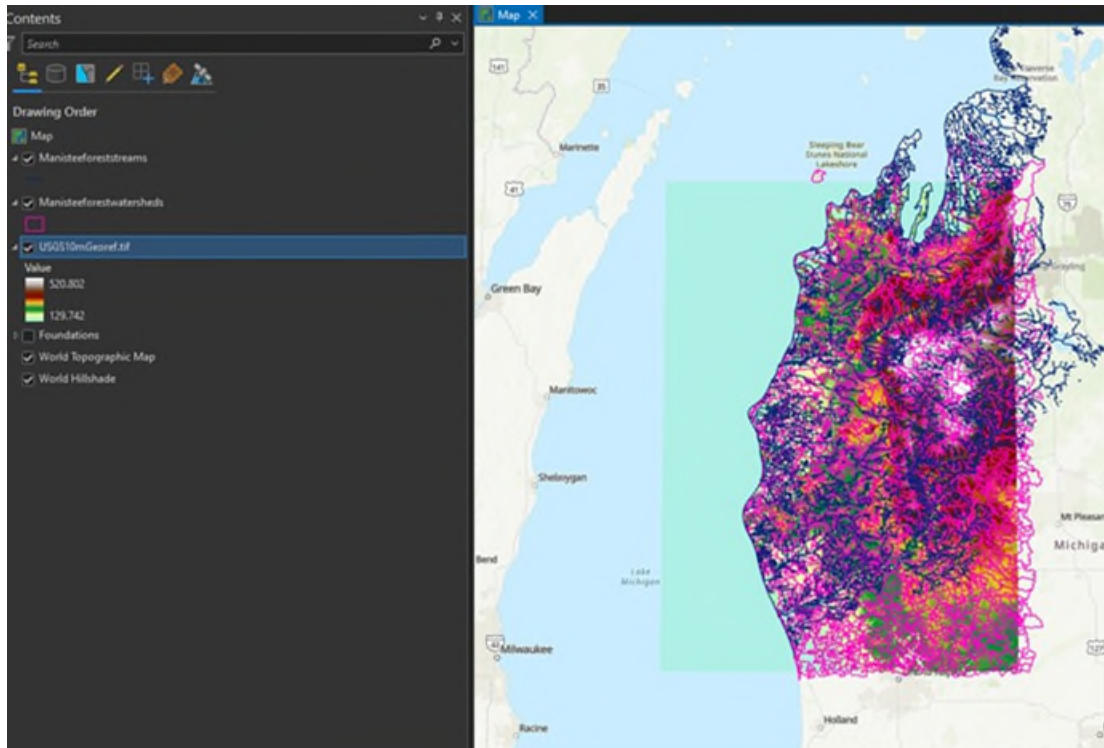


Batch Processing

Step 1

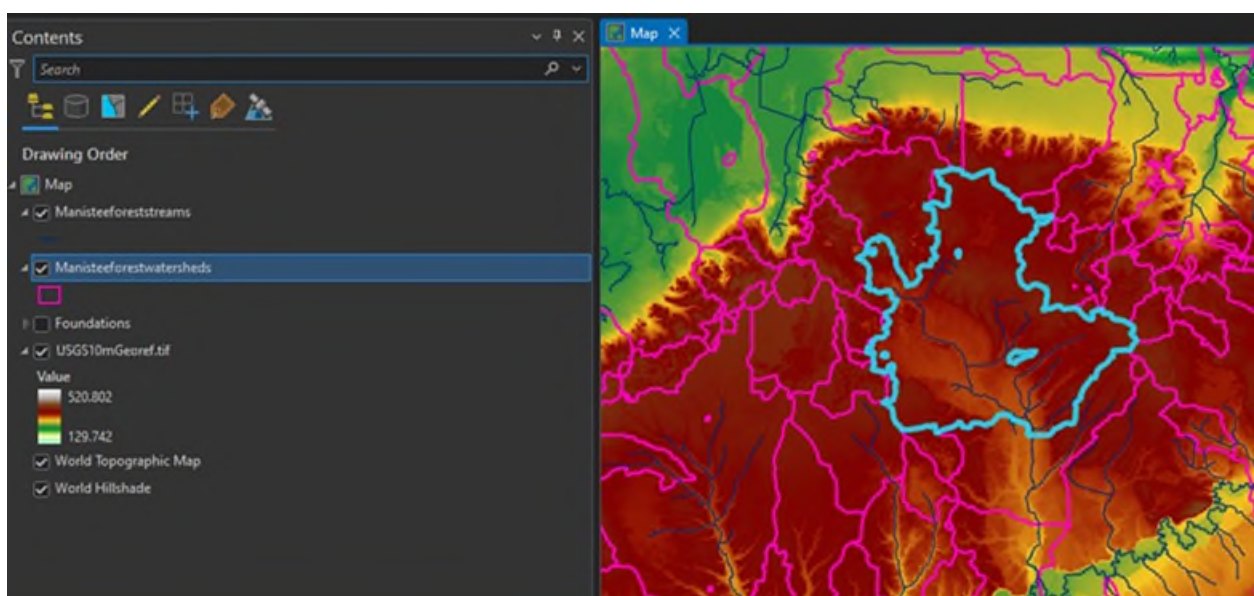
Step 1: Pull in Data

- Pull in your watershed layer, your DEM, and your streams layer, and symbolize appropriately.



Step 2: Select Areas to Run

- Use the Select tool to select the area from the EGLE Working layer that you'd like to hydro-enforce



- Fill out tool

Geoprocessing ⌵ ⌵ ✕

⬅ **Hydro-enforcement** ⊕

Parameters Environments ?

Output Directory
Batchtesthydroenforcement1 📁

Watershed File
Manisteeforestwatersheds ⌵ 📁

i The input has a selection. Records to be processed: 1 ↺

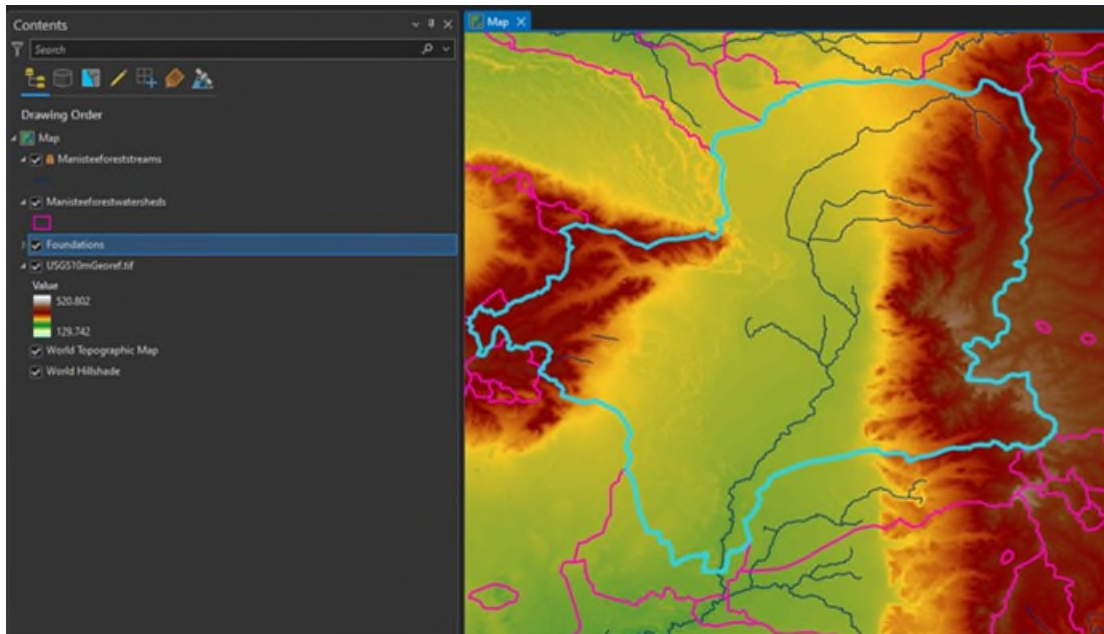
Input DEM
USGS10mGeoref.tif ⌵ 📁

Stream feature class
Manisteeforeststreams ⌵ 📁

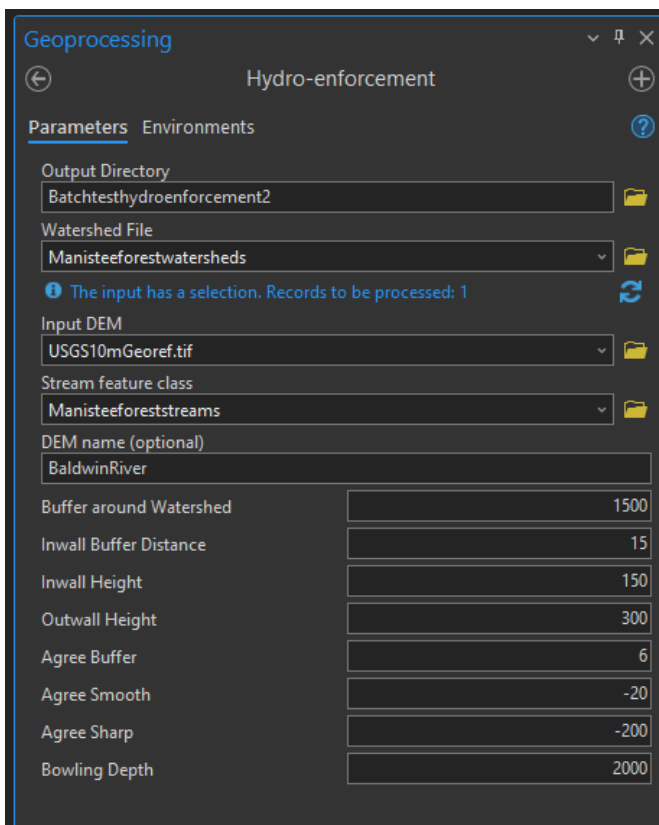
DEM name (optional)
AndersonCreek

Buffer around Watershed	1500
Inwall Buffer Distance	15
Inwall Height	150
Outwall Height	300
Agree Buffer	6
Agree Smooth	-20
Agree Sharp	-200
Bowling Depth	2000

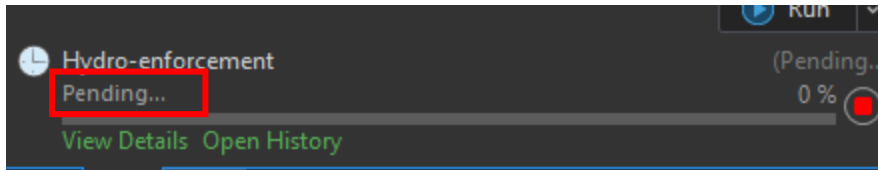
- Repeat. Clear your selection and select a new area to delineate.



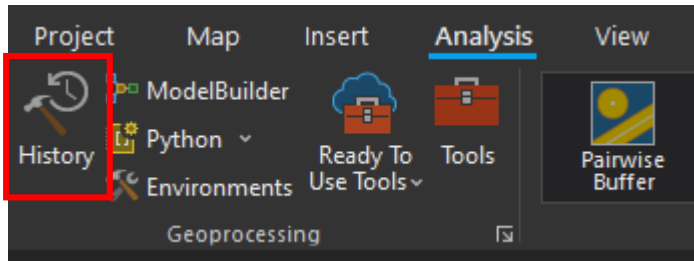
- Exit the hydro-enforcement tool and re-enter it. Fill your inputs with the new selection and hit 'Run'



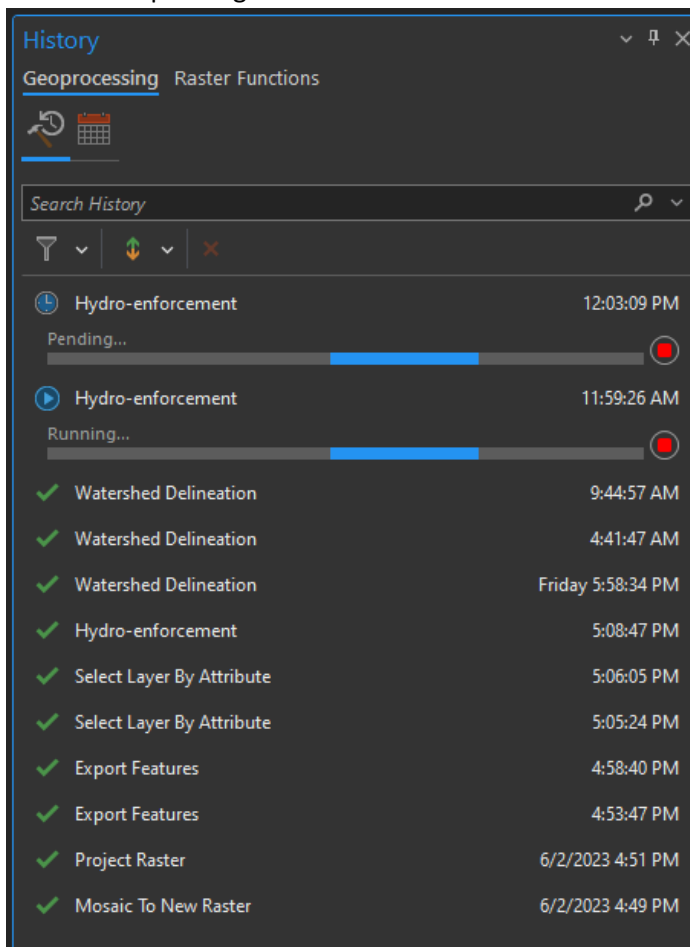
- When you select 'Run', you will get a message that the tool is pending.



- Open the 'Geoprocessing History' tab, located in the Geoprocessing group on the Analysis tab.



- Here you can see the geoprocessing tools you have run in the past, what is currently running, and what is pending to run next.



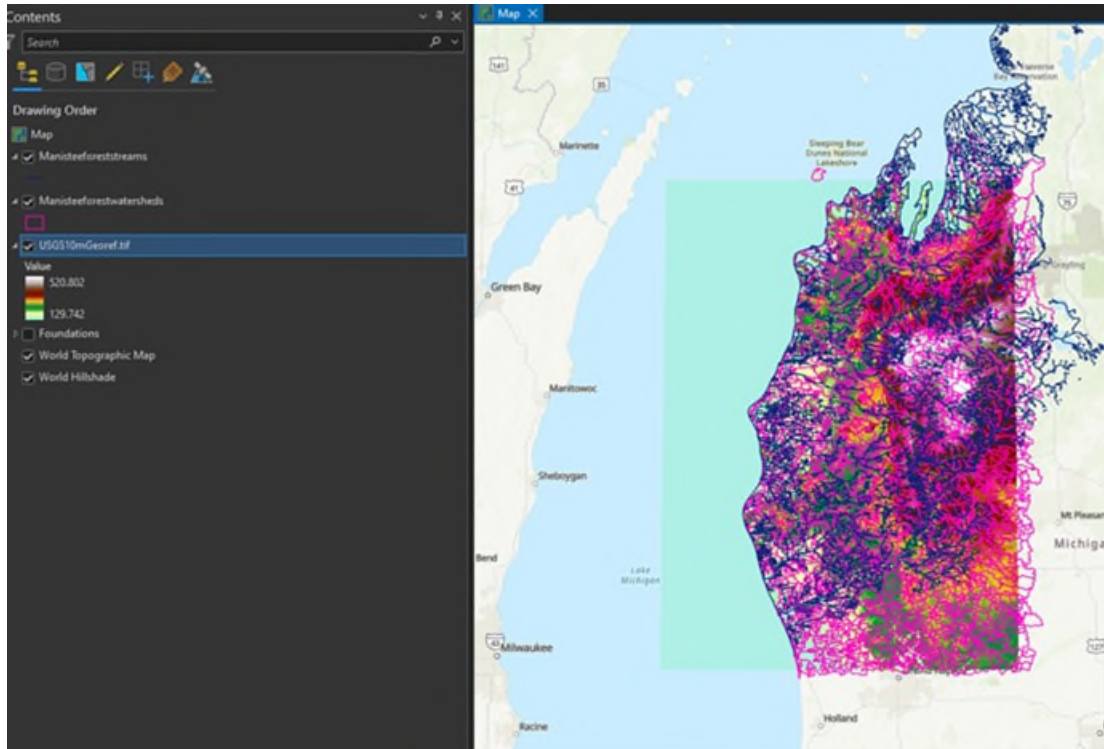
- There is technically not a limit to how many tools one can set in the queue but be careful as setting too many can cause the system to crash. MTRI has had success setting up to 10 processes in the queue at a time.
- This process can then be repeated for the watershed delineation tool.

Scheduling Processes

- One can also schedule geoprocessing to lessen the stress on the system.

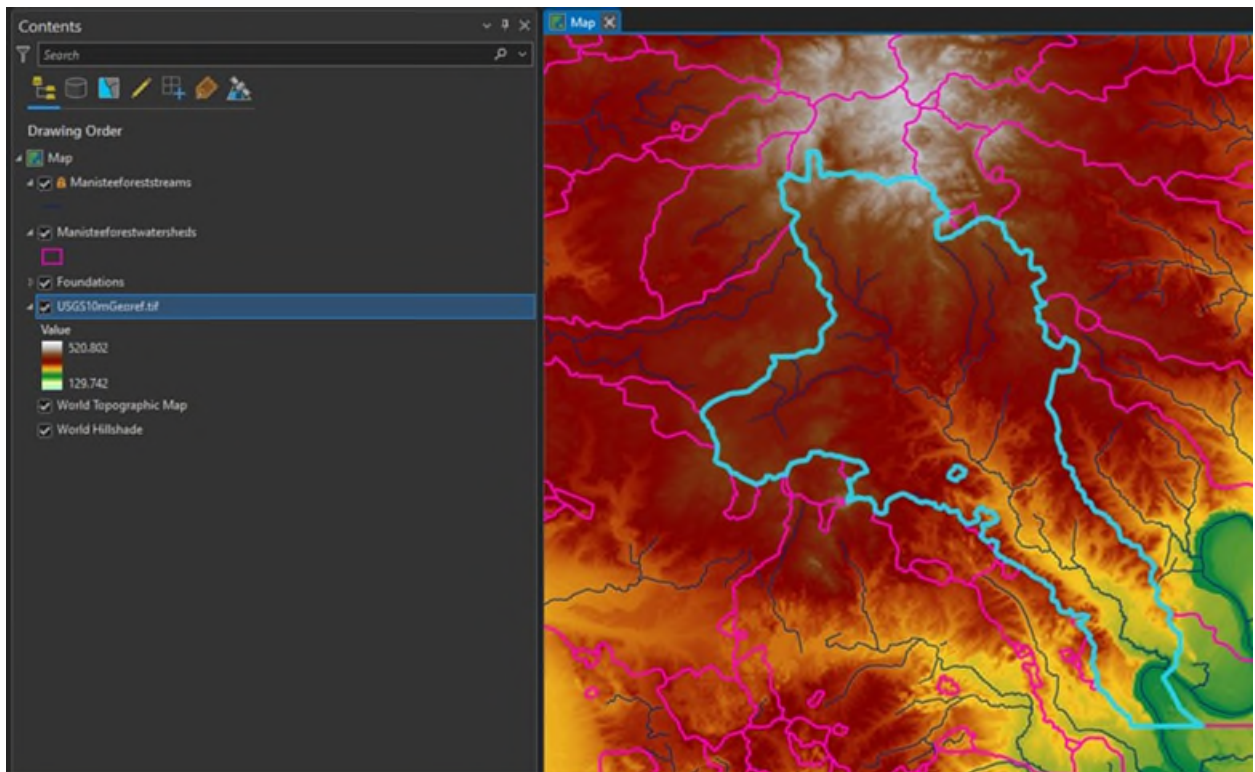
Step 1: Pull in Data

- Pull in your watershed layer, your DEM, and your streams layer, and symbolize appropriately.



