2014

Digital Terrain Analysis Manual

Zumbro River Watershed

Restoration Prioritization

BARR

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<u>Abbreviations and Symbols</u>

BMP	Best Management Practice
CP	Conservation Practice
CPI	Crop Productivity Index
CSA	Critical Source Area
CTI	Compound Topographic Index
DEM	Digital Elevation Model
DTA	Digital Terrain Analysis
ESRI	Environmental Systems Research Institute
GIS	Geographic Information System
GPS	Global Positioning System
HUC	Hydrologic Unit Code
LiDAR	Light Detection and Ranging
NPS	Non-Point Source (pollution)
NRCS	National Resource Conservation Service
PMZ	Priority Management Zone
SDP	Sediment Delivery Potential
SPI	Stream Power Index
SSURGO	Soil Survey Geographic Database
TA	Terrain Analysis
TMDL	Total Maximum Daily Load
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation
Z	Elevation

Manual Overview

This document provides digital terrain analysis methods and procedures for creating Critical Source Area (CSA) predictions in association with the Zumbro River Watershed Restoration Prioritization and Sediment Reduction project. It is to be used in conjunction with the Field Assessment and Sensitive Site Identification Guidance manuals. Digital terrain analysis is the preferred method for locating CSA's due to its efficiency and high-quality, readily accessible input data. It has been the focus of several recent studies in Minnesota with overall accuracies ranging from 78-88% (see Appendix section A.1 for details). The project is seeking to determine the feasibility of using existing LiDAR and other GIS data to identify and rank a list of CSAs throughout the Zumbro River Watershed. The top 50 ranked sites from the list will then be targeted for Best Management Practice (BMPs) implementation planning for their more significant, larger-scale, water-quality benefits. For this project, GIS software is used to perform a terrain analysis, which employs elevation data to characterize the physical features of the landscape. Terrain analysis can be used to identify locations with a high potential for erosion and pollutant runoff. These identified source areas can then be assessed for further evaluation. Additional spatial analyses can also be incorporated, including source proximity to a water body and soil erosion risk factors. Terrain analysis and other spatial analyses do not eliminate the need for field assessments. However, they can reduce the amount of time spent in the field and enhance data collection efforts by enabling technicians to select potentially sensitive sites.

It is important to note that many of the sites identified as sensitive by the GIS analysis will already have appropriate management and operation. Thus, these tools also provide an important opportunity to recognize producer accomplishments and track program progress necessary for supporting basin management and Total Maximum Daily Load efforts.

<u>Digital Terrain Analysis Technical Manual</u>

Zumbro River Watershed Restoration Prioritization & Sediment Reduction Project

2014

Digital Terrain Analysis Manual

Overview

This manual requires the use of Esri's ArcGIS computer software with Spatial Analyst extension installed. The basic version (ArcView license) is sufficient for the methods described in this manual. This manual is also designed to accommodate users of either ArcGIS versions 9.0 to 9.3.1 or 10.0 to 10.2 – the former will be referred to as 9.x and later as 10.x from here on. Other GIS-based software programs that are able to process large raster datasets and calculate logical map algebra should work for terrain analysis processing but will not be covered in this manual.

The terrain analysis process involves combining primary attributes to form secondary attributes. The core primary attributes used for this terrain analysis include flow direction, flow accumulation, and slope. Secondary attributes include Stream Power Index (SPI) and Compound Topographic Index (CTI).

SPI is calculated as the product of the natural log of both slope and flow accumulation. High SPI values displayed in GIS represent areas on the landscape where high slopes and flow accumulations exist and thus areas where flows can concentrate with erosive potential. For this reason, SPI is very useful for determining potential Critical Source Area (CSA) locations. CTI is the quotient of both slope and flow accumulation. It can show areas on a landscape that pond and store water, and is therefore useful for locating potential wetland locations. The plan and profile curvature terrain attributes are also used primarily to identify upland sinkhole locations, and to aid in ravine identification (see appendix section A.3).