Step 2: Select Areas to Run

- Use the Select tool to select the area from the EGLE Working layer that you'd like to hydro-enforce



Step 3: Run Tool

- Open tool and fill in inputs

Geoprocessing

Hydro-enforcement

Parameters Environments

Output Directory
Scheduletesthydroenforcement1

Watershed File
Manisteeforestwatersheds

The input has a selection. Records to be processed: 1

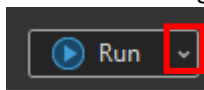
Input DEM
USGS10mGeoref.tif

Stream feature class
Manisteeforeststreams

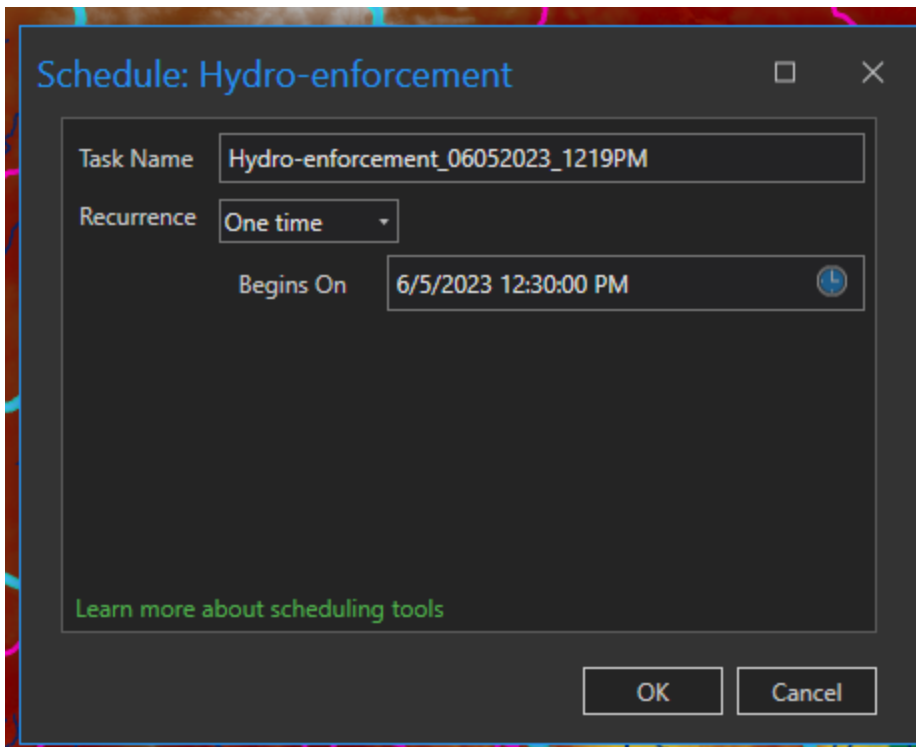
DEM name (optional)
MuskegonRiver

Buffer around Watershed	1500
Inwall Buffer Distance	15
Inwall Height	150
Outwall Height	300
Agree Buffer	6
Agree Smooth	-20
Agree Sharp	-200
Bowling Depth	2000

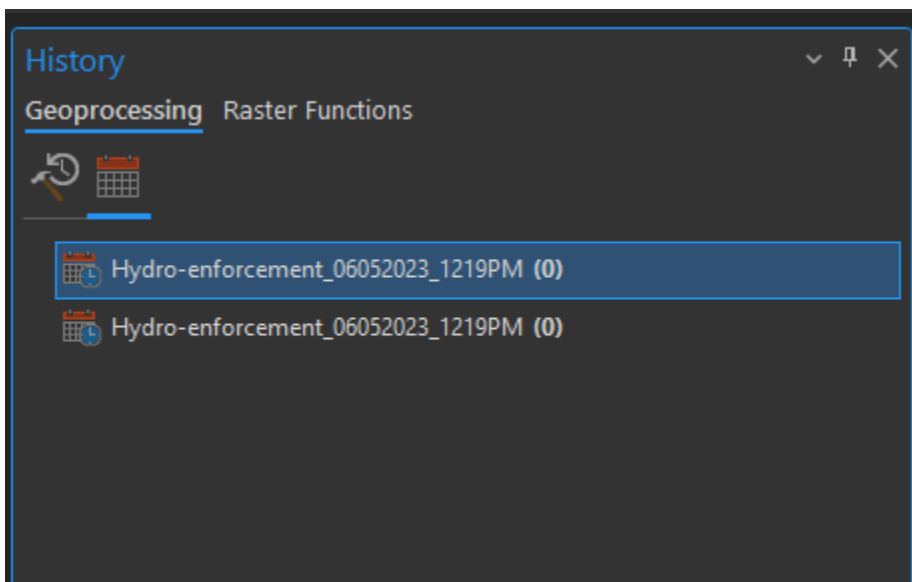
- Instead of hitting 'Run', select the dropdown arrow next to the word 'Run'



- Select the time that you'd like this tool to begin running.



- Enter the History tab and select the Calendar Icon. Here you can see what process you have scheduled and when it's meant to begin.
- This process can then be repeated for the watershed delineation tool.



- This may be useful if one is planning on, for example, running several processes over the weekend – the processes can be scheduled several hours apart to provide the software time to process without crashing.

MTU_Hydro_Tool_1.0.5

RCN Tool step by step

May 15 2025

General Overview of the RCN Tool

This tool follows the workflow created by S. Greiner and EGLE to conduct SCS/NRCS runoff analyses. The parameters are related to land use, land treatment, hydrological condition, hydrological soil group, and antecedent soil moisture condition in the drainage basin. The first iteration of this tool included two versions: the LWM_RCNTool0.0.1_NLCDMTRI, and the LWM_RCNTool 0.0.1_MIRIS. There were also separate 2.9.5 and 3.0+ versions of the tool. We have combined these versions, so any user should be able to download just one tool.

RCN Tool Inputs

- **Directory:** Folder where all required files are saved. Only required if 'County Specific Soils Table' is not filled out
- **Output Folder:** Folder where output files will be saved.
- **County:** Shapefile that holds county information – used to direct tool to appropriate County Specific Soils Table.
 - **When using soil layers from SSURGO:** This is a specific shapefile input titled "RCNTool_countylayer.shp". This layer is formatted specifically to match the county code organization utilized by SSURGO. In this county code organization, most counties will match the traditional state of Michigan county code pattern. But the following areas stray away from this pattern:
 - Lake/Wexford: merged and are county code "600"
 - Manistee/Benzie: merged and are county code "614"
 - Keewenaw county and Isle Royale National Park: Are counted separately with county codes "605" and "606"
- **Soils Layer:** Soils shapefile, traditionally the 'MUPolygon' from the Soil Survey Geographic Database (SSURGO). Newly downloaded layers from NRCS can also be used.
- **Landuse Layer:** Land use/Land cover layer. Can be a raster or a vector file. Can use any shapefile that matches up with RCN table and Landuse Table. Traditionally used MIRIS, can use NLCD_MTRI Reclassed Layer or NLCD 2021 as well.
- **Watershed Layer:** Shapefile that will clip other layers to the study area, typically a shapefile of a watershed created with the Watershed Delineation tool.
- **RCN Table:** Reference table built for the specific land cover/landuse spatial layer – sum of 'Class' + 'Value' is joined to this table after the intersection between the Soils and the Landuse spatial layers are conducted.

- **RCN Field:** Column in the RCN field that you would like to use to calculate the RCN. Defaults to last column in table. Can be used for any RCN table, but created specifically for NLCDMTRI RCN workflow
- **Landuse Table:** Reference table for landuse spatial layer – matches landcover description to ‘Class’ column.
- **County Specific Soils Table (filled by directory input):** Reference table to specific soil names in different counties. *‘Directory’ is the input that will allow for this parameter to be filled. Please do not use this variable. This variable still holds functionality in tool “RCN Tool_MUPolygonworkflow - 1.0.0”*
- **General Soils Table:** Reference table matching soil class to ‘Value’

RCN Tool Outputs

- [numberedwatersheds].shp: each watershed run creates intermediate watershed shapefiles. Ignore these.
- **[number]_data folder:** holds all intermediate files for each watershed output. This folder is useful if you run into an error, but is a way to allow for easy deletion of intermediate files. Each shapefile will contain the number associated with its watershed. This folder contains:
 - **Clipped_land.shp:** Shapefile of clipped land use/cover layer, if your input was a raster layer this will be the result of converting the raster layer to a vector layer
 - **Clipped_soil.shp:** Shapefile of clipped soil spatial layer
 - **countysoilMUSYM.shp:** Soils spatial layer with county specific soils table joined
 - **general_county_soils.shp:** Soils spatial layer with county specific soils table and general soils table joined
 - **landuse_intersect.shp:** First intersected layer, landuselayer.shp intersected with general_county_soils.shp
 - **landusetable_save.shp:** landuse_intersect.shp exported into a separate file to preserve joins
 - **landuseinterSUM.shp:** landusetable_save with column created to calculate ‘Class’ + ‘Value’
 - **landuselayer.shp:** Land use / cover spatial layer with landuse table joined.
 - **csv.interfields.csv:** Allows for a join between the county code and the soil ID to ensure that multi-county watersheds are being attributed soil ID definitions from the appropriate county specific soil layer
 - **general_county_soils.shp:** Soil spatial layer, county specific soil tables, and general soil table join
 - **intersect.shp:** intersect between csv.intervields.csv and general_county_soils, allows for county-specific soil attribution
 - **landuse_intersect.shp:** preliminary intersect of landuse and soil layers
 - **landuse_table_save.shp:** Join between LULC spatial layer and LULC table
 - **musym_intersect.shp:**
- **Zippped_files:** Also included for easier error detection, and can be deleted. Copy of the soil spatial layer and tables
- **RCN_completed.shp:** Final product – shapefile with RCN values
- **Statistics.dbf:** Final product – contains overall RCN value for area

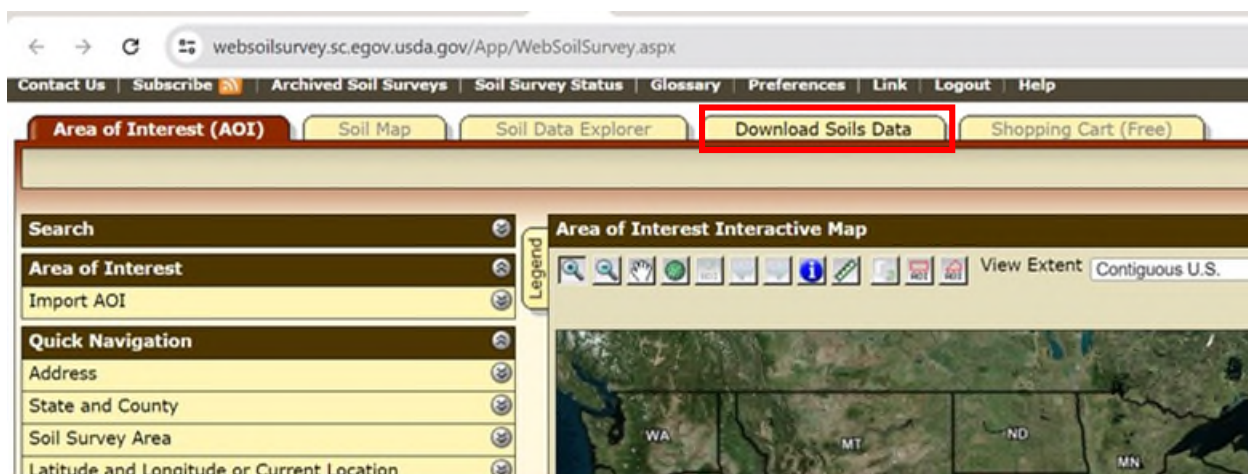
Step By Step Tutorial

Step 1: Build your Directory

- To build your RCN without filling in the County Specific Soils layer, make sure that you have all of your County Specific Soils layer files in one folder. We have updated the tool to allow these inputs to be pulled directly from the zipped file that one can download from the SSURGO website. The County Specific Soil Tables created by EGLE can also be utilized when running off of EGLE's MUPOLYGON dataset.
- All inputs should be held within your Directory folder. This includes **County**, your **Soils Layer** (either downloaded from the SSURGO website or the EGLE MUPOLYGON dataset), your **Landuse layer** (likely created through the Raster to Polygon Watershed Clipper, found on page 84), your **Watershed layer**, and your RCN, Landuse, and Soils tables.
- *If you'd like to set the layers you are planning on using as a default into the tool using ArcPro's default setting workflow, go to **Step 4**.*

Step 2: Download Updated Soils Layer dataset from SSURGO website

- Go to the SSURGO website and select 'Download Soils Data':
<https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx>



- Select the county/counties where your watershed resides and download the .zip file into the directory that you've created

Download Soils Data for...

Your AOI (SSURGO)

Soil Survey Area (SSURGO)

General Information

Link [Description of Soil Survey Geographic \(SSURGO\) Database](#)

Download Contents Tabular data, spatial data (if available), template database (if selected), and FGDC metadata

Spatial Data Format ESRI Shapefile, Geographic WGS84

Options

State:

County (optional):

Only show Soil Survey Areas updated since...

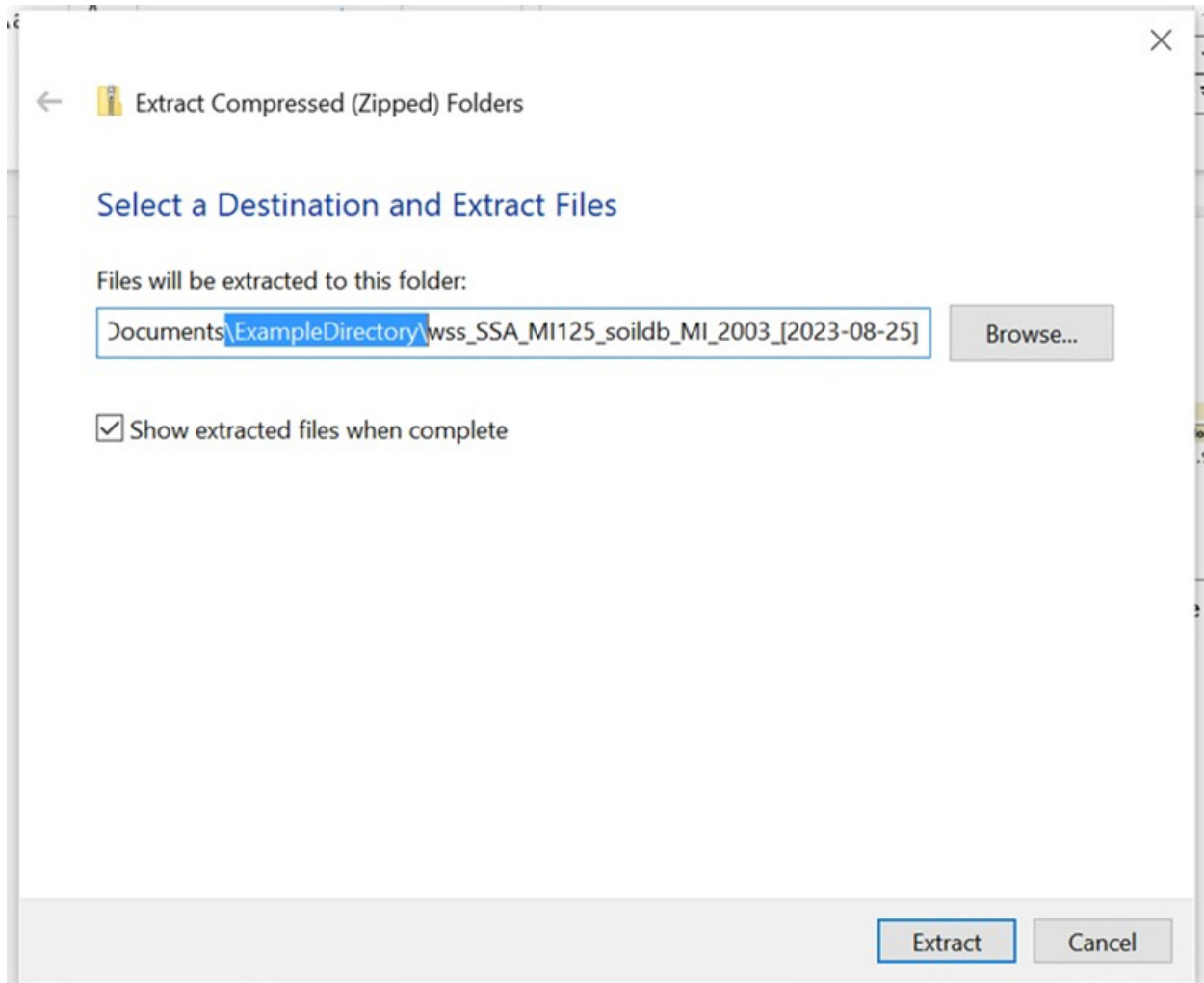
Sort by...

Include Template Database ☒

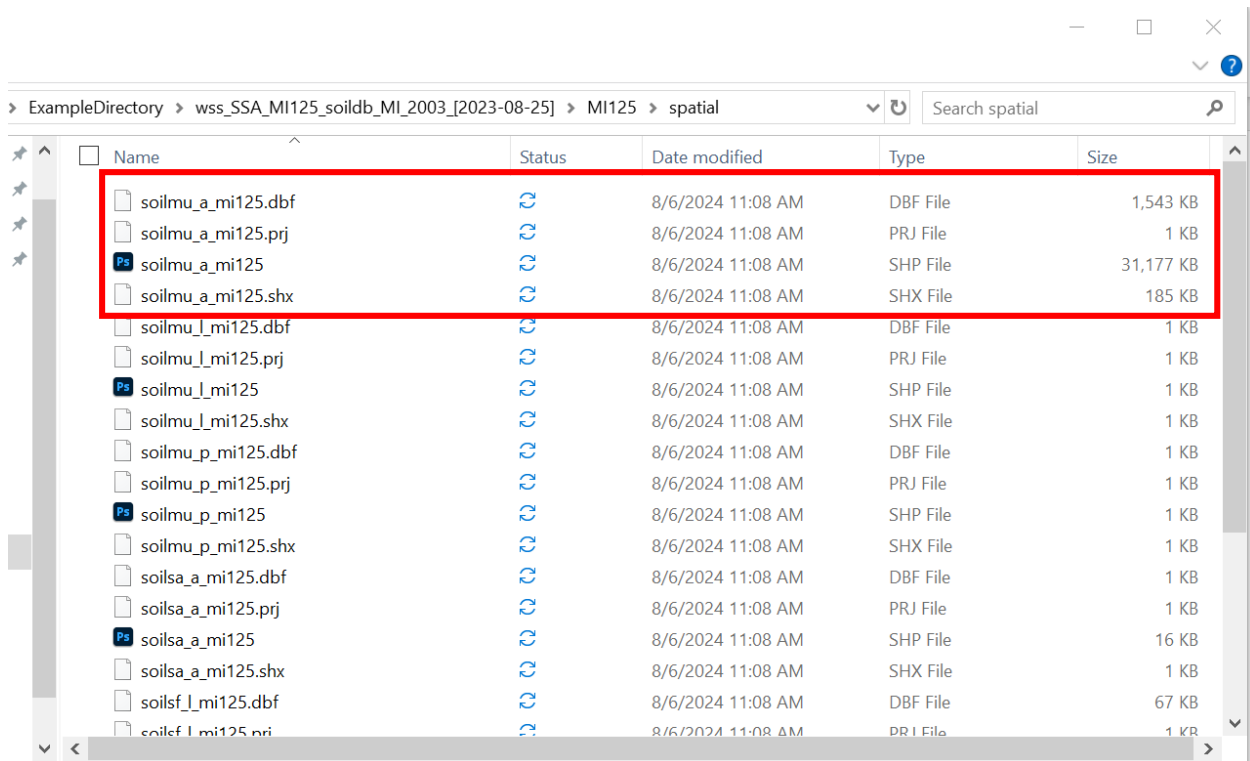
Soil Survey Area (SSURGO) Download Links

Name	Area Symbol	Data Availability	Version	Template Database	Download Size	Download Link
Oakland County, Michigan	MI125	Tabular and Spatial, complete	Survey Area: Version 22, Aug 25, 2023 Tabular: Version 22, Aug 25, 2023 Spatial: Version 14, Aug 29, 2022	soildb_MI_2003 Access 2003 Version 36	35.9 MB	wss_SSA_MI125_soildb_MI_2003_[2023-08-25].zip

- ***Make that you have a zipped and an extracted version of this file in the same directory.***



- When the folder is extracted, there will be multiple files available for you to use. In order to find the soils shapefile that can be plugged into the tool, select:
 - **wss_SSA_MI(countynumber)_soildb_MI_2003_[date] -> MI(countynumber) -> spatial**
- This will bring you to a folder containing polygon, line, and point shapefile data. Make sure to select the shapefile labeled **soilmu_a_mi(countynumber).shp** to use as the soils spatial layer for this tool.