Procedure

The digital terrain analysis core processes can be visualized using the following flow chart (fig. 1).
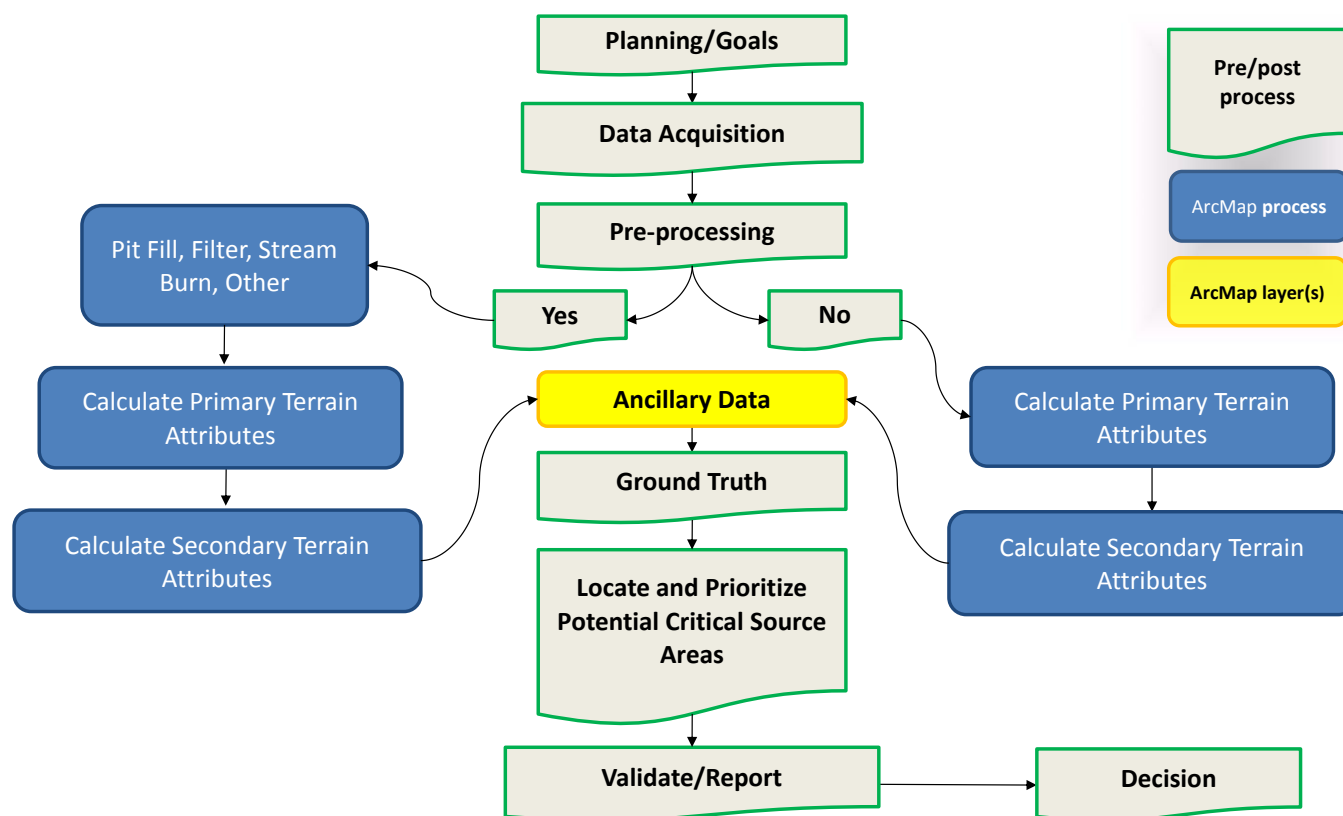
Figure 1. Digital terrain analysis flow chart

Digital terrain analysis begins with a planning process where project goals are established and an appropriate scale for assessment is defined. The spatial scale will determine the amount of data acquisition necessary to address project goals. The attributes created may or may not require pre-processing. This again is at the discretion of the project goals. The attributes are either primary or secondary in nature, depending on whether they derive directly from elevation data or a secondary product. The attributes, when combined with relevant ancillary data, should provide enough information to locate and prioritize potential Critical Source Areas (CSAs). Ground truthing is an important step necessary to relate mapping to planned goals. The objective of ground truthing is to determine best-fit threshold values for a given Area of Interest (AOI) by comparing digital terrain attributes to real-world conditions. When thresholds have been established, CSAs can then be located and prioritized using a combination of primary attributes, secondary attributes, and ancillary data. CSA validation is used to determine accuracy of predictions and reveal the existence of commission and omission errors. This step is fundamental to the user learning process since locating potential CSAs digitally is an adaptive process and validation provides opportunities to improve visualization and prediction techniques. Evaluation of site conditions should accompany field validation. The Field Assessment and Sensitive Site Identification Guidance manuals were developed to assist in site evaluations, and to direct efforts and track results when visiting priority sites in the field. The final step is to make decisions regarding how to address field-verified CSAs. This may involve contacting and working with land owners, determining which BMPs are most suited for the agroecoregion, and/or securing conservation practice funds for BMP implementation, among others.

Data acquisition

For the initial primary attribute calculations, only a raster DEM is required, but ancillary data will be necessary to create CSA predictions – most of which are available at the Minnesota 'data deli' website: http://deli.dnr.state.mn.us/

- Digital Elevation Model (DEM) – A Digital Elevation Model contains one elevation value (as measured above Mean Sea Level) in each pixel, or cell, of data. Ideally, LiDAR elevation data should be used in terrain analysis for its high spatial resolution and accuracy characteristics. LiDAR data are available for the entire State of Minnesota, downloadable at the county level from either of the two links below:
  ftp://ftp.lmic.state.mn.us/pub/data/elevation/lidar/
  ftp://lidar.dnr.state.mn.us/
  LiDAR data from the above sources provide DEM's in both 1 and 3 meter resolutions. Digital terrain analyses are best processed using a 3 meter DEM to minimize processing times and file sizes while maintaining a high level of elevation detail (Galzki, et al., 2011).
  - *Note:* When downloading LiDAR data, an ftp client such as FileZilla should be used due to large file sizes associated with LiDAR geodatabases. LiDAR datasets for some counties exceed 5 gigabytes and can be computationally inefficient to acquire and process. In some cases, it may be necessary to use lower resolution DEM data. 30m DEM data is still readily available throughout the state, though it should be noted that this will considerably reduce the ability to accurately predict CSA locations (Srinivasan et al., 2009).
- Surface waters – Current stream data containing both perennial and intermittent networks along with lake/wetland layers will be necessary to determine hydrologic connection to secondary attributes.
- Watershed catchments – Watershed data at various spatial scales. These are typically ordered from the number of digits in a hydrologic unit code (HUC) – from 2 digits representing regional watersheds to 12 digits representing subwatersheds. These layers are also convenient for use as an output extent when creating a clipped raster subset (see DEM clipping in Pre-process section).
- Cities and political boundaries – Political boundary and populated area data can be useful for spatial orientation, locating areas of interest, and improving map presentation.
- Land cover/land use – The most current National Land Cover Database (NLCD) raster layer.
- Environmental Benefits Index – The EBI layer integrates soil erosion risk, water quality risk and habitat quality factors to determine the relative conservation value of a parcel of land. It can be useful for locating regions with high erosion risk. The Soil Erosion Risk portion of the EBI can also be used alone to aid with CSA placement. The EBI and its individual layers are available at a 30m resolution for most of the State of Minnesota here:
  http://www.bwsr.state.mn.us/ecological_ranking/
- NRCS GIS Engineering tools – The freeware python-based toolset is compatible with ArcGIS 9.3 and 10.x, allowing for seamless integration and familiar, user friendly interfaces identical to default ArcGIS Arctools. The NRCS tools include processes for hydro-conditioning, watershed delineation, conservation planning and more. Direct download link:
  ftp://ftp.lmic.state.mn.us/pub/data/elevation/lidar/tools/NRCS_engineering/NRCS_GIS_ENGINEERING_TOOLS_ver1.1.7.zip

- <u>High resolution aerial orthophotos</u> – Orthorectified and georeferenced photos should be used to ensure correct alignment with surface features. Color or Color Infrared (CIR) photos with at least 5 meter resolution are preferred with leaf-off photos (spring or fall) being ideal. Recently acquired FSA National Aerial Imagery Program (NAIP) digital photos from Spring, Summer, and Fall throughout Minnesota are readily available at:
  http://www.mngeo.state.mn.us/chouse/airphoto/
  ArcGIS software users can connect the MNGEO's web map service though a GIS server. This will negate the need to download any photos. Instructions for connection are here:
  http://www.mngeo.state.mn.us/chouse/wms/how_to_use_wms.html
  1. Open ArcMap and click on 'Add Data'
  2. Look in the Catalog, and click on 'GIS Servers'
  3. Highlight 'Add WMS Server' so that it appears in the Name window, and hit 'Add'. An 'Add WMS Server' window will pop up.
  4. To bring up the Imagery server, type '**http://geoint.lmic.state.mn.us/cgi-bin/wms?**'(without quotes) in the URL window. You can click on the 'Layers' button to see a list of the layers available under the wms. Click 'OK'.
  5. To bring up the Scanned DRG server, type '**http://geoint.lmic.state.mn.us/cgi-bin/wmsz?**' (without quotes) in the URL window. You can hit the 'Get Layers' button to see a list of the layers available under the wms. Click 'OK'.
  6. Now when you look under 'GIS Servers' you have two new entries: 'LMIC WMS server (aerial photography) on geoint.lmic.state.mn.us' and 'LMIC WMS server (quad sheet drgs) on geoint.lmic.state.mn.us'
  7. Still in the 'Add Data' window under 'GIS Servers', highlight one of the services listed under #6 to bring it into the 'Name' window, then click on 'Add'. The service, with all of its layers, has now been added to your ArcMap project.
- <u>Other</u> – Other useful information could range from regional data such as soils (SSURGO data) and Crop Productivity Indices (CPI); feedlots, culverts, and point source locations to field specific information such as individual landowner nutrient application rates, existing conservation practice locations, artificial drainage placement, etc.