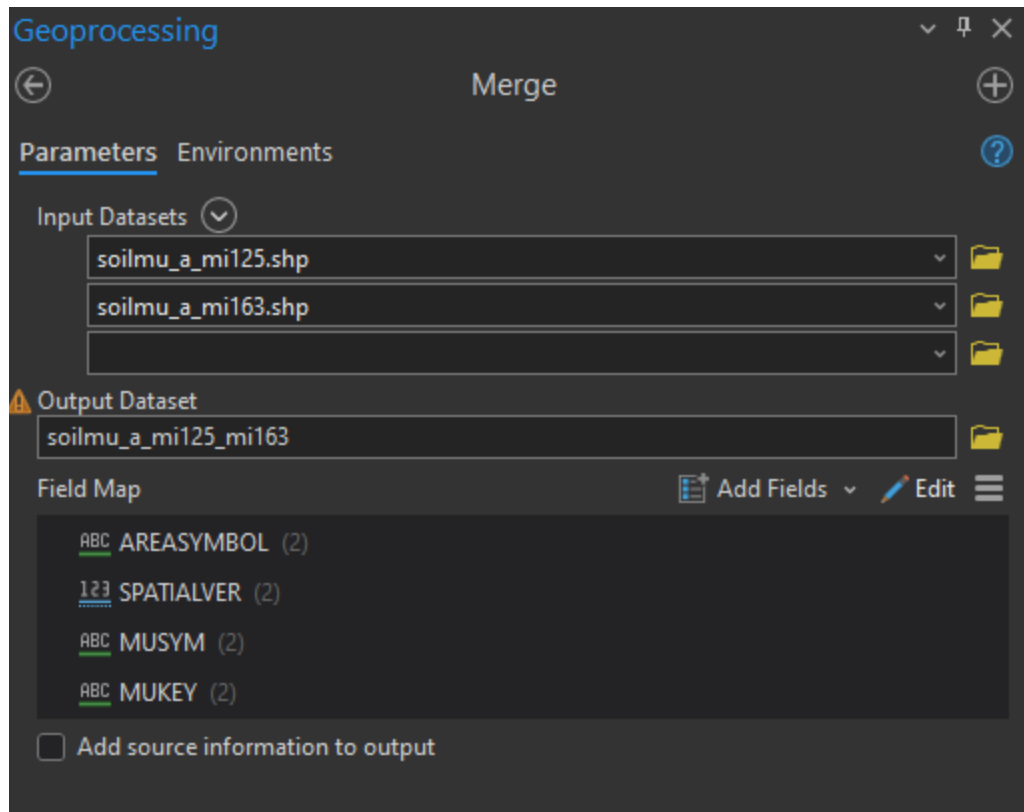


Name	Status	Date modified	Type	Size
soilmu_a_mi125.dbf		8/6/2024 11:08 AM	DBF File	1,543 KB
soilmu_a_mi125.prj		8/6/2024 11:08 AM	PRJ File	1 KB
soilmu_a_mi125.shp		8/6/2024 11:08 AM	SHP File	31,177 KB
soilmu_a_mi125.shx		8/6/2024 11:08 AM	SHX File	185 KB
soilmu_l_mi125.dbf		8/6/2024 11:08 AM	DBF File	1 KB
soilmu_l_mi125.prj		8/6/2024 11:08 AM	PRJ File	1 KB
soilmu_l_mi125.shp		8/6/2024 11:08 AM	SHP File	1 KB
soilmu_l_mi125.shx		8/6/2024 11:08 AM	SHX File	1 KB
soilmu_p_mi125.dbf		8/6/2024 11:08 AM	DBF File	1 KB
soilmu_p_mi125.prj		8/6/2024 11:08 AM	PRJ File	1 KB
soilmu_p_mi125.shp		8/6/2024 11:08 AM	SHP File	1 KB
soilmu_p_mi125.shx		8/6/2024 11:08 AM	SHX File	1 KB
soilsa_a_mi125.dbf		8/6/2024 11:08 AM	DBF File	1 KB
soilsa_a_mi125.prj		8/6/2024 11:08 AM	PRJ File	1 KB
soilsa_a_mi125.shp		8/6/2024 11:08 AM	SHP File	16 KB
soilsa_a_mi125.shx		8/6/2024 11:08 AM	SHX File	1 KB
soilsf_l_mi125.dbf		8/6/2024 11:08 AM	DBF File	67 KB
soilsf_l_mi125.prj		8/6/2024 11:08 AM	PRJ File	1 KB

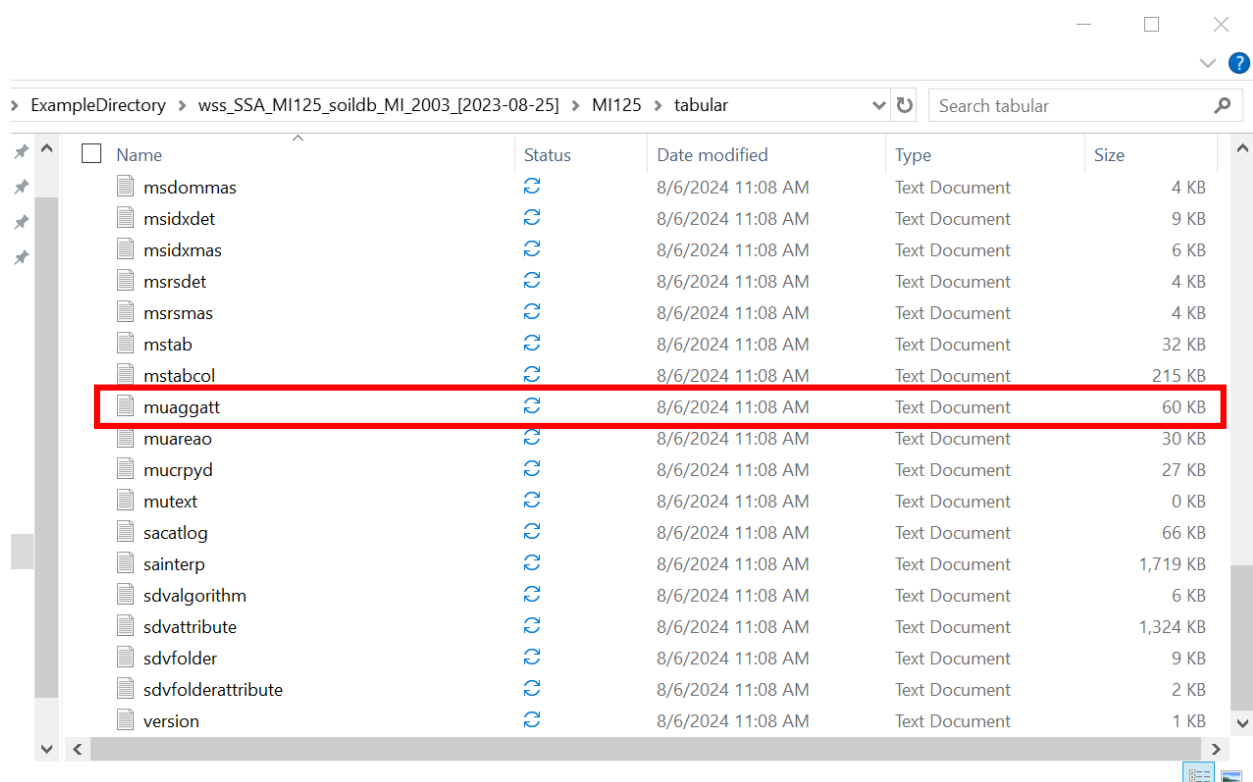
- Our tool then automatically reads the updated county specific soil table that is contained within the zip file for each county soil layer. *You do not need to pull it out for use, simply leave the ‘County Specific Soils Table’ value blank within the tool as described in Step 3.*
- If you would like to view the updated county specific soil table, it can be found under:
 - `wss_SSA_MI(countynumber)_soildb_MI_2003_[date] -> MI(countynumber) -> tabular -> muaggatt.txt`
 - *muaggatt stands for ‘Mapunit Aggregated Attribute’. Page 70 of the document linked below provides metadata for this table:*
<https://www.nrcs.usda.gov/sites/default/files/2022-08/SSURGO-Metadata-Tables-and-Columns-Report.pdf>

If your watershed is in multiple counties:

- You will need to download both county soil datasets, and save them both within the same example directory. You will need to merge the two spatial datasets in order to input them into the tool. For example, if you are running a watershed in Oakland and Wayne county, you can input your soil spatial layers into the Merge geoprocessing tool to create one dataset. **Input the CountyID of each county** into the name of your merged soil dataset.



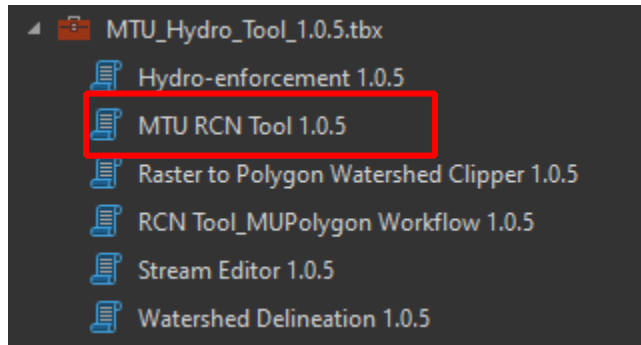
- You do not have to do anything to the updated county specific soil table. If they are saved in the proper directory, the tables will be combined automatically by the RCN Tool.



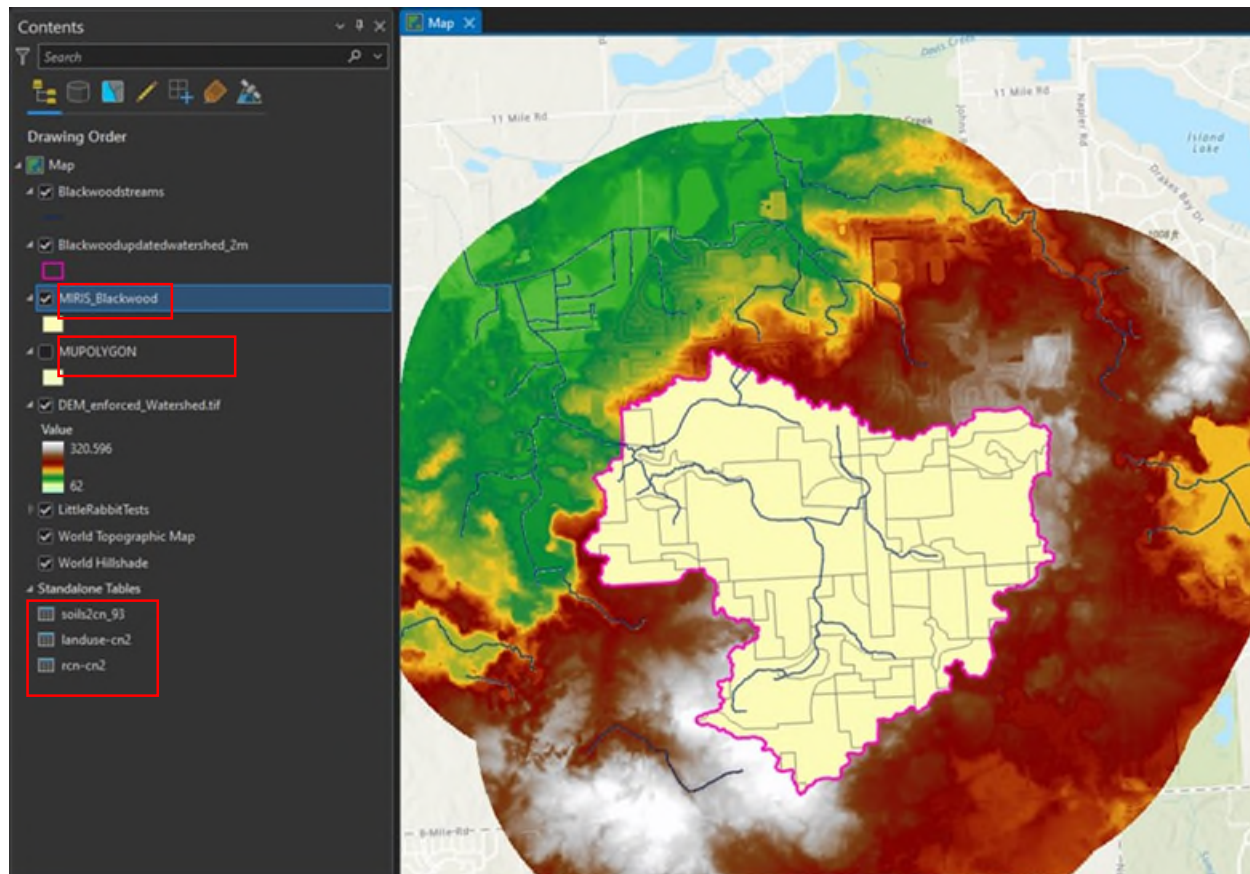
Name	Status	Date modified	Type	Size
msdommas		8/6/2024 11:08 AM	Text Document	4 KB
msidxdet		8/6/2024 11:08 AM	Text Document	9 KB
msidxmas		8/6/2024 11:08 AM	Text Document	6 KB
msrsdet		8/6/2024 11:08 AM	Text Document	4 KB
msrsmas		8/6/2024 11:08 AM	Text Document	4 KB
mstab		8/6/2024 11:08 AM	Text Document	32 KB
mstabcol		8/6/2024 11:08 AM	Text Document	215 KB
muaggatt		8/6/2024 11:08 AM	Text Document	60 KB
muareao		8/6/2024 11:08 AM	Text Document	30 KB
mucrpyd		8/6/2024 11:08 AM	Text Document	27 KB
mutex		8/6/2024 11:08 AM	Text Document	0 KB
sacatlog		8/6/2024 11:08 AM	Text Document	66 KB
sainterp		8/6/2024 11:08 AM	Text Document	1,719 KB
sdvalgorithm		8/6/2024 11:08 AM	Text Document	6 KB
sdvattribute		8/6/2024 11:08 AM	Text Document	1,324 KB
sdvfolder		8/6/2024 11:08 AM	Text Document	9 KB
sdvfolderattribute		8/6/2024 11:08 AM	Text Document	2 KB
version		8/6/2024 11:08 AM	Text Document	1 KB

Step 3: Select the RCN Tool

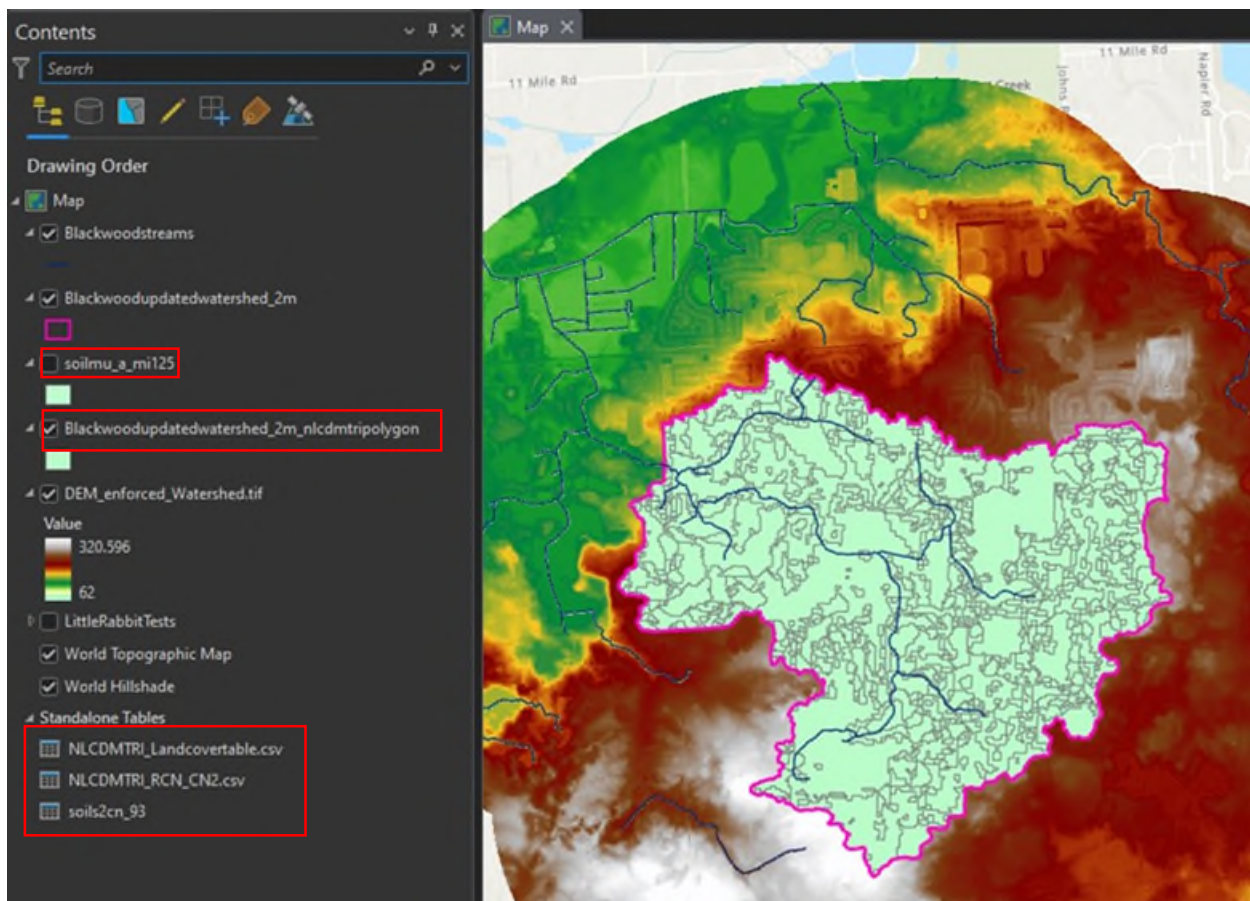
Go to the MTU_Hydro toolbox and select the RCN Tool



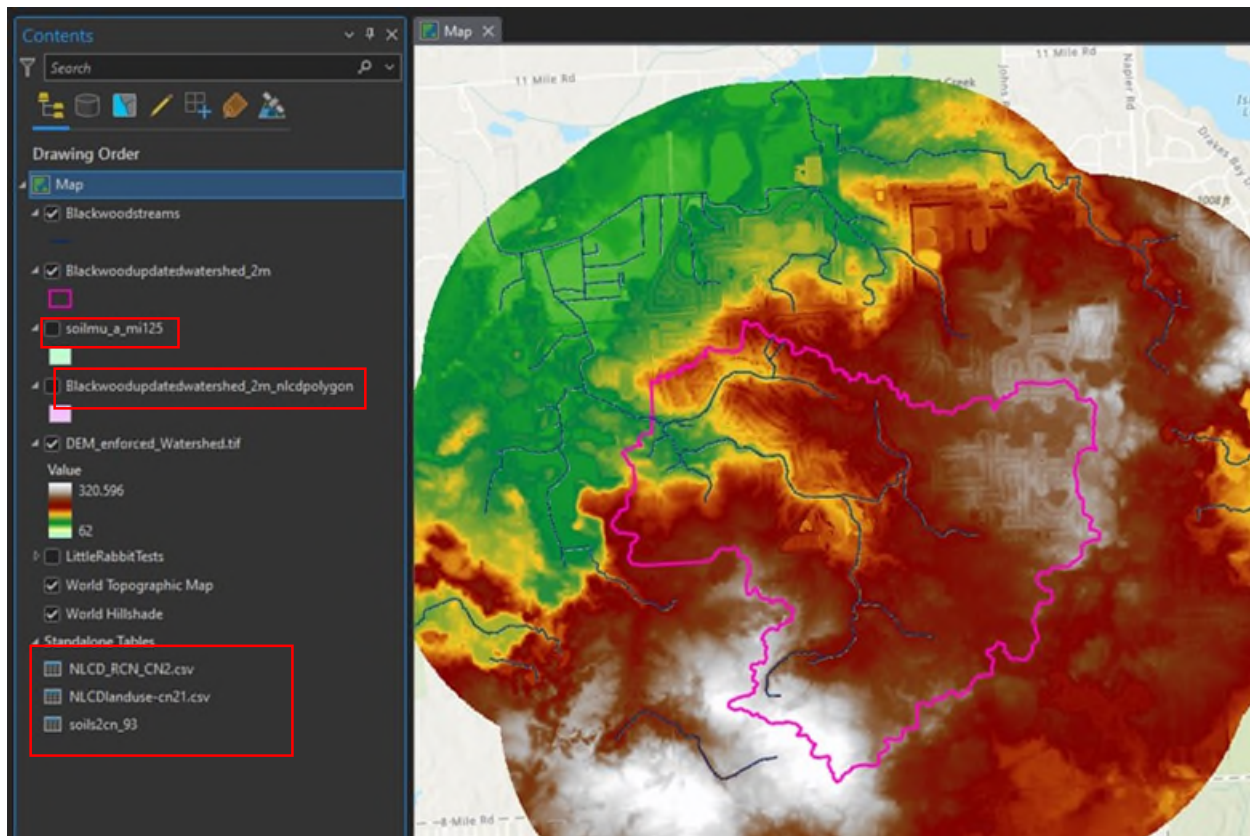
- If you are using the MIRIS 1978 land use layer and the MUPOLYGON soil layer, pull in said layers and all necessary layers/tables into your project. As a reminder, the landuse table must be a vector layer to work correctly in this tool. The tables for each landuse/cover layer can be found in the example folder. Use these paths in the example folder to find the appropriate layers:
 - Landuse Layer: MTU Hydro Toolbox_1_0_5_walkthrough -> landusespatiallayers -> Blackwood -> MIRIS -> MIRIS_Blackwood.shp
 - Soils Table: MTU Hydro Toolbox_1_0_5_walkthrough -> wss_SSA_MI0125_soildb_MI_2003_[2023-08-25] -> MI125->spatial-> soilmu_a_mi125.shp
 - RCN table: MTU Hydro Toolbox_1_0_5_walkthrough -> MIRIS Tables -> rcn-cn2.dbf
 - Landuse table: MTU Hydro Toolbox_1_0_5_walkthrough -> MIRIS Tables -> landuse-cn2.dbf
 - Soils table: MTU Hydro Toolbox_1_0_5_walkthrough -> MIRIS Tables -> soils2cn_93.dbf