Pre-process DEM

Digital Elevation Models can benefit from pre-processing before terrain analysis is conducted. The amount of pre-processing required may depend on the user's local knowledge of their Area of Interest (AOI) and its characteristics, and the resolution and quality of the original DEM. A semi-automated utility for both creating AOIs and hydrologically conditioning DEMs will be presented here. Alternatively, advanced GIS users may find it advantageous to create their own Python scripts and/or ModelBuilder flow paths within ArcGIS to semi-automate pre-process and terrain attribute calculations to decrease processing times and ensure consistent outputs.

- Activate Spatial Analyst Extension
  This initial step is necessary for certain Arctool processes to run. ArcGIS will remember your selection and automatically activate selected extensions every time the program is run.

  1. From the **Tools** menu (ArcMap 9.x) or **Customize** menu (10.x), select **Extensions…** and check-on the **Spatial Analyst** extension.
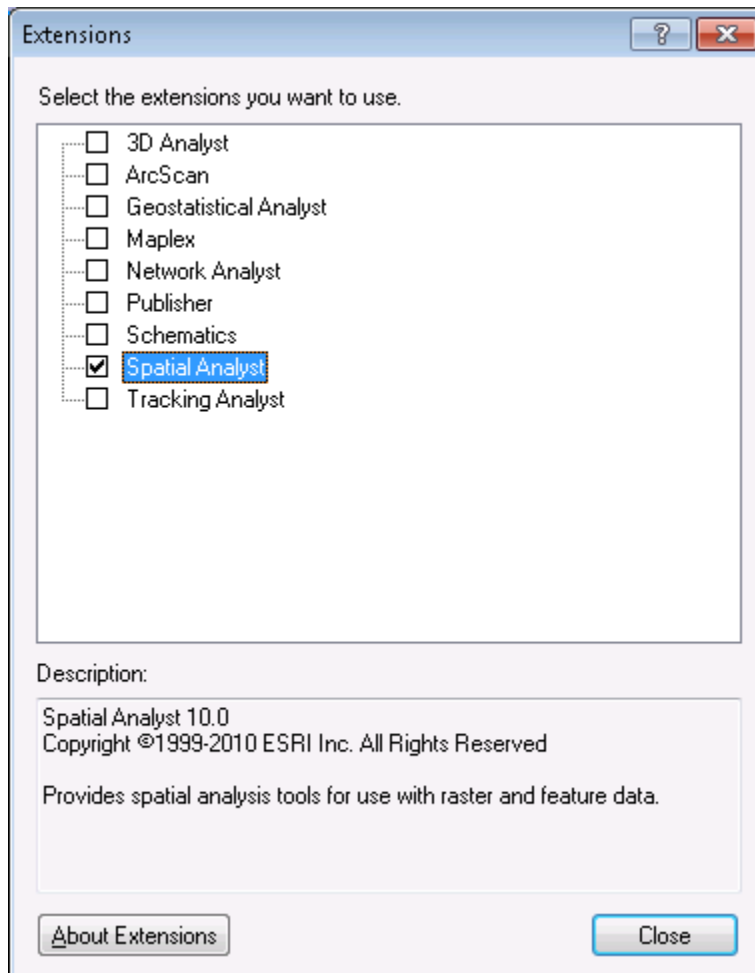
  2. Click Close.

- Hydrologic Conditioning

Hydrologic conditioning (HC) is the process of modifying a DEM to change flow routing and drainage. The most common practice of HC is to remove "digital dams" that block the hypothetical flow of water typically associated with road crossings and other obstructions. One method of removing digital dams is to "burn" the stream through the obstruction to force flow downstream.

HC can be a time consuming process, thus it is important to consider whether your project goals would benefit from the operation, and if so, how much correction is needed and at what scale. For instance, some projects may only warrant burning the largest culverts along high order streams while others may require burning tile lines at the field scale.

Some points to consider:

o   HC will only change terrain analysis attributes in close proximity to the digital dams removed.

o   HC is most useful when combined with pit filling – if pit filling is not necessary or suitable in your AOI, HC will provide minimal terrain analysis benefits. However, if pit filling is to be used, hydro-conditioned DEMs will tend to produce more accurate terrain attributes within filled depressions. For instance, when filling all sinks in a DEM, HC can improve flow routing by unblocking large depression areas that would otherwise fill with hypothetical water to force flow over obstructions. The Stream Power Index signatures in those unblocked depressions will be more representative of actual overland flow when sinks have been filled.