- If you are using the NLCD_MTRI Reclassed layer, pull in said layer and all necessary layers/tables into your project. As a reminder, the tables for each landuse/cover layer can be found in the example folder. For the NLCD_MTRI Reclassed Layer, use these paths in the example folder to find the appropriate layers:
 - Landuse Layer: MTU Hydro Toolbox_1_0_5_walkthrough -> Landusespatiallayers -> Blackwood -> NLCDMTRI -> Blackwoodupdatedwatershed_2mNLCDMTRIpolygon
 - Soils layer: MTU Hydro Toolbox_1_0_5_walkthrough -> wss_SSA_MI0125_soildb_MI_2003_[2023-08-25] -> MI125->spatial-> soilmu_a_mi125.shp
 - RCN table: MTU Hydro Toolbox_1_0_5_walkthrough -> NLCDMTRI Tables -> NLCDMTRI_RCIN_CN2.csv
 - Landuse table: MTU Hydro Toolbox_1_0_5_walkthrough -> NLCDMTRI Tables -> NLCDMTRI_Landcovertable.csv
 - Soils table: MTU Hydro Toolbox_1_0_5_walkthrough -> NLCDMTRI Tables -> soils2cn_93.dbf

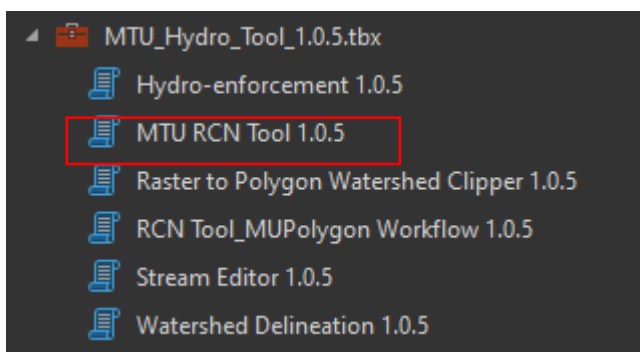


- If you are using the NLCD 2021layer, pull in said layer and all necessary layers/tables into your project. As a reminder, the tables for each landuse/cover layer can be found in the example folder. For the NLCD_MTRI Reclassed Layer, use these paths in the example folder to find the appropriate layers:
 - Landuse layer: MTU Hydro Toolbox_1_0_5_walkthrough->Landusespatiallayers -> Blackwood -> NLCD-> Blackwoodupdatedwatershed_2mNLCDpolygon
 - Soils layer: MTU Hydro Toolbox_1_0_5_walkthrough -> wss_SSA_MI0125_soildb_MI_2003_[2023-08-25] -> MI125->spatial-> soilmu_a_mi125.shp
 - RCN table: MTU Hydro Toolbox_1_0_5_walkthrough -> NLCDTables -> NLCD_RCN_CN2.csv
 - Landuse table: MTU Hydro Toolbox_1_0_5_walkthrough-> NLCDTables -> NLCDlanduse-cn21.csv
 - Soils table: MTU Hydro Toolbox_1_0_5_walkthrough -> NLCDTables -> soils2cn_93.dbf

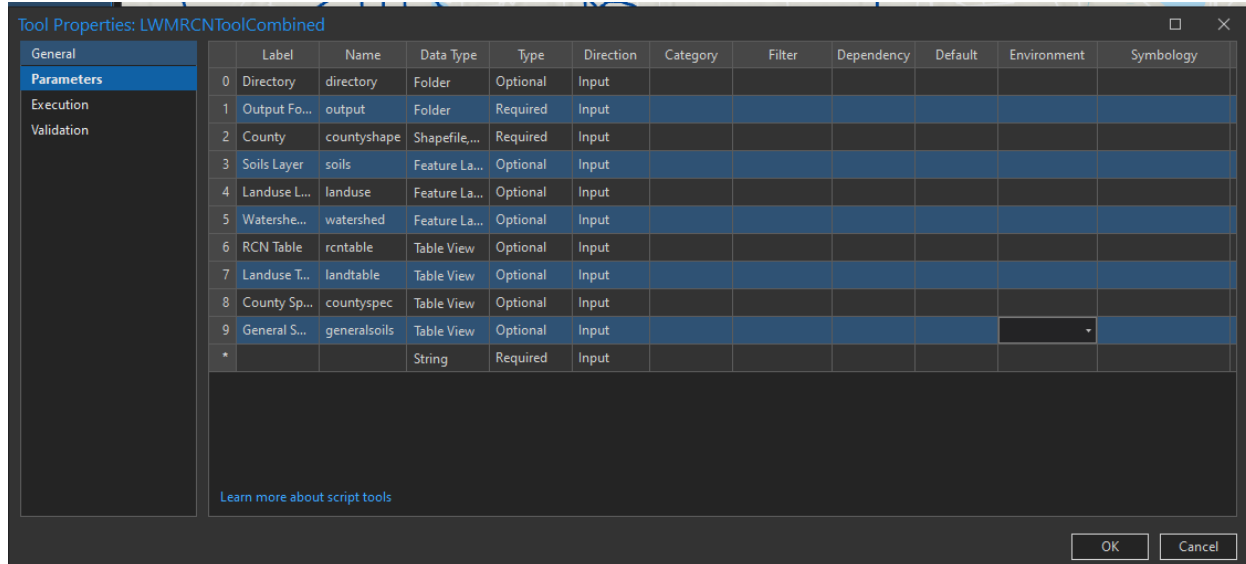


Step 4: Building Defaults

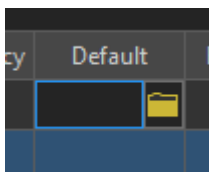
- If you'd prefer to set these layers as defaults into the tool using ArcGIS Pro settings, right click on the tool in the Catalog Pane and hit 'Properties'.



- Go to the 'Parameters' tab of the 'Properties' pop-up.



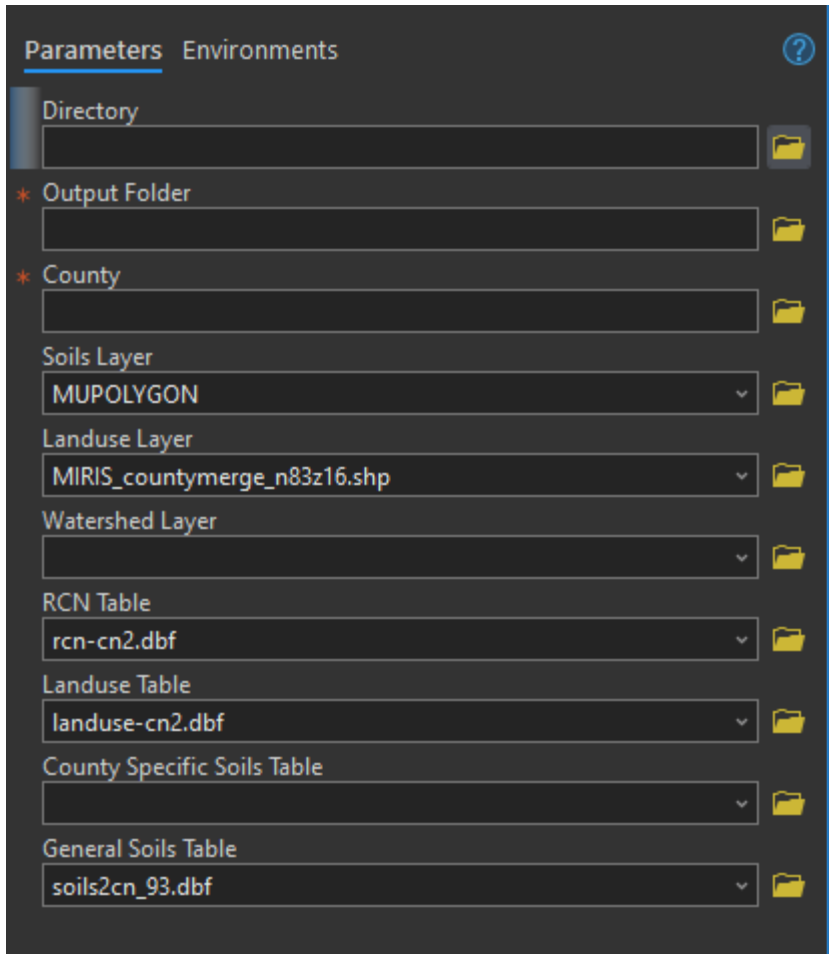
- Click a row under the 'Default' column, and an option to add a file will appear.



- Go through and add in the files that you'd like to have as a default in the tool.

	Label	Name	Data Type	Type	Direction	Category	Filter	Dependency	Default	Envirc
0	Directory	directory	Folder	Optional	Input					
1	Output Fo...	output	Folder	Required	Input					
2	County	countysshape	Shapefile,...	Required	Input					
3	Soils Layer	soils	Feature La...	Optional	Input				J:\project\MDOT_HydrologicCalculations\d...	
4	Landuse L...	landuse	Feature La...	Optional	Input				J:\project\MDOT_HydrologicCalculations\d...	
5	Watershe...	watershed	Feature La...	Optional	Input					
6	RCN Table	rcntable	Table View	Optional	Input				J:\project\MDOT_HydrologicCalculations\d...	
7	Landuse T...	landtable	Table View	Optional	Input				J:\project\MDOT_HydrologicCalculations\d...	
8	County Sp...	countyspec	Table View	Optional	Input					
9	General S...	generalsoils	Table View	Optional	Input				J:\project\MDOT_HydrologicCalculations\d...	
*			String	Required	Input					

- Hit 'Ok' and close the 'Properties' pop-up. Then open the tool. Your defaults should appear in the appropriate columns.



The screenshot shows the 'Parameters' tab of a software interface. It contains several input fields and dropdown menus, each with a folder icon to its right. The fields are: 'Directory' (empty), '* Output Folder' (empty), '* County' (empty), 'Soils Layer' (dropdown with 'MUPOLYGON' selected), 'Landuse Layer' (dropdown with 'MIRIS_countymerge_n83z16.shp' selected), 'Watershed Layer' (empty), 'RCN Table' (dropdown with 'rcn-cn2.dbf' selected), 'Landuse Table' (dropdown with 'landuse-cn2.dbf' selected), 'County Specific Soils Table' (empty), and 'General Soils Table' (dropdown with 'soils2cn_93.dbf' selected). A question mark icon is in the top right corner.

Step 5: Run Tool

- Open the tool and fill in the input parameters. *If you have your 'County Specific Soils Table' files within one directory, you do not need to input your County Specific Soils Table. If you have your NRCS-downloaded folder within a directory, you also do not need to input a County Specific Soils Table.*
- If you have your defaults preset, you will still have to choose your output folder and drag in your watershed layer and county specific soils layer. If you do not have your defaults preset, you will have to pull in each layer either from its folder or from the project.
- Example for MIRIS input parameters:

Geoprocessing

MTU RCN Tool 1.0.5

Parameters Environments

Directory

MTU Hydro Toolbox_1_0_5_walkthrough

Output Folder

test2

County

RCNTool_countylayer.shp

Soils Layer

soilmu_a_mi125.shp

Landuse Layer

MIRIS_Blackwood.shp

Watershed Layer

Blackwoodupdatedwatershed_2m.shp

RCN Table

rcn-cn2.dbf

RCN Field

Landuse Table

landuse-cn2.dbf

County Specific Soils Table

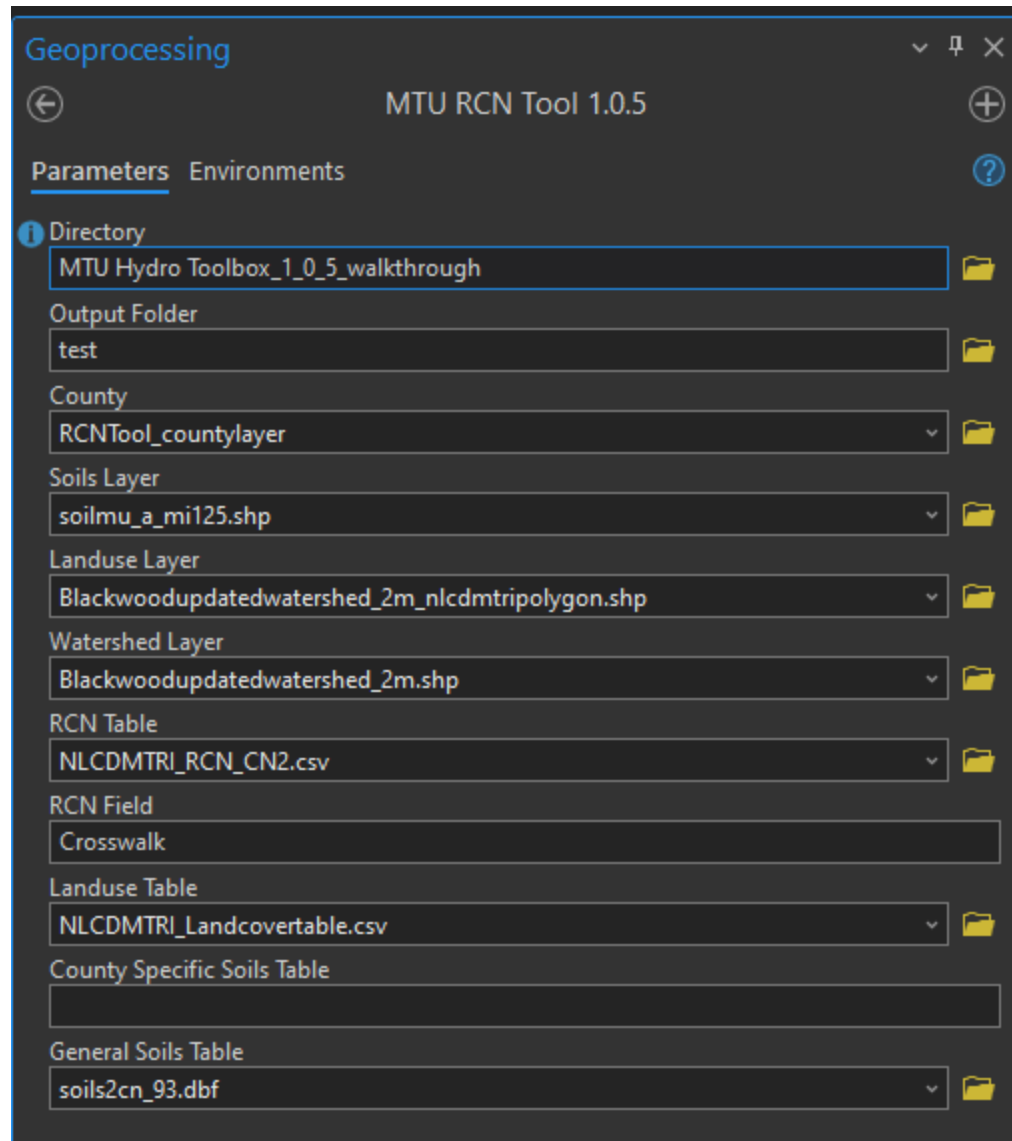
General Soils Table

soils2cn_93.dbf

- Example for NLCDMTRI input parameters:
 - This is the area where RCN_Field comes into play. As the RCN table for the NLCDMTRI parameter contains three potential columns that could allow for RCN calculations, please input the column name that you would like to use for your run.

Classvalue	RCNUpdated	Crosswalk	USACE
114	<Null>	85	85
414	<Null>	85	85
514	<Null>	85	85
714	<Null>	85	85
814	<Null>	85	85
914	<Null>	85	85
1014	<Null>	85	85
1014	<Null>	85	85

- The example below is calling “Crosswalk” to conduct RCN calculations



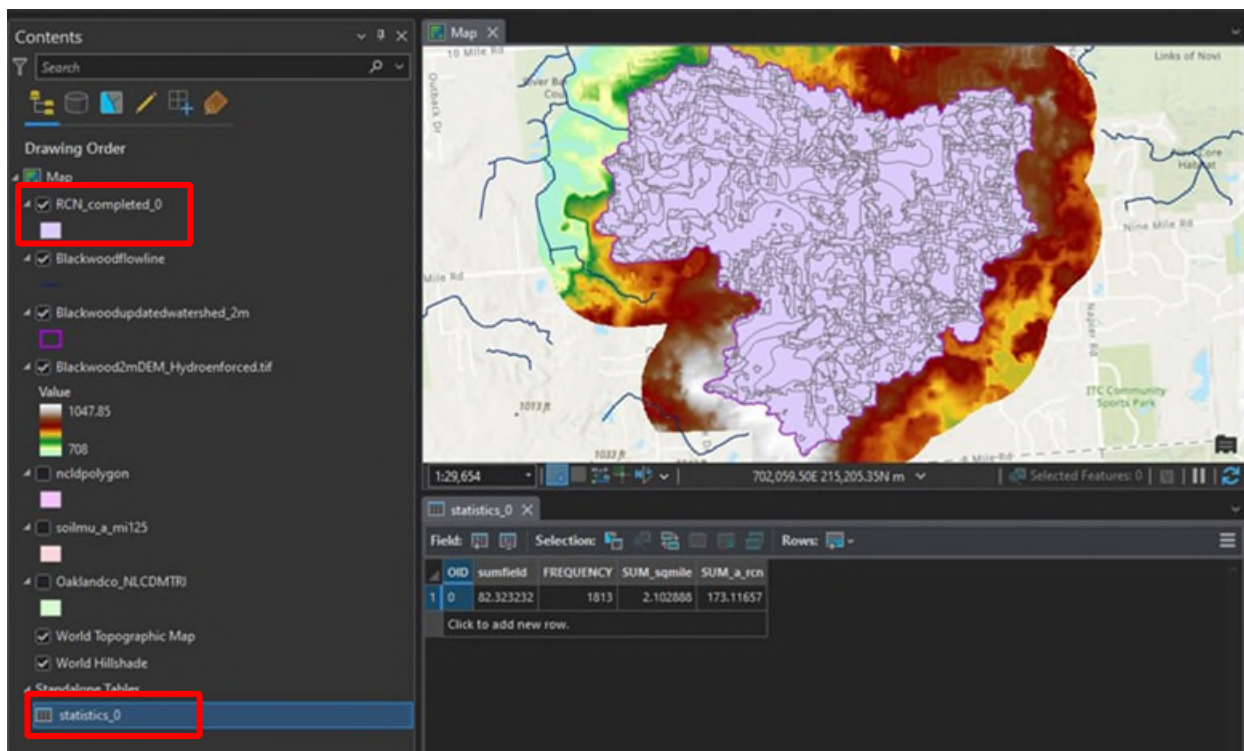
The screenshot shows the Geoprocessing window for the MTU RCN Tool 1.0.5. The Parameters tab is active, and the following parameters are configured:

Parameter	Value
Directory	MTU Hydro Toolbox_1_0_5_walkthrough
Output Folder	test
County	RCNTool_countylayer
Soils Layer	soilmu_a_mi125.shp
Landuse Layer	Blackwoodupdatedwatershed_2m_nlcdmtripolygon.shp
Watershed Layer	Blackwoodupdatedwatershed_2m.shp
RCN Table	NLCDMTRI_RCN_CN2.csv
RCN Field	Crosswalk
Landuse Table	NLCDMTRI_Landcoverable.csv
County Specific Soils Table	
General Soils Table	soils2cn_93.dbf

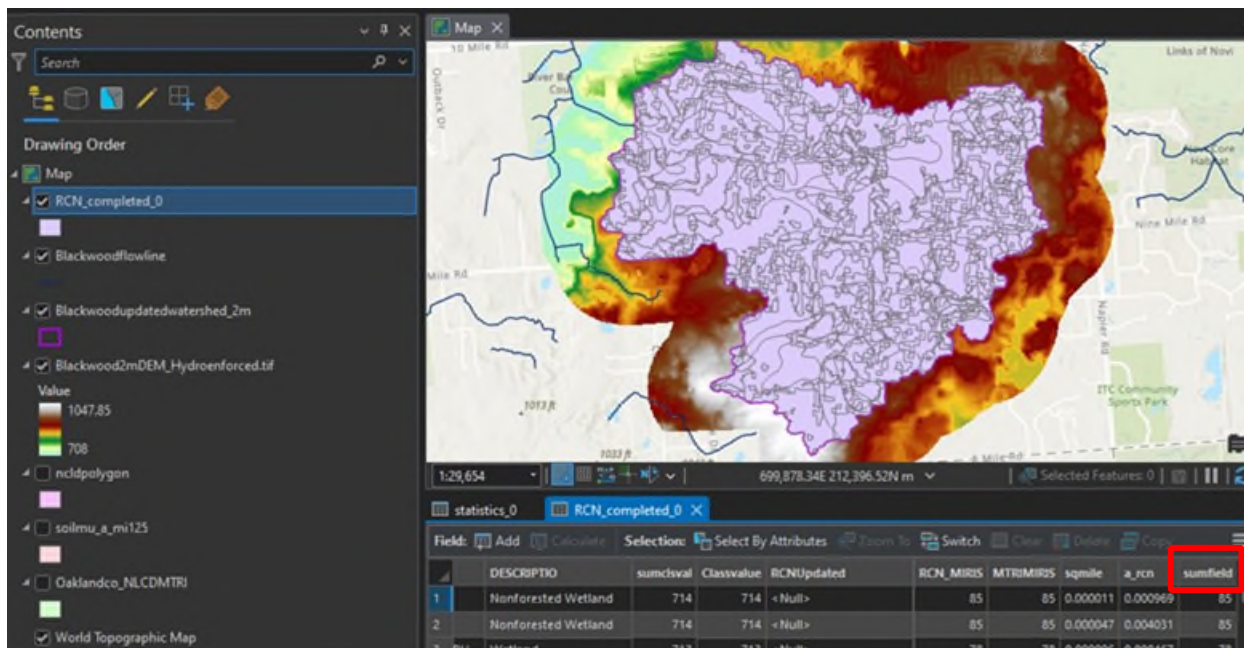
- Example for NLCD2021 input parameters:



- 183



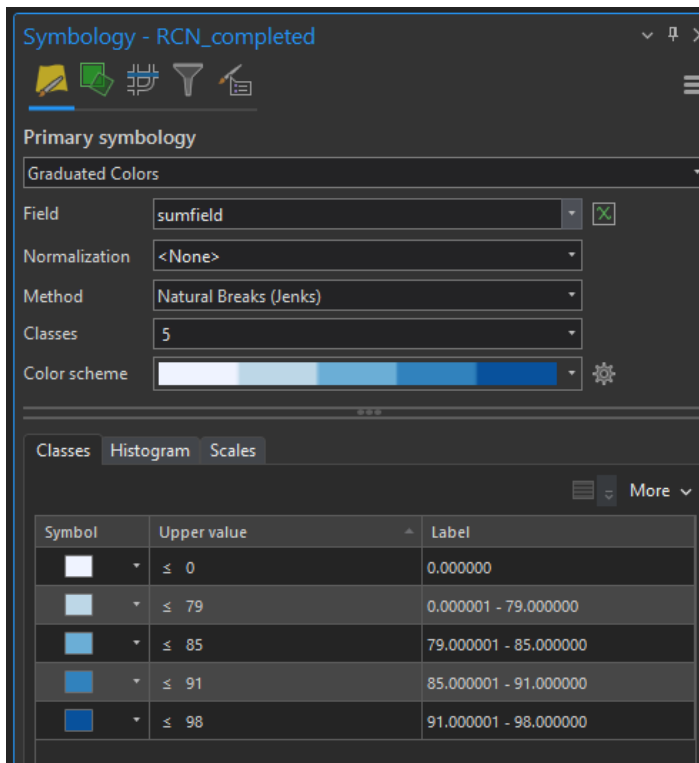
- The 'RCN' column in the spatial layer will hold the individual RCN values for each polygon.



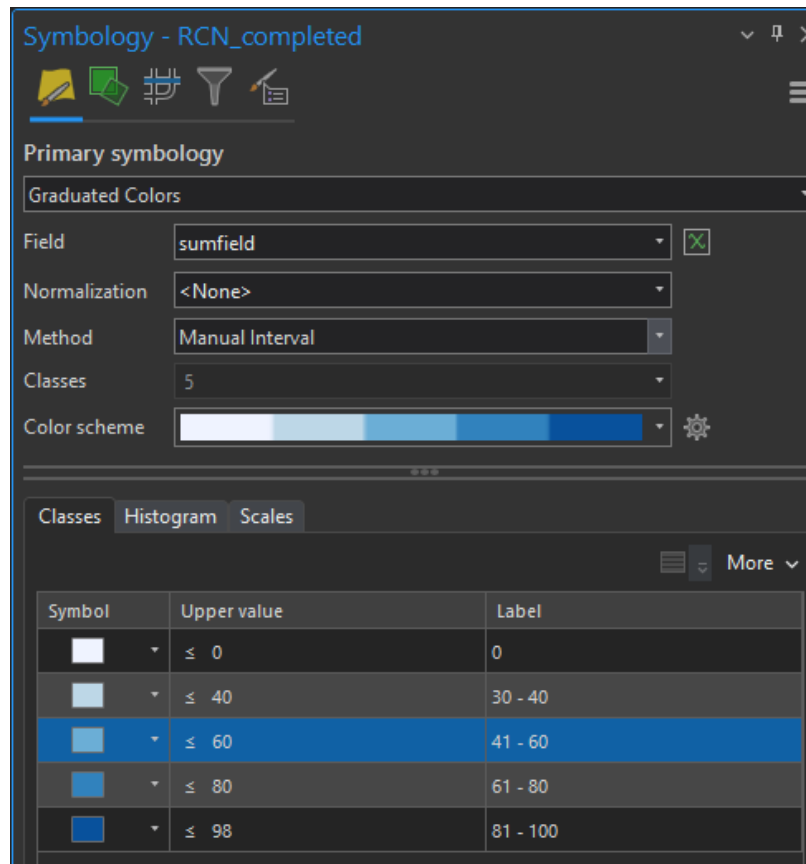
Step 7: Symbolize output.

- While having the RCN_completed layer selected, hit 'symbology', and change the primary symbology from 'Single Symbol' to 'Graduated Colors'

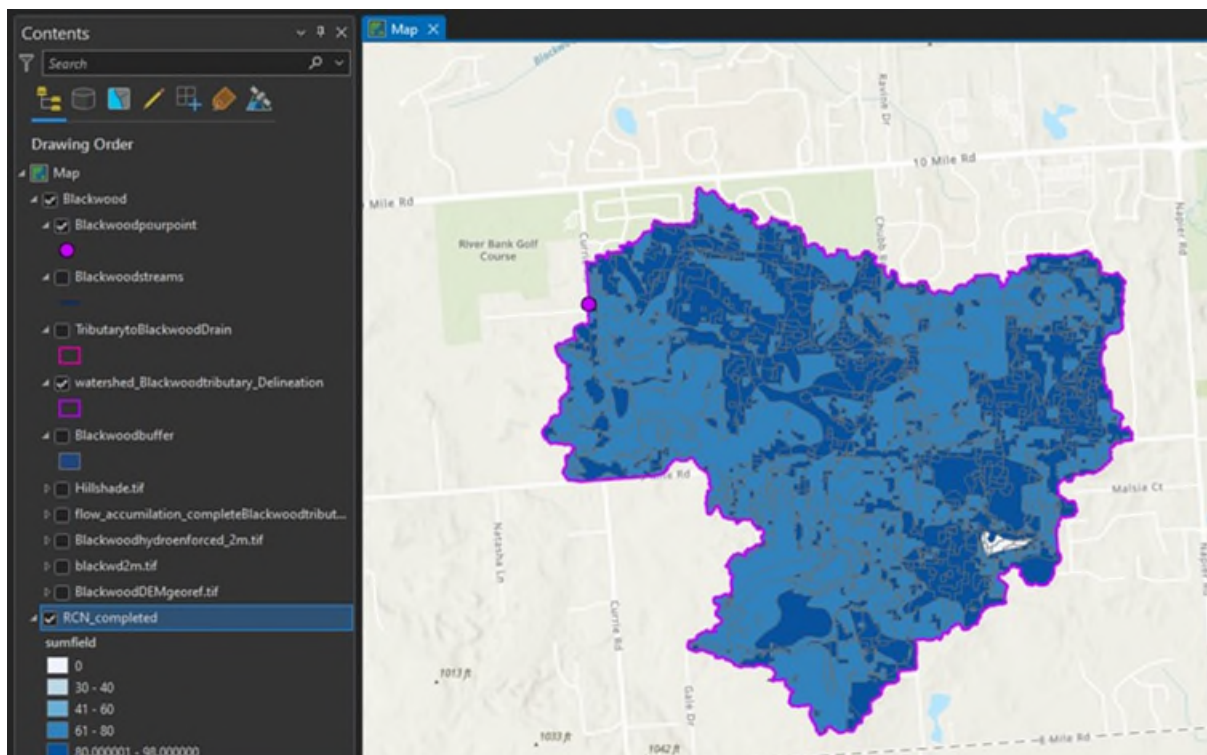
- Select 'Blue 5 classes'



- Change the 'upper value' columns to values that more appropriately reflect the needed analysis. This example uses equalized intervals of these values while recognizing that RCN values begin at 30.



- Congratulations! You've finished building your RCN layer for your watershed!



MTU_Hydro_Tool_1.0.5

RCN Tool_MUPolygon Workflow

May 15 2025

General Overview of the RCN Tool_MUPolygon Workflow

Due to substantial restructuring of the code that had to occur to incorporate updates requested at the September 11, 2024 in-person meeting and the February 2nd, 2025 intermediate meeting, the workflow that allowed for usage of the MUPolygon and the County Specific .txt files had to be removed from the original tool. In order to allow for more testing to be done with the MUpolygon soil spatial later and the EGLE-generated .txt files, this functionality was preserved in the RCN Tool_MUPolygon workflow. This is a heavily simplified version of the RCN tool, with no directory functionality or ability to run updated soil datasets. Please use the more advanced RCN Tool for any process other than testing with the MIRIS dataset and the MUPolygon soil spatial layer.

RCN Tool_MUPolygon Workflow Inputs

- **Output Folder:** Folder where output files will be saved.
- **County:** Shapefile that holds county information – used to direct tool to appropriate County Specific Soils Table
- **Soils Layer:** Soils shapefile, traditionally the 'MUPolygon' from the Soil Survey Geographic Database (SSURGO). Newly downloaded layers from NRCS can also be used.
- **Landuse Layer:** Land use/Land cover layer. Can be a raster or a vector file. Can use any shapefile that matches up with RCN table and Landuse Table. Traditionally used MIRIS, can use NLCD_MTRI Reclassed Layer or NLCD 2021 as well.
- **Watershed Layer:** Shapefile that will clip other layers to the study area, typically a shapefile of a watershed created with the Watershed Delineation tool.
- **RCN Table:** Reference table built for the specific land cover/landuse spatial layer – sum of 'Class' + 'Value' is joined to this table after the intersection between the Soils and the Landuse spatial layers are conducted.
- **RCN Field:** Column in the RCN field that you would like to use to calculate the RCN. Defaults to last column in table
- **Landuse Table:** Reference table for landuse spatial layer – matches landcover description to 'Class' column.
- **County Specific Soils Table:** Reference table to specific soil names in different counties, i.e. "oakland.sls"
- **General Soils Table:** Reference table matching soil class to 'Value'

RCN Tool_MUPolygon Workflow Outputs

- **Clipped_land.shp:** Shapefile of clipped land use/cover layer, if your input was a raster layer this will be the result of converting the raster layer to a vector layer
- **Clipped_soil.shp:** Shapefile of clipped soil spatial layer

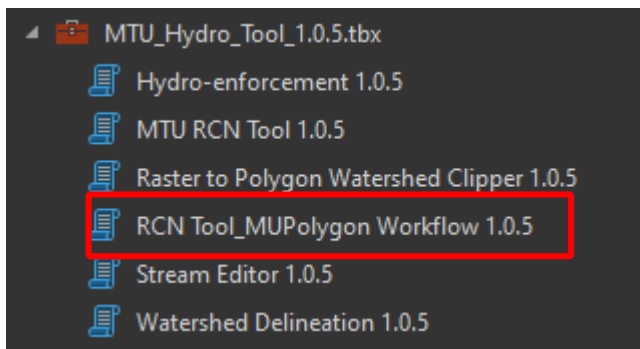
- **Clippedlanduse.tif:** If your land use/cover layer was a raster layer, there will be a clipped output of this layer.
- **countysoilsMUSYM.shp:** Soils spatial layer with county specific soils table joined
- **general_county_soils.shp:** Soils spatial layer with county specific soils table and general soils table joined
- **landuse_intersect.shp:** First intersected layer, landuselayer.shp intersected with general_county_soils.shp
- **landusetable_save.shp:** landuse_intersect.shp exported into a separate file to preserve joins
- **landuseinterSUM.shp:** landusetable_save with column created to calculate 'Class' + 'Value'
- **landuselayer.shp:** Land use / cover spatial layer with landuse table joined.
- **RCN_completed.shp:** Final product – shapefile with RCN values
- **Statistics.dbf:** Final product – contains overall RCN value for area

Step by Step Tutorial

As stated above, this is a significantly simplified version of the RCN tool. This tool is only available without a directory function, and can only be used on the MUPolygon layer and the MIRIS dataset.

Step 1: Select the RCN Tool_MUPolygon workflow

Go to the MDOT_toolbox and select the RCN Tool_MUPolygon workflow.



Step 2: Run the RCN Tool_MUPolygon Workflow

Below is a screenshot of the tool with example inputs:

Geoprocessing

RCN Tool_MUPolygon Workflow

Parameters

Environments

Output Folder

mupolygonblackwood

County

mupolygonblackwood

Soils Layer

MUPOLYGON

Landuse Layer

MIRIS_Blackwood.shp

Watershed Layer

Blackwoodupdatedwatershed_2m.shp

RCN Table

rcn-cn2.dbf

Landuse Table

landuse-cn2.dbf

County Specific Soils Table

oaklandsils.txt

General Soils Table

soils2cn_93.dbf

Refer to RCN Tool instructions for instructions on how to analyze and symbolize output.

MTU_Hydro_Tool_1.0.5

Stream Editor

May 15 2025

General Overview of the Stream Editor

This tool allows the user to either: a) quickly create a new stream layer for a watershed, or b) quickly add to a previously existing stream layer for a watershed. This stream layer can then be used to more accurately hydro-enforce a DEM.

Stream Editor Inputs

- **Output:** Folder where output files will be saved.
- **Existing Streams:** Existing flowline feature class or shapefile. Not required if you're building a completely new flowline layer.
- **New Streams:** Where you will build your new streams layer.
- **Stream Name (Optional):** What you'd like your stream stream layer to be titled.

Stream Editor Outputs

- **Merged_New_Streams_(streamname):** Final shapefile
- **New_Streams_(streamname):** Only displays streams that have been added by user
- **Snapped_New_Streams_(streamname):** Another preliminary file that only displays streams added by user

Step By Step Tutorial

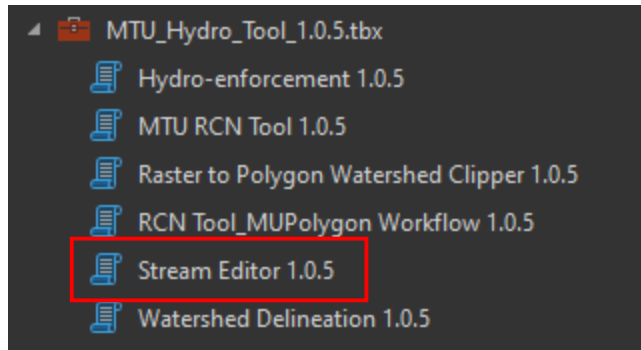
Step 1: Determine if you are creating a new stream file or if you are editing one that previously existed.

Pull your watershed into the project and determine if you already have a stream file that may be useful to build off of.

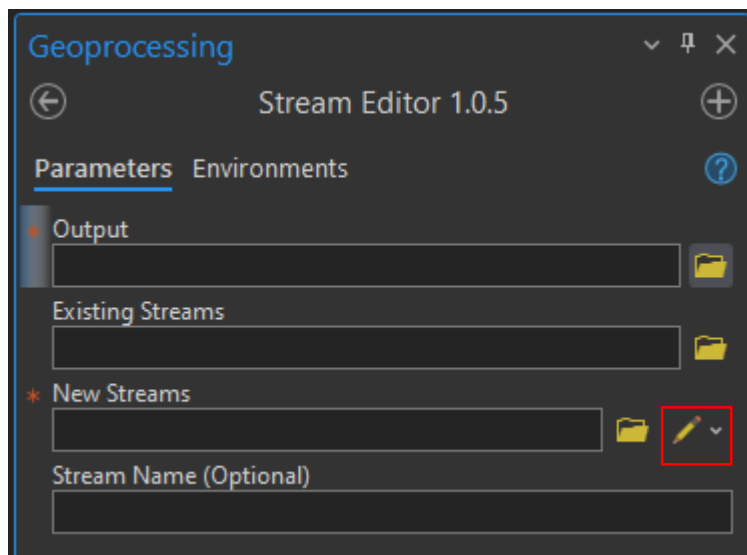
If you need to build an entirely new stream file:

Step 2: Build your stream file

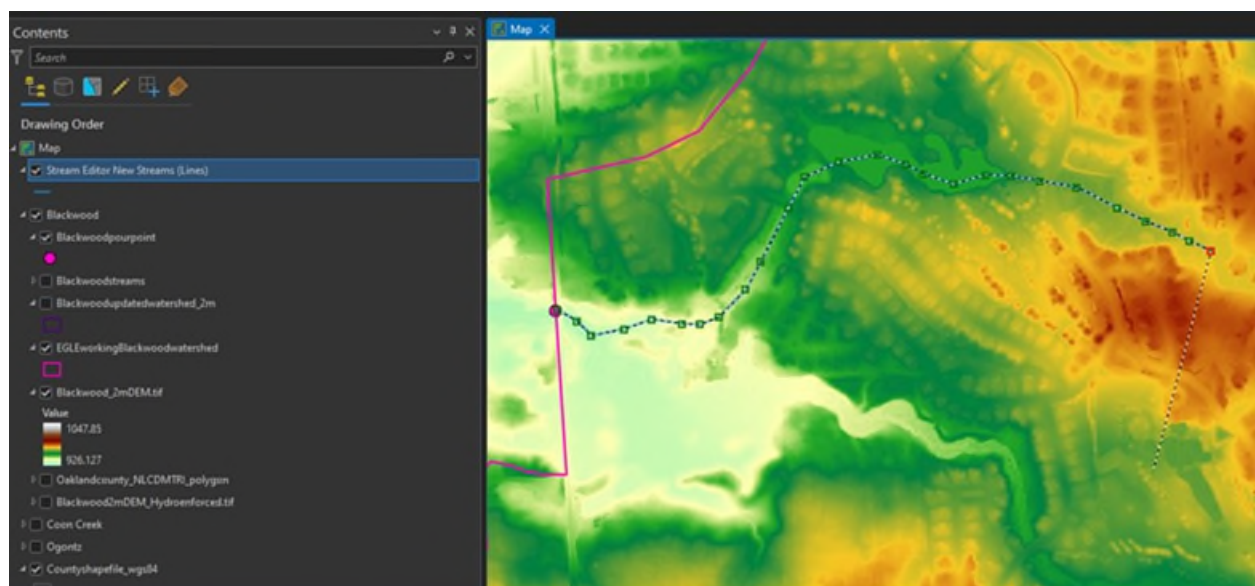
Open the tool.



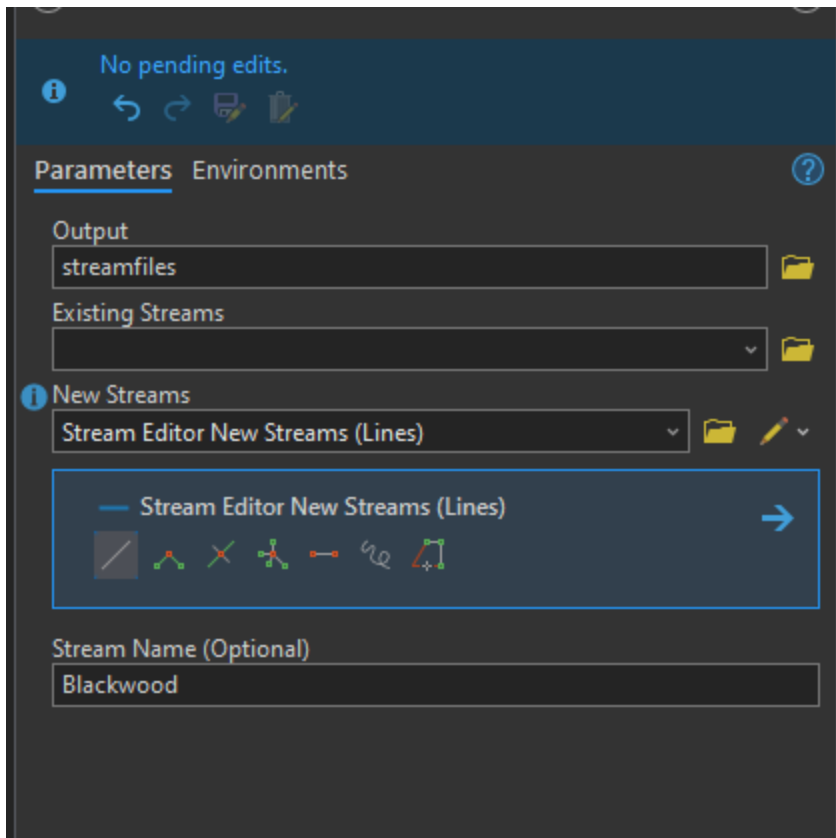
Create an output folder to save your stream, then hit the pencil next to 'New Streams'. Select 'Lines'.



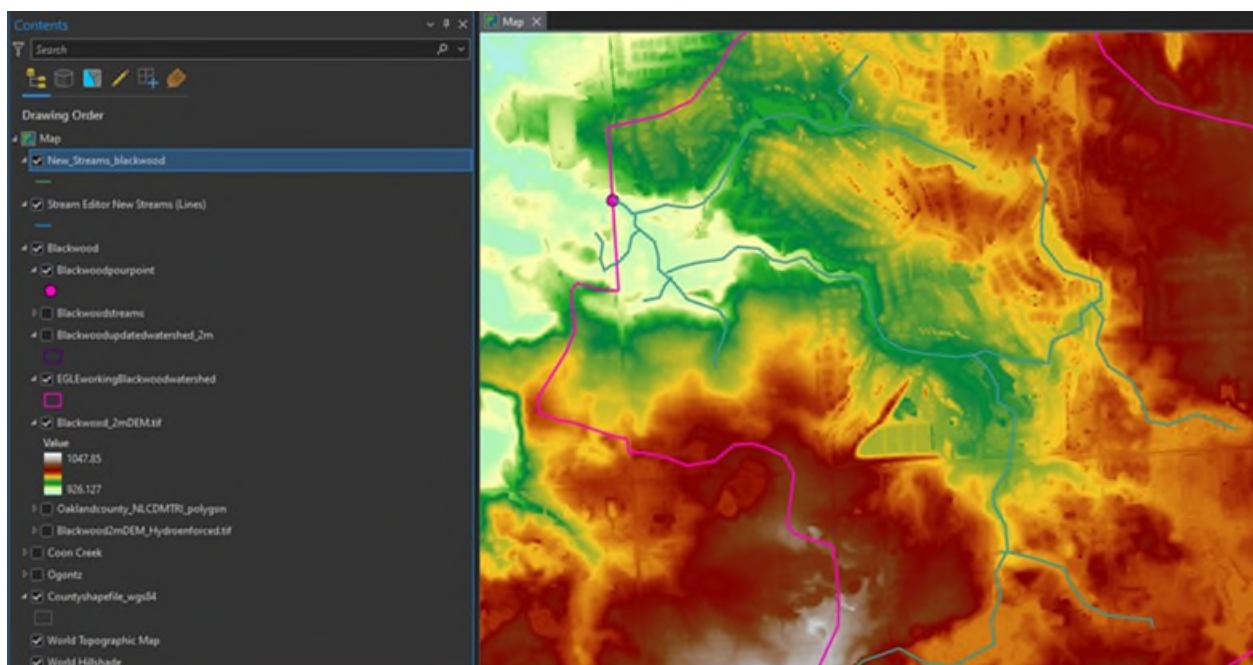
Use any references you have available to build your stream lines. This example uses the MiSAIL 2m DEM.



When you're finished, make sure there are no pending edits and give your stream a name.



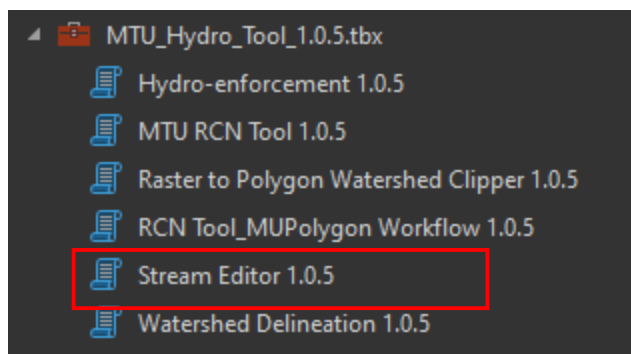
Your stream will then be output into your map.



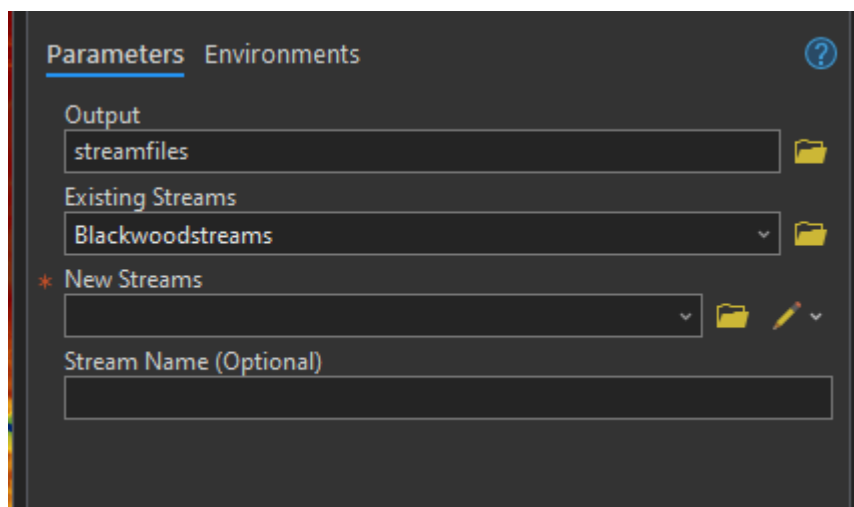
If you are adding to an already-created stream file:

Step 2: Build your stream file

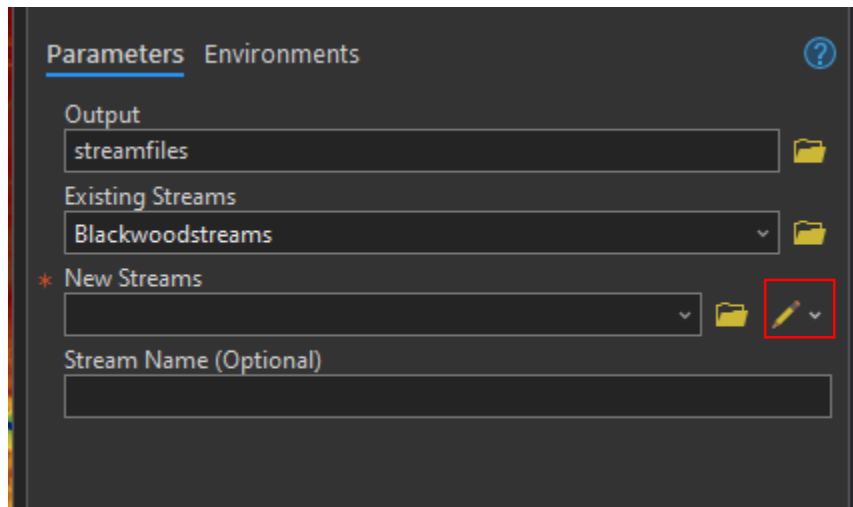
Open the tool.



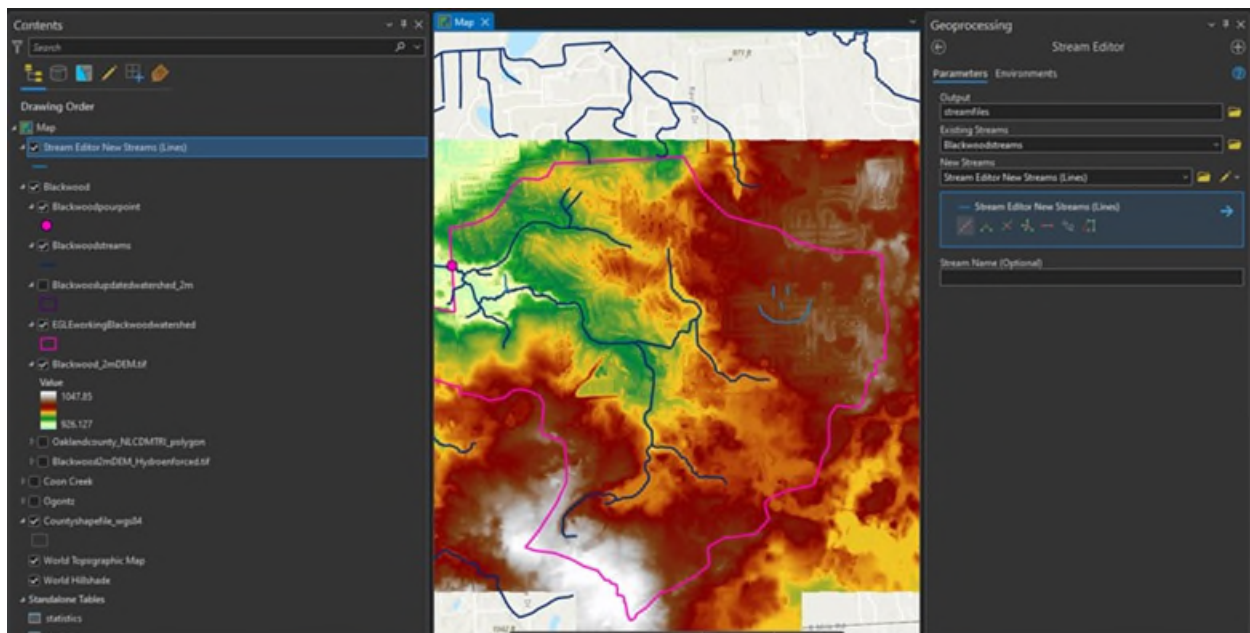
Create an output folder to save your stream, and input the path to your already created stream file.



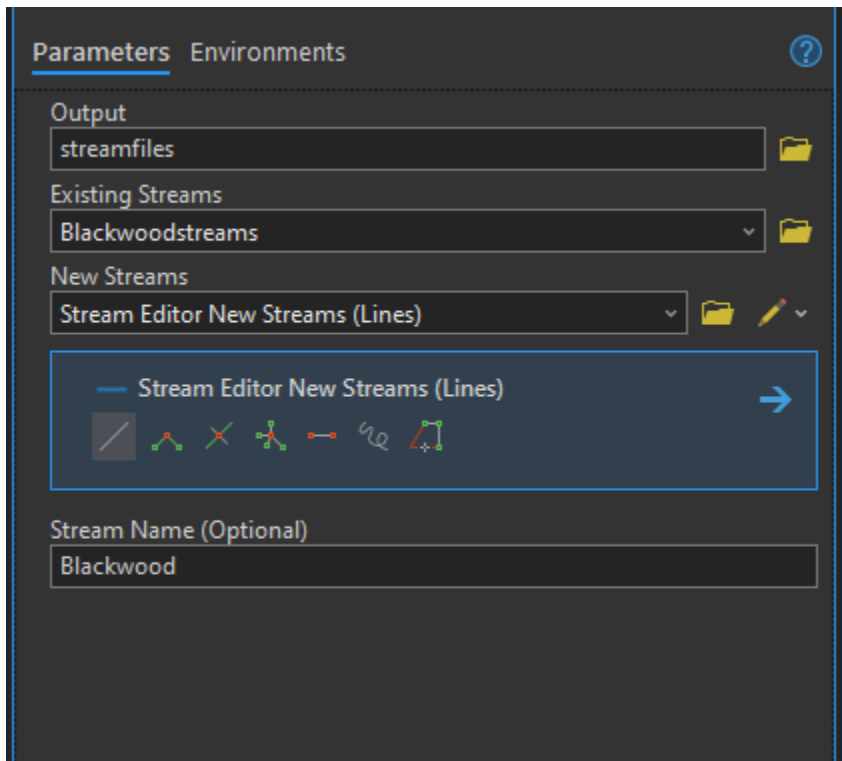
Hit the pencil next to 'New Streams'. Select 'Lines'.



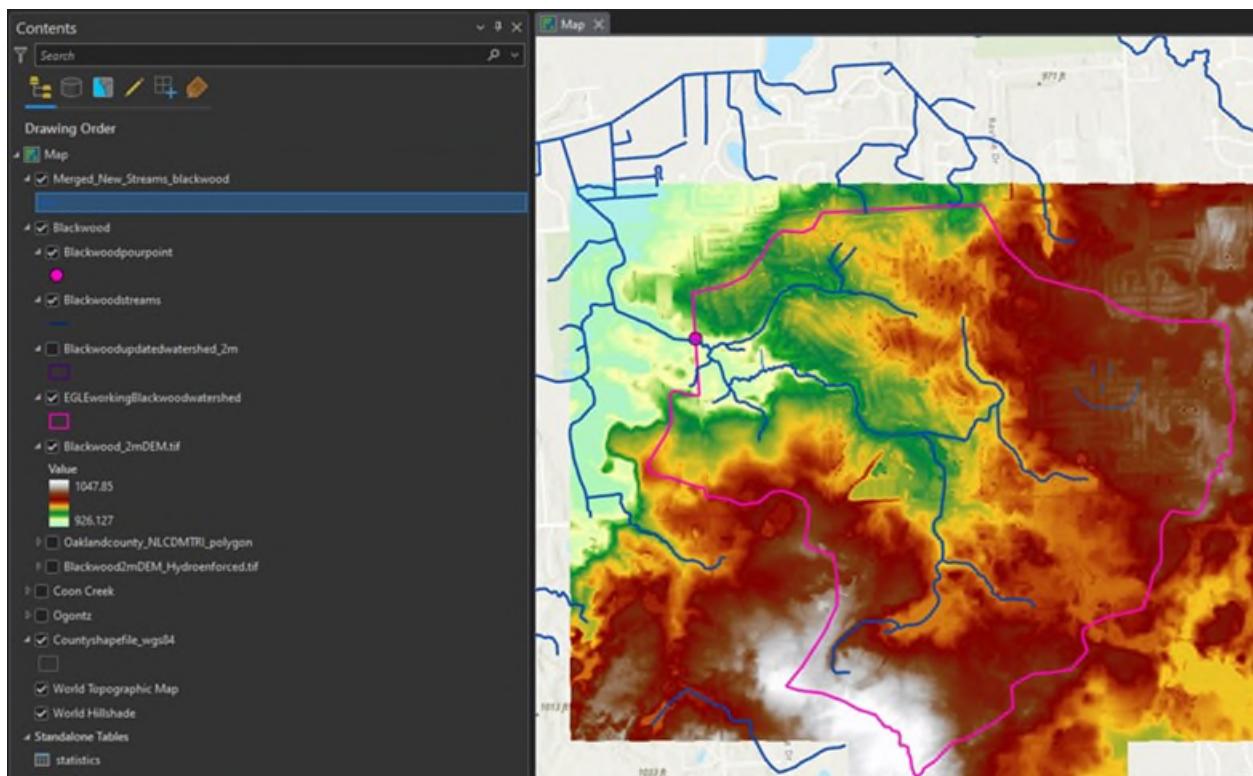
Add any stream lines required. (A smiley face was added to illustrate the change in the stream layer. Please don't actually add smiley faces to your stream layers!)



Add your stream line and hit Run.



Your stream will automatically upload into your map.



MTU_Hydro_Tool_1.0.5

Raster to Polygon Watershed Clipper

May 15 2025

General Overview of the Raster to Polygon Watershed Clipper

This tool allows the user to clip a raster layer to an appropriate size for the watershed you are working on building RCN values for, and then converts the layer from a polygon to a shapefile. This allows one to have the statewide layer saved in an easily viewable and reasonably-sized raster layer, while being able to quickly convert it into a vector layer for functionality. It is important to note that this tool has no individual naming capabilities, and **does not input into ArcGIS Pro on its own**. Vector land use/cover layers can be very energy-intensive, and may slow your computer down, so it is only necessary to upload this layer into your ArcGIS Pro map for analysis.

Raster to Polygon Watershed Clipper Inputs

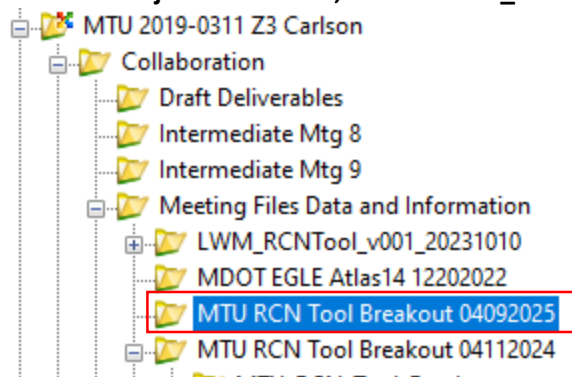
- **Output Folder:** Folder where output files will be saved.
- **Watershed Outline:** Shapefile or feature class that holds the outline of the watershed you'd like to clip to. You can also use a shapefile of a county or any other required study site outline.
- **Raster Layer:** Input Land use/cover Raster Layer

Raster to Polygon Watershed Outputs

- **(layername)polygon:** Final shapefile
- **Temppoly(layername):** temp shapefile
- **Clipped_nlcdmtri:** Clipped raster file

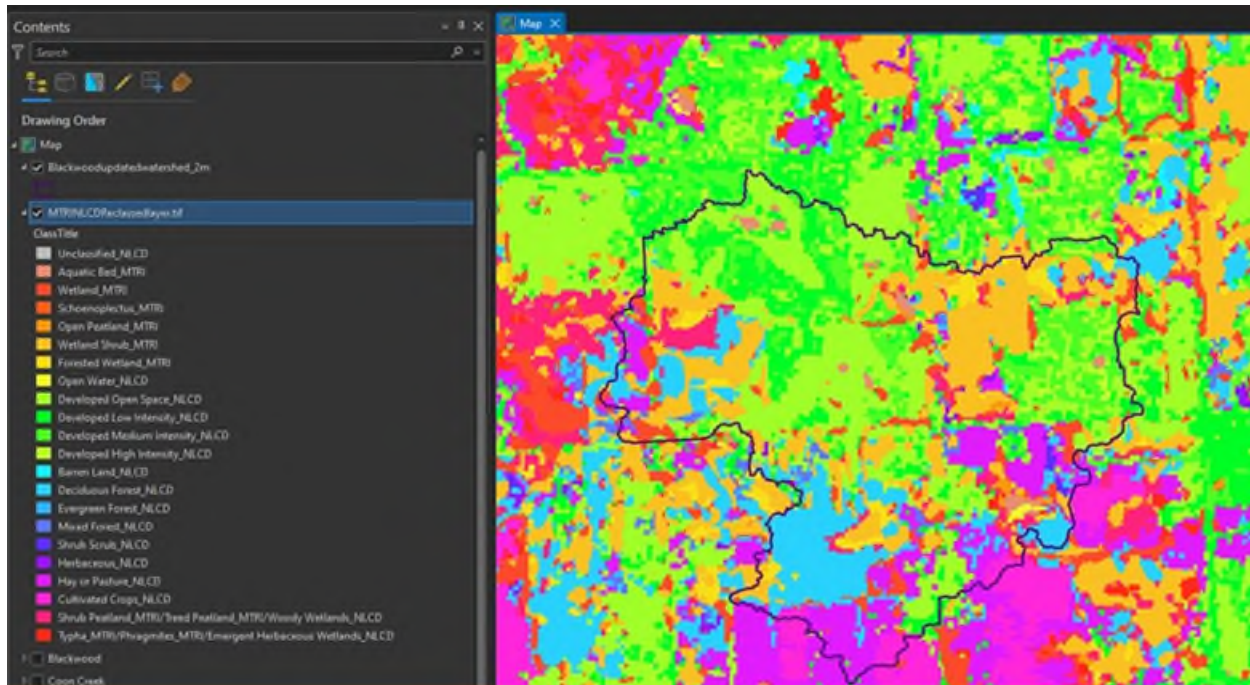
LULC Datasets that can be used in this tool

- **NLCD 2019 or 2021:**
- **NLCD/MTRI 2019 or 2021**
- **MIRIS 1978 Raster version (should not be necessary)**
- **Saved here in the Projectwise folder, under "LULC_FullLayers.zip":**

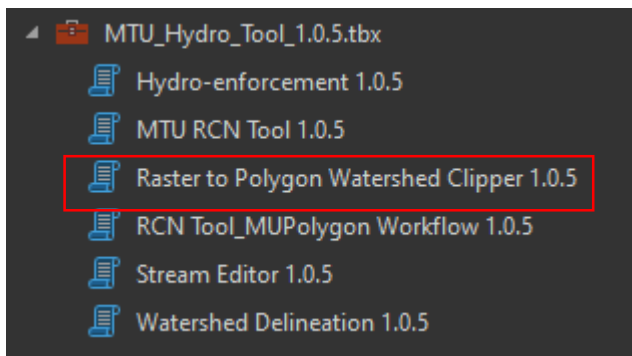


Step By Step Tutorial

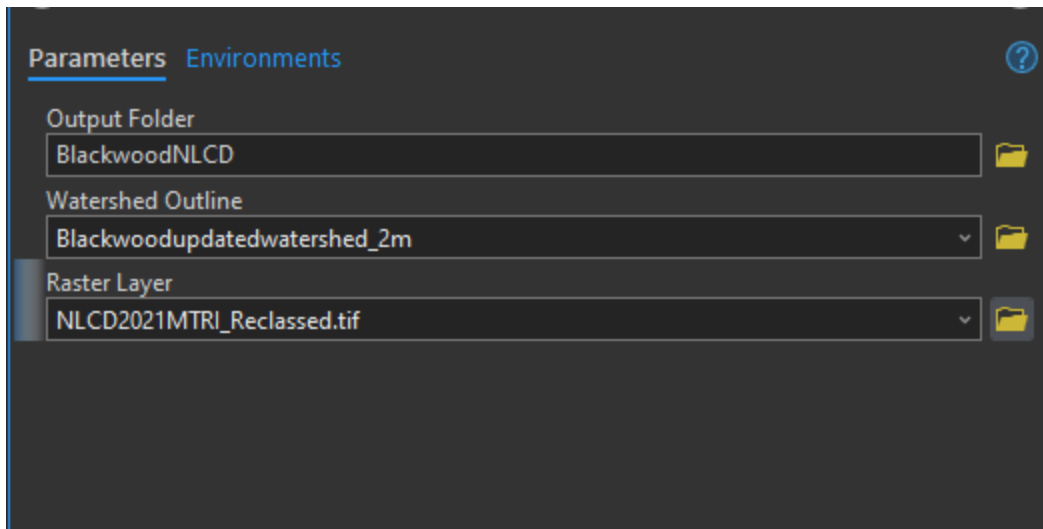
Step 1: Pull your watershed and the NLCD_MTRI layer into your project



Step 2: Open the tool



Build an output folder and input the watershed outline and the NLCD_MTRI Raster layer into the tool.



Hit Run, and the polygon version of the NLCD_MTRI raster layer, the NLCD 2019 or 2021 raster layer, or the MIRIS raster layer will be output into your output folder with the same name as the watershed outline used to generate it.

k:) > project > MDOT_HydrologicCalculations > workingdir > VanHuis > blackwood_nlcdmtritest				
Name	Date modified	Type	Size	
 Blackwoodupdatedwatershed_2m_clipped_nlcdmtri.tfw	4/1/2025 5:07 PM	TFW File	1 KB	
 Blackwoodupdatedwatershed_2m_clipped_nlcdmtri.tif	4/1/2025 5:07 PM	TIF File	11 KB	
 Blackwoodupdatedwatershed_2m_clipped_nlcdmtri.tif.aux.xml	4/1/2025 5:07 PM	Microsoft Edge H...	2 KB	
 Blackwoodupdatedwatershed_2m_clipped_nlcdmtri.tif.vat.cpg	4/1/2025 5:07 PM	CPG File	1 KB	
 Blackwoodupdatedwatershed_2m_clipped_nlcdmtri.tif.vat.dbf	4/1/2025 5:07 PM	DBF File	6 KB	

Appendix D: Watershed Composite RCN Layer Intersection Workflow

Documentation of EGLE's RCN Layer Workflow as explained by S. Greiner. Documented by S. Toivonen.

Layers:

- County soil Layer (shapefile) – from Web Soil Survey
- MIRIS_countymerge – land cover/use data

Standalone tables:

- County Soils Table – Each county has its own table created by EGLE.
- Landuse – cn2.dbf – EGLE lookup table needed for Joins
- Rcn-cn2.dbf – EGLE runoff curve number (RCN) lookup table needed for Joins
- Soils2cn-93.dbf – EGLE lookup table needed for soil Joins

Workflow

Step 1) Soil Joins

- In the contents pane, right click the County soil layer and select 'New Join'.
- Select the county lookup table and join through the 'MUSYM' and 'ID' fields.

Step 2) Soil Joins

- Join the County soil layer to the 'Soils2cn-93.dbf' table through the 'hydrgroup' and 'SoilClass' fields.
- **Export the layer to save the joins, the joins will not stay permanently without doing this.**

Step 3) Land use Joins

- In the contents pane, right-click the MIRIS land use layer and select 'New Join'.
- Select the landuse-cn2.dbf and join through the fields 'Code' and 'IGDS_TEXT'.
- **Export the layer to save the joins. The joins will not stay permanently without doing this.**

Step 4) Use the intersect tool to intersect the Soil and land use layers.

Step 5) New Field to prepare for step 6 joins

- In the Attribute table, create a new field named 'Sum_Class_Value'; field type 'Long'.
- Use the 'Field Calculator' and add the 'Class' + 'Value'.

Step 6) RCN table Joins

- In the contents pane, right-click the intersected soil and land use layer and select 'New Join'.
- Join to the rcn-cn2.dbf using the fields 'Sum_Class_Value' and 'COMP-CODE'.

- Export the layer to save the joins, the joins will not stay permanently without doing this. **THIS IS THE FINAL LAYER.**

Step 7) New Fields to calculate the composite RCN for the watershed

- Open the attribute table from the layer you exported in step 6 (this should be an intersected soil and land use layer with permanent RCN table joins).
- Create three new fields named 'Area_RCN', 'Area_sqMiles', and 'Sum Field'; Field type Double or Float.
- Use the calculate geometry to populate the 'Area_sqMiles'.
- Use the Field Calculator to populate the 'Area_RCN' field = 'RCN' x 'Area_sqMiles'.
- Use the Summarize function in the 'SumField';
 - o Field: 'Area_sqMiles'; Function: Sum
 - o Field: 'Area_RCN'; Function: Sum

This spits out a new standalone table with three fields:

- o 'Area_sqMiles' -> the sum of all 'Area_sqMiles'
- o 'Area_RCN' -> the Sum of all 'Area_RCN'
- o 'SumField' -> NULL

Step 8) Populate the 'SumField' for final result.

- Use the Field calculator to fill the NULL value in 'SumField'.
 - o Equation: = 'Area_RCN'/'Area_sqMiles'
- This gives the composite runoff curve number value, which should be between 30-100.
 - o 30 being the low runoff value (more permeable surfaces) and 100 being the high runoff value (more impermeable surfaces)

Appendix E: LULC Dataset Comparison

This appendix summarizes the comparison of classes in the NLCD and MTRI land cover datasets against the MIRIS land use dataset.

Class	1						2						3		4								5			
IDGS Code	1	11	111	112	113	115	12	121	122	123	124	126	13	138	14	141	142	143	144	145	146	17	171	172	173	
IDGS Description	Urban	Residential	Multi-Family: High Rise	Multi-Family: Low Rise	Single Family	Mobile Home Park	Commercial	Primary/Central Business District	Shopping Center/Mall	Strip Commercial	Secondary/Neighborhood Business	Institutional	Industrial	Industrial Park	Transportation	Air Transportation	Rail Transportation	Water Transportation	Road Transportation	Communications	Utilities	Extractive	Open Pit	Underground	Wells	
MIRIS	residential						commercial, services, and institutional						Industrial		Transit, communication, utilities								Extractive			
NLCD-MTRI Crosswalk	Developed, High Intensity	Developed, Medium Intensity	Developed, High Intensity	Developed, Medium Intensity	Developed, Low Intensity	Developed, Low Intensity	Developed, High Intensity						Developed, High Intensity		Developed, High Intensity								No Equivalent in NLCD			
SCS Runoff Crosswalk	res 1/8 acre	res 1/3 acre	res 1/8 acre	res 1/4 acre	res 1 acre	res 1/4 acre	Commercial						Industrial		paved	paved	paved	Industrial	paved	Industrial	Industrial	No Equivalent in SCS				

Class	6			7			8	9		10				11										
IDGS Code	19	193	194	2	21	29	22	23	24	3	31	32	33	4	41	42	411	412	413	414	421	422	423	429
IDGS Description	Open Land	Outdoor Recreation	Cemeteries	Agriculture	Cropland	Other Agriculture	Orchards	Confined Feeding	Permanent Pasture	Open Field	Herbaceous	Shrub	Prairie	Woodland	Deciduous	Coniferous	Northern Hardwood	Central Hardwood	Aspen/White Birch	Lowland Hardwood	Pine	Other Upland Conifer	Lowland Conifer	Christmas Tree Plantation
MIRIS	open and other				cropland, rotation, and permanent pasture	other agricultural land	orchards, vineyards, and ornamental	confined feeding operations	permanent pasture		herbaceous rangeland	shrub rangeland	pine or oak opening (savanna)	forest land	forest land	coniferous forest	Broadleaved forest				Coniferous forest		forest land	
NLCD-MTRI Crosswalk	Developed, Open Space			Cultivated Crops			Cultivated Crops	Hay/Pasture		Herbaceous		Shrub/Scrub	Herbaceous	Mixed Forest	Deciduous Forest	Evergreen Forest	Deciduous Forest				Evergreen Forest		Evergreen Forest	
SCS Runoff Crosswalk	open good: grass cover > 75% of area	open good: grass cover > 75% of area	open fair: grass cover 50-75% of area		Crop	Crop	Orchard	Industrial	Pasture	Meadow			Forest	Meadow	Forest									

Class	12					13					14				15			16	17
IDGS Code	5	51	52	53	54	6	61	611	612	624	62	621	622	623	7	72	73	74	999
IDGS Description	Water	Stream	Lake	Reservoir	Great Lakes	Wetland	Forested Wetland	Wooded Wetland	Shrub/Scrub Wetland	Submerged Aquatics	Nonforested Wetland	Aquatic Bed Wetland	Emergent Wetland	Flats Wetland	Barren	Beaches and Riverbanks	Sand Dune	Exposed Rock	Unidentified
MIRIS		streams and waterways	lakes	reservoirs	great lakes	wetlands		forested wetlands		wetlands		non-forested (non-wooded) wetlands			Barren	beaches and riverbanks	Sand other than beaches	bare exposed rock	
NLCD-MTRI Crosswalk	Open water					Woody Wetlands (NLCD includes Shrub Peatland and Treed Peatland from MTRI)	Forested Wetland (MTRI)	Woody Wetlands (NLCD includes Shrub Peatland and Treed Peatland from MTRI)	Wetland Shrub (MTRI)	Aquatic Bed (MTRI)	Wetland (MTRI)	Aquatic Bed (MTRI)	Emergent Herbaceous Wetlands (NLCD includes Typha and Phragmites from MTRI)	Open Peatland (MTRI)	Barren Land			Barren Land	Unclassified
SCS Runoff Crosswalk	Water					swamp veg				swamp w /water at least 1/3 is open	swamp w /water at least 1/3 is open			swamp veg	Fallow				

Appendix F: Flood Discharge Regression Equations Variable Development

Drainage Area Sq. Miles (DASQMI)

Description: The total drainage area contributing to the stream gage in *square miles*.

For the Regression inputs, total drainage areas were provided by EGLE from a geodatabase named 'USGS_Gages.gdb'. Future basins can be delineated using the previous methods, such as those based on topographic maps, or the new MITRI watershed delineation tool.

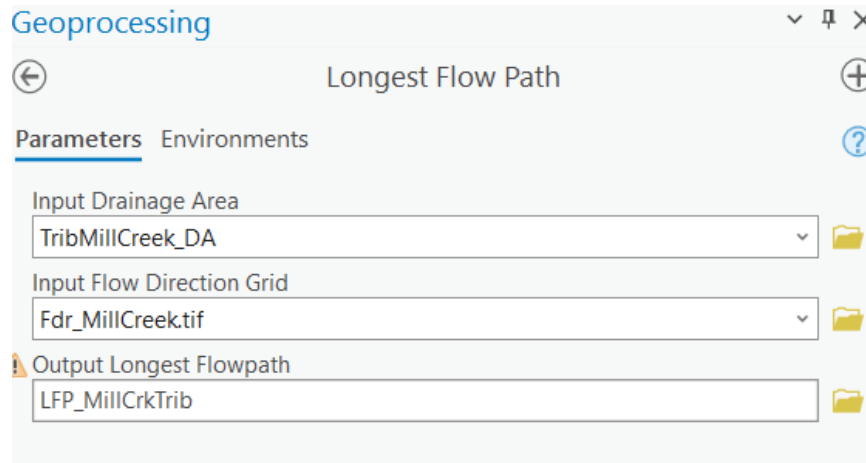
Longest Flow Path Slope (LFPSL)

Method reference: Ohio Regression Equations (Koltun et al., 2006)

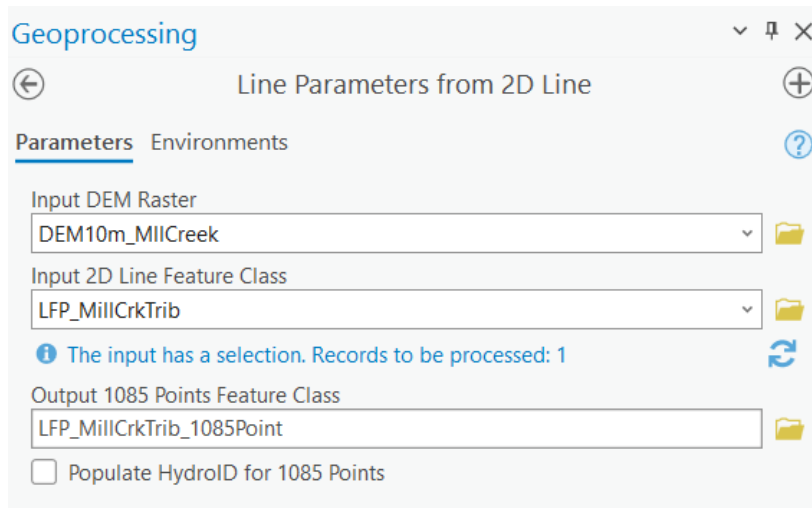
Description: The slope of the longest flow path defined by the longest flow path tool in ESRI ArcHydro using a 10-meter DEM. The slope is the elevation change divided by the length between points, 10 and 85 percent of the distance along the longest flow path in *feet per mile*.

Data:

- Watershed Boundary (contributing areas only)
 - 10-meter Digital Elevation Model (USGS, 2023)
-
- 1) Download and install the ArcHydro Toolbox (ESRI, n.d.) in the Catalog Tab
 - 2) Use 'Extract by Mask' to clip raster to watershed boundary
 - 3) Use the 'Fill' tool to fill sinks in the Watershed DEM
 - 4) Next, create a flow direction raster with the 'Flow Direction' tool
 - 5) Input the watershed boundary polygon and flow direction raster into the 'Longest Flow Path Tool.'
- If the watershed boundary feature contains multiple polygons including contributing and noncontributing areas, the tool will find a flow path for each polygon. Select the polyline for the contributing area.



- 6) Next, find the slope between the 10th and 85th percent of the longest flow path using the 'Line Parameters 2D line' tool using the original DEM and longest flow path line from step 5.



- 7) The Longest Flow path line attribute table is now updated and includes a column named 'slp1085FM,' which stands for slope between the 10th and 85th percentiles along the longest flow path in *feet per mile*.

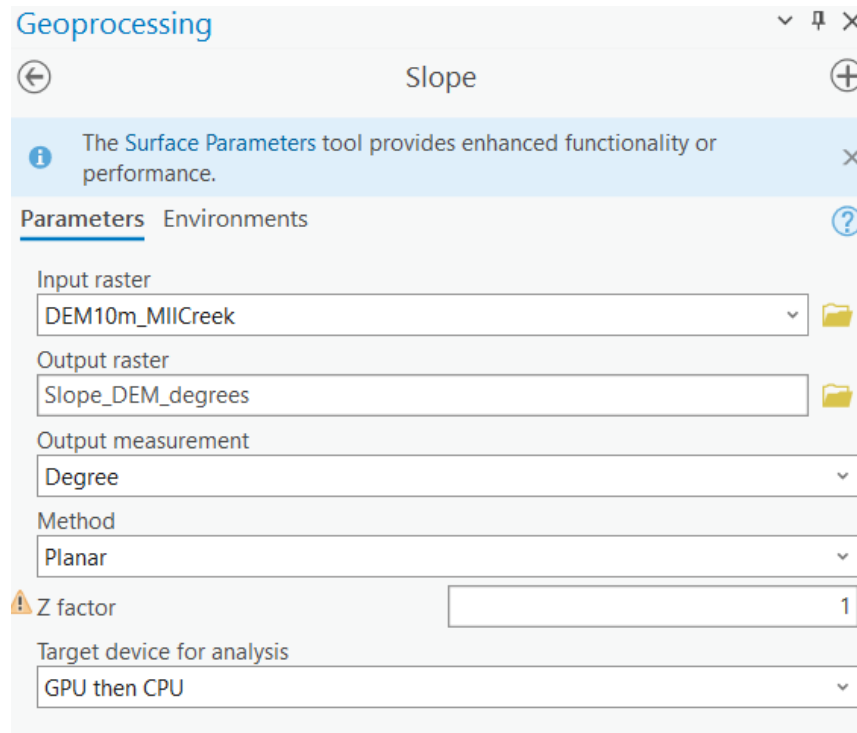
Watershed Slope (WS SLOPE)

Description: The mean basin slope computed using the ArcGIS Pro slope tool, measured in *degrees*.

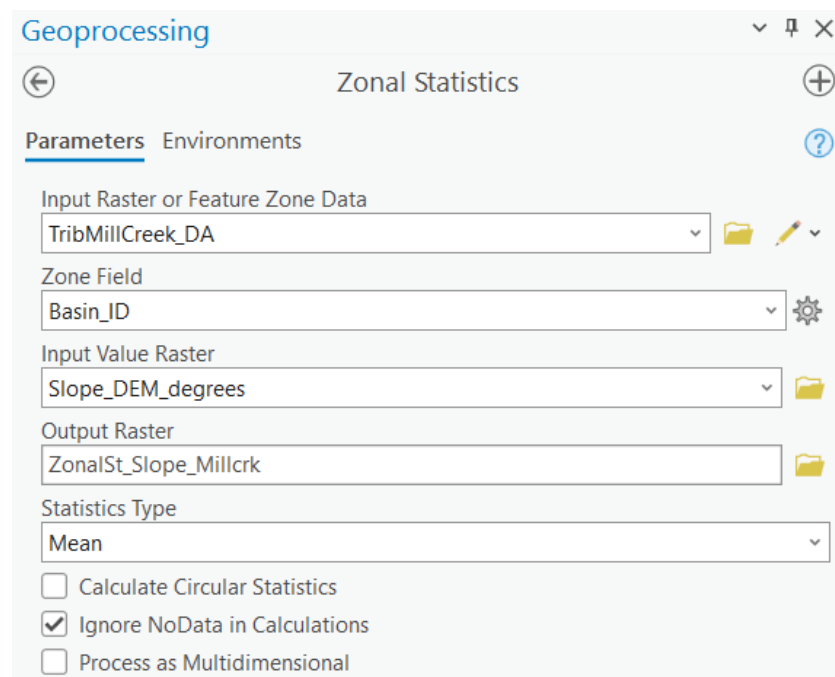
Data:

- 10-meter Digital Elevation Model (USGS, 2023)
- Watershed Boundary layer

- 1) Use 'Extract by Mask' to clip the raster to the watershed boundary.
- 2) Next, open the 'Slope' tool from the spatial analyst toolbox and input the watershed DEM, and set the output measurement to degrees:



- 3) Next, use the Zonal Statistics tool to find the mean watershed slope:



Circularity Ratio (CR)

Method reference: Ohio Regression Equations (Koltun, 2003)

Description: *Dimensionless* measurement of basin shape.

Data:

- Total Drainage Area (sq. miles) is denoted as $DA_{SQ.MILES}$.
- Perimeter of the Total Drainage Area (miles), denoted as $Perimeter$.

1) Calculate the circularity ratio (dimensionless):

$$CR = PERIMETER / \sqrt{(4\pi (DA_{SQ.MILES}))}$$

Slenderness Ratio (SLENRAT)

Description: The length of the longest flow path squared divided by the total drainage area, *dimensionless*.

Data:

- Longest Flow Path polyline (miles) is denoted as LFP_{MILES} in the equation below. This is the same polyline as used in calculating the Longest Flow Path Slope (LFP_SL_10_85_FM).
- Total Drainage Area (sq. miles) is denoted as $DA_{SQ.MILES}$.

1) Calculate the slenderness ratio (dimensionless):

$$SLENRAT = \frac{(LFP_{MILES})^2}{DA_{SQ.MILES}}$$

Mean Annual Snowfall (SNOW)

Description: The mean annual snowfall (*inches*) over a watershed.

Data:

- National Oceanic and Atmospheric Administration 30-year Climate Normals for 1991–2020 (Palecki et al., 2021).

- 1) Download station data from the NOAA National Centers for Environmental Information Datasets (Normals Annual/Seasonal, 1991-2020). Either a station search or interactive map tool (<https://www.ncei.noaa.gov/maps/normals/>) may be used to select stations.
- 2) Convert station-based snowfall data (point format) to a continuous raster surface using the Point to Raster tool in ArcGIS Pro.

- 3) Clip or align the snowfall raster to the watershed extent.
- 4) Apply zonal statistics as a table to compute the mean annual snowfall across raster cells within each watershed boundary.

24-hour Precipitation Indices: 24 hr,2 yr and 24hr,100 yr ($RAIN_{24,2}$, $RAIN_{24,100}$)

Description: The maximum 24-hour precipitation depths that occur on average once every 2 and 100 years in *inches*.

Data:

- NOAA Atlas 14 Rainfall Grids: 24hr,2 yr and 24hr, yr (NOAA, 2023)
- 1) Download the annual maximum series (AMS) frequency values for the Midwest or the Ohio River Basin NOAA Atlas 14 Rainfall frequency raster.
 - 2) Use the ‘Zonal statistics’ to calculate the mean rainfall depth for the watershed.

Saturated Hydraulic Conductivity (KSAT)

Method reference: Wisconsin Regression Equations (Walker et al., 2017)

Description: Measured in *micrometers per second*, it is the ease with which water can move through a porous medium.

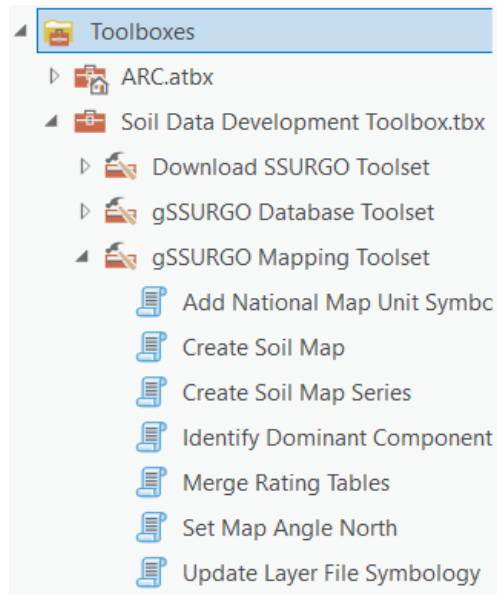
Data:

- Watershed Boundary (contributing areas only)
 - Saturated Hydraulic Conductivity 0 to 30 cm shapefile (KSAT_0to30_Midwest.shpfile) from SSURGO (Soil Survey Staff, 2020a)
- 1) Clip watershed boundary to the KSAT 0-30 shapefile.
 - 2) Use the ‘Zonal Statistics’ tool to find the mean KSAT value for the watershed.

Layer Development:

The SSURGO Soil Data Development Toolbox (Soil Survey Staff, 2020b) was used to create the KSAT_0to30_Midwest shapefile. The Toolbox has not been updated for use in ArcGIS Pro yet. ArcMap 10.3.x is required.

- 1) Access SSURGO Databases and Soil Data Development Toolbox (Soil Survey Staff, 2020b).
- 2) Download the toolbox and add it to your toolboxes in the Catalog tab.
- 3) In the Toolbox under the gSSURGO Mapping Toolset open the ‘Create Soil Map’ tool:



- 4) Input the county or state SSURGO geodatabase, 'Saturated Hydraulic Conductivity', set the depth top to 0 cm and bottom depth to 30 cm.
- 5) The output is a Saturated Hydraulic Conductivity (KSAT) shapefile with values in column 'SDV_KSAT_D' column.

Hydrologic Soil Groups (SOILA, SOILD)

Description: The *percentage* of the total drainage area of hydrologic soil units A and D. Dual hydrologic soil groups (A/D, B/D, C/D) need to be designated based on the land cover. Soils that occur on developed or agricultural land are classified as the first hydrologic soil group listed in the dual soil type (i.e., A, B, or C), consistent with drained conditions. If a dual-listed soil occurs on any other land cover type, the soil is classified as the hydrologic soil group with the highest runoff potential, Soil D, consistent with undrained conditions.

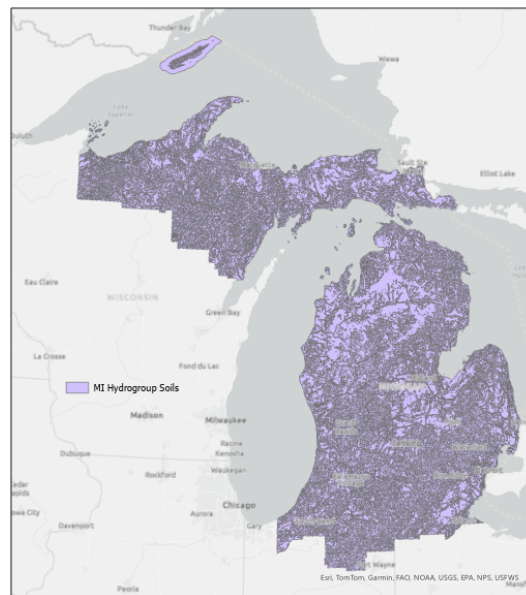
Data:

- Gridded Soil Survey Geographic (gSSURGO) Database (Soil Survey Staff, 2020a)
- Land Cover Raster from NLCD_MTRI 2021 Land Cover database (Bourgeau-Chavez et al., 2015; Dewitz, 2023)
- Land Cover Raster from National Land Cover Dataset 2021 (Dewitz, 2023)
- Watershed Boundary

Layer Development:

- 1) Obtain soils data from the Web Soil Survey (Soil Survey Staff, 2020a) for all Michigan counties and boundary counties in Wisconsin, Indiana, and Ohio.

- 2) Mosaic the NLCD 2021 raster to the NLCD_MTRI raster to cover surrounding states' counties. (The NLCD_MTRI 2021 raster covers the state of Michigan but does not extend to the surrounding states.) Following this step, this mosaiced raster is referred to as the land cover raster.
- 3) Using the soils data, assign an initial hydrologic soil group (HSG) raster as follows:
 - Value 1 = Class A
 - Value 2 = Class A/D
 - Value 3 = Class B
 - Value 4 = Class B/D
 - Value 5 = Class C
 - Value 6 = Class C/D
 - Value 7 = Class D
 - Value 8 = Water
- 4) Modify the 'Muaggatt.txt' table to 'Muaggatt_mod.txt'. This modification reclassifies NULL hydrologic soil group (HSG) values based on the description field. If the description field contains the string 'Urban' then the NULL value is reclassified as class 'D'; and if the description field contains the string 'water' then the NULL value is reclassified as class 'W'. Otherwise, the NULL value remains NULL.
- 5) The 'Muaggatt_mod.txt' table is joined to the corresponding county soil data. To save the join, the vector data is exported.
- 6) All joined, exported soil data is then merged into a statewide and boundary state counties soil data vector file.

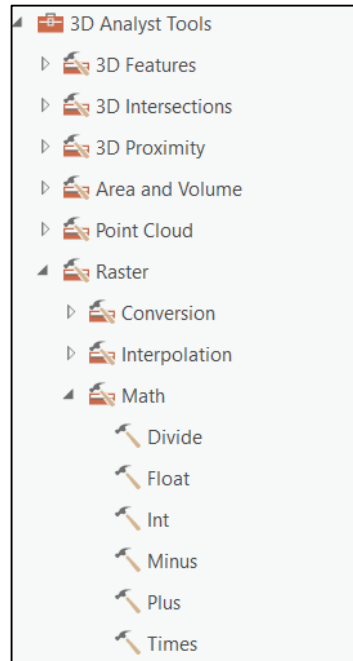


- 7) Transform the vector file into a HSG raster dataset using the 'Polygon to Raster' tool.

8) Classify the land cover raster into two classes:

- **DEVELOPED** = ‘Developed, Open Space’, ‘Developed, Low Intensity’, ‘Developed, Medium Intensity’, ‘Developed, High Intensity’, ‘Pasture/Hay’, and ‘Cultivated Crops’
- **OTHER** = All other land cover classes
- Assign value 9 to the ‘DEVELOPED’ class and value 10 to the ‘OTHER’ class.

9) Use the ‘Raster Calculator’ tool to multiply the HSG raster and land cover raster.



10) The output raster will contain multiples of 9 and 10:

		Developed	Undeveloped
	Value	9	10
A	1	9	10
A/D	2	18	20
B	3	27	30
B/D	4	36	40
C	5	45	50
C/D	6	54	60
D	7	63	70
W	8	72	80

11) Reclassify the output raster into four HSG groups (A-D) and Water (W), based on the following raster values:

Soil A = Values 9, 10, 18

Soil B = Values 27, 30, 36
 Soil C = Values 45, 50, 54
 Soil D = Values 20, 40, 60, 63, 70
 Water = 72, 80

Hydrologic Soil Group	Final Classification Value	Raster Math Values	Original Raster Value
A		1 9, 10, 18	1
B		2 27, 30, 36	3
C		3 45, 50, 54	5
D		4 20, 40, 60, 63, 70	7
W		5 72, 80	8

12) Sum the 'COUNTS' column in the attribute table.

13) Divide the sum by each category to determine the percentage of HSG category for the watershed.

Channel Swamp (CHSWAMP)

Description: The *percentage* of the longest flow path that passes through swamp, lake, or pond polygons of the National Wetlands Inventory (NWI) dataset.

Data:

- NWI USFWS Polygon Data - Version 2 (USFWS, 2024)
- Longest Flow Path Polyline (from procedure for Longest Flow Path Slope)

1) Start by selecting polygons that intersect the longest flow path line

Select By Location

Input Features

MI_Wetlands

The input has a selection. Records to be processed: 17

Relationship

Intersect

Selecting Features

LFP_MillCrkTrib

Search Distance

Meters

Selection Type

New selection

☐ Invert Spatial Relationship

- 2) Next, use the ‘Intersect’ tool to identify which line segments of the longest flow path intersect the NWI polygons.
- 3) Open the attribute table of your new intersected layer, select all rows that have a ‘riverine’ wetland type and remove them from the table.

Id: Add Calculate Selection: Select By Attributes Zoom To Switch Clear Delete						
OBJECTID *	Shape *	FID_MI_Wetlands	ATTRIBUTE	WETLAND_TY	ACRES	Shape_Len
3	Polyline	348322	PEM1B	Freshwater Emergent W...	1.968263	403.4737
4	Polyline	348349	PEM1B	Freshwater Emergent W...	33.989465	2342.2307
5	Polyline	348529	PEM1C	Freshwater Emergent W...	0.799356	221.482
6	Polyline	348572	PEM1C	Freshwater Emergent W...	3.297453	480.6465
7	Polyline	348968	PFO1/SS1C	Freshwater Forested/Sh...	16.448848	1699.9476
8	Polyline	349081	PFO1B	Freshwater Forested/Sh...	64.522993	3216.5036
9	Polyline	349173	PFO1C	Freshwater Forested/Sh...	3.159532	563.0655
10	Polyline	349387	PSS1/EM1C	Freshwater Forested/Sh...	62.429048	3627.2681
11	Polyline	349390	PSS1/EM1C	Freshwater Forested/Sh...	5.673719	640.3227
12	Polyline	349502	PSS1B	Freshwater Forested/Sh...	5.289744	724.2680
17	Polyline	349542	PSS1C	Freshwater Forested/Sh...	1.270071	293.8815
13	Polyline	350222	R5UBFx	Riverine	1.202711	2441.1172
14	Polyline	350236	R5UBFx	Riverine	3.806627	7709.4854
15	Polyline	350262	R5UBFx	Riverine	1.270324	2580.8788
16	Polyline	350265	R5UBFx	Riverine	0.639115	1301.3705

- 4) Select the ‘Length_MI’ column, right-click, and choose the ‘Calculate Geometry’. Update the column by selecting ‘Length’ and ‘Miles’.
- 5) Sum the ‘Length_MI’ column and divide by the entire longest flow path length to calculate the percentage of the longest flow path that is wetland.

Land-Use Categories

Description: The *percentage* of the total drainage area covered by various land use categories. Land use categories used in this study include forest (FOREST), wetland (WETLAND), developed land (DEV), cultivated crops and hay (CRPHAY), herbaceous upland (HERB), and open water (WATER).

Data:

- Land Cover Raster (NLCD_MTRI 2021, mosaiced with NLCD 2021 for interstate watersheds)
- Watershed Boundary Layer

- 1) Extract by mask to the watershed boundary.
- 2) Reclassify NLCD_MTRI 2021 raster as follows:
CRPHAY = ‘Hay or Pasture’, ‘Cultivated Crops’

- Values 23, 24
- DEV** = ‘Developed Open Space’, ‘Developed Low Intensity’, ‘Developed Medium Intensity’, and ‘Developed High Intensity’
- Values 13, 14, 15, 16
- HERB** = ‘Herbaceous’
- Values 22
- WATER** = ‘Open Water’
- Value 12
- FOREST** = ‘Deciduous Forest’, ‘Evergreen Forest’, ‘Mixed Forest’
- Values 18, 19, 20
- WETLAND** = ‘Aquatic Bed’, ‘Wetland’, ‘Schoenoplectus’, ‘Open Peatland’, ‘Forested Wetland’, ‘Shrub Peatland’, ‘Typha/Phragmites’
- Values 2, 3, 4, 7, 10, 11, 25, 26

2	8067861	Aquatic Bed_MTRI
3	18516798	Wetland_MTRI
4	2	Schoenoplectus_MTRI
7	3942047	Open Peatland_MTRI
10	67879039	Wetland Shrub_MTRI
11	117883481	Forested Wetland_MTRI
12	299003093	Open Water_NLCD
13	38194407	Developed Open Space...
14	31886388	Developed Low Intensit...
15	18913016	Developed Medium Int...
16	7419837	Developed High Intensi...
17	2964008	Barren Land_NLCD
18	180880795	Deciduous Forest_NLCD
19	32777755	Evergreen Forest_NLCD
20	49332478	Mixed Forest_NLCD
21	9875022	Shrub Scrub_NLCD
22	21078043	Herbaceous_NLCD
23	27182897	Hay or Pasture_NLCD
24	210757224	Cultivated Crops_NLCD
25	88293159	Shrub Peatland_MTRI/Tr...
26	10867625	Typha_MTRI/Phragmite...

- 3) For areas of interstate watersheds in Ohio, Indiana, or Wisconsin, reclassify NLCD 2021 raster as follows:

- CRPHAY** = ‘Pasture/Hay’, ‘Cultivated Crops’
- Values beginning with 8

DEV = ‘Developed, Open Space’, ‘Developed, Low Intensity’, ‘Developed, Medium Intensity’, and ‘Developed, High Intensity’

- Values 21, 22, 23, 24

HERB = ‘Grassland/Herbaceous’, ‘Sedge/Herbaceous’

- Values 71, 72

WATER = ‘Open Water’

- Value 11

FOREST = ‘Deciduous Forest’, ‘Evergreen Forest’, ‘Mixed Forest’

- Values beginning with 4

WETLAND = ‘Emergent Herbaceous Wetlands’ and ‘Woody Wetlands’

- Values beginning in 9

NLCD Land Cover Classification Legend

- 11 Open Water
- 12 Perennial Ice/ Snow
- 21 Developed, Open Space
- 22 Developed, Low Intensity
- 23 Developed, Medium Intensity
- 24 Developed, High Intensity
- 31 Barren Land (Rock/Sand/Clay)
- 41 Deciduous Forest
- 42 Evergreen Forest
- 43 Mixed Forest
- 51 Dwarf Scrub*
- 52 Shrub/Scrub
- 71 Grassland/Herbaceous
- 72 Sedge/Herbaceous*
- 73 Lichens*
- 74 Moss*
- 81 Pasture/Hay
- 82 Cultivated Crops
- 90 Woody Wetlands
- 95 Emergent Herbaceous Wetlands

* Alaska only

Geoprocessing

Reclassify

Parameters Environments

Input raster: NLCD21_MillCrk

Reclass field: Value

Reclassification

Value	New
23	2
24	2
41	4
42	4
43	4
71	7
81	8
82	8
90	9
95	9
NODATA	NODATA

Classify Unique

Output raster: Reclass_NLCD1

☐ Change missing values to NoData

4) Sum the ‘COUNTS’ column in the attribute table.

5) Divide the sum by each ‘COUNT’ for the *percentage* of land cover per class for the watershed.

REFERENCES

- Bourgeau-Chavez, L., Endres, S., Battaglia, M., Miller, M. E., Banda, E., Laubach, Z., Higman, P., Chow-Fraser, P., and Marcaccio, J., 2015, Development of a Bi-National Great Lakes Coastal Wetland and Land Use Map Using Three-Season PALSAR and Landsat Imagery. *Remote Sensing*, 7(7), 8655-8682, <https://doi.org/10.3390/rs70708655>.
- Dewitz, J., 2023, National Land Cover Database (NLCD) 2021 Products: U.S. Geological Survey data release, <https://doi.org/10.5066/P9JZ7AO3>. Available online at <https://www.mrlc.gov/data/type/land-cover>.
- ESRI, n.d., Arc Hydro GIS for Water Resources, <https://www.esri.com/en-us/industries/water-resources/arc-hydro>.
- Koltun, G.F., 2003, Techniques for estimating flood-peak discharges of rural, unregulated streams in Ohio: U.S. Geological Survey Water-Resources Investigations Report 2003–4164, 75 p., <https://pubs.er.usgs.gov/publication/wri034164>.
- Koltun, G.F., Kula, S.P., and Puskas, B.M., 2006, A Streamflow Statistics (StreamStats) web application for Ohio: U.S. Geological Survey Scientific Investigations Report 2006–5312, 62 p., <https://doi.org/10.3133/sir20065312>.
- National Oceanic and Atmospheric Administration (NOAA), 2023, NOAA Atlas 14 Precipitation Frequency Estimates, GIS Format (Volume 2: Ohio River Basin). Precipitation Frequency Data Server (PFDS). https://hdsc.nws.noaa.gov/pfds/pfds_gis.html
- Soil Survey Staff, 2020a, Gridded Soil Survey Geographic (gSSURGO) Database for Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service. Available online at <https://websoilsurvey.nrcs.usda.gov/app/> (Version 2.4, August 2020).
- Palecki, M., Durre, I., Applequist, S., Arguez, A. and Lawrimore, J., 2021, U.S. Climate Normals Data (1991-2020): Annual Snowfall. NOAA National Centers for Environmental Information. Available online at <https://www.ncei.noaa.gov/maps/normals/>.
- Soil Survey Staff, 2020b, Soil Data Development Toolbox, United States Department of Agriculture, Natural Resources Conservation Service. Available online at <https://www.nrcs.usda.gov/resources/data-and-reports/gridded-soil-survey-geographic-gssurgo-database>.
- U.S. Fish and Wildlife Service, 2024, National Wetlands Inventory (digital data). U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C. Available online at: <https://www.fws.gov/program/national-wetlands-inventory/wetlands-data>.
- U.S. Geological Survey, 2023, 3D Elevation Program 10-Meter Resolution Digital Elevation Model. U.S. Geological Survey. Available online at <https://apps.nationalmap.gov/downloader/>.

Walker, J., Peppler, M., Danz, M.E., and Hubbard, L., 2017, Flood-frequency characteristics of Wisconsin streams: U.S. Geological Survey Scientific Investigations Report 2016-5140, <https://doi.org/10.3133/sir20165140>.