The left image shows an example of how water ponds (in blue) behind road crossings when using a non-conditioned DEM. There are culverts present at both crossings (circled in yellow), though the DEM does not recognize culverts and sees the road as an obstruction – known as a digital dam. Ideally all DEM's used for SPI creation should be hydrologically corrected, though the process can be time consuming and small culverts may not show up in aerial photography making field verification necessary.

ArcGIS includes tools that can be used to hydrologically condition DEMs, such as **Topo to Raster** (Vaughn 2012). Several 2nd party applications also exist with HC capabilities. The NRCS GIS Engineering toolset introduced in the Data Acquisition section is one such utility recommended for its ability to burn streams through a semi-automated process of digitizing culverts. The user must input culverts either by importing a polyline shapefile or by manually digitizing their locations.

See the Data Acquisition section for the NRCS tools zip file download link. Once the file is downloaded to your computer, follow the readme instructions to install the software:

```
[from the version1.1.7_ReadMe.txt]


Installing the tools:
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No special or admin privileges are required, simply unzip the zip file
to a local directory.
An "NRCS_GIS_ENGINEERING_TOOLS" folder will be created in specified
location. Within the NRCS_GIS_ENGINEERING_TOOLS folder there will be
an "NRCS Engineering Tools.tbx" toolbox file and a "SUPPORT" folder.
The support folder contains the necessary scripts, files, and
symbology layers, and must always reside in the same directory as the
toolbox.


Adding to ArcMAP:
-----------------
Enable the ArcToolbox window (if necessary), right click, and select
"Add Toolbox".
Browse to the location where the files were unzipped, then the
"NRCS_GIS_ENGINEERING_TOOLS" Folder within, and click once to select
or highlight the NRCS Engineering Tools Toolbox, then click the "Open"
button in the bottom right hand corner of the dialog box.


ArcMap Settings:
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Make sure that the Spatial and 3D Analyst extensions are enabled by
going to the Customize > Extensions Menu (ArcGIS10) or the Tools >
Extensions Menu (ArcGIS 9.3). 9.3 Users should also go to the Tools >
Options Menu, click on the Geoprocessing Tab, and make sure that both
"Overwrite the outputs of Geoprocessing Operations" and "Add Results
of geoprocessing operations" options are selected. "Results are
temporary by default" should also be UN-CHECKED.
---------------
END
```

When properly setup in ArcMap, the NRCS tools should resemble the following image in your ArcToolbox:

The following section will guide users on area of interst and hydrologic conditioning DEM pre-processing using the NRCS GIS Engineering Tools. For manual AOI raster clipping, see Appendix section A.2.

1. Launch **ArcToolbox** by clicking the toolbar icon   (9.x) or **ArcToolbox** in the **Geoprocessing** menu (10.x).
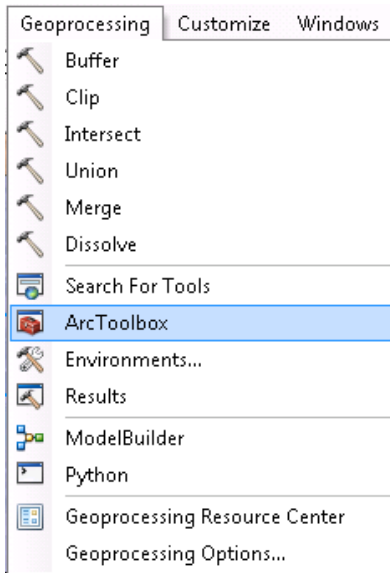
2. Expand the **NRCS Engineering Tools**, then expand the **Watershed Tools** toolset, followed by the **Watershed Delineation** toolset. Double-click the **Define Area of Interest** tool to start it. Minnesota LiDAR data acquired at the county level can contain very large file sizes. It is therefore important to minimize the spatial area to be processed to reduce output files sizes and increase processing times. The **Define Area of Interest** tool creates a subset of a raster dataset and will be used for this purpose.

   *Note:* There are several additional ways to find this (or any) tool in ArcToolBox:
   o Select the **Index** tab at the bottom of ArcToolbox and scroll through the list to find **Clip** (Data Management) (9.x).
   o Select the **Search** tab at the bottom and type in 'fill' to find any tools with fill in their titles (9.x).
   o From the **Geoprocessing** menu, choose **Search For Tools** (10.x).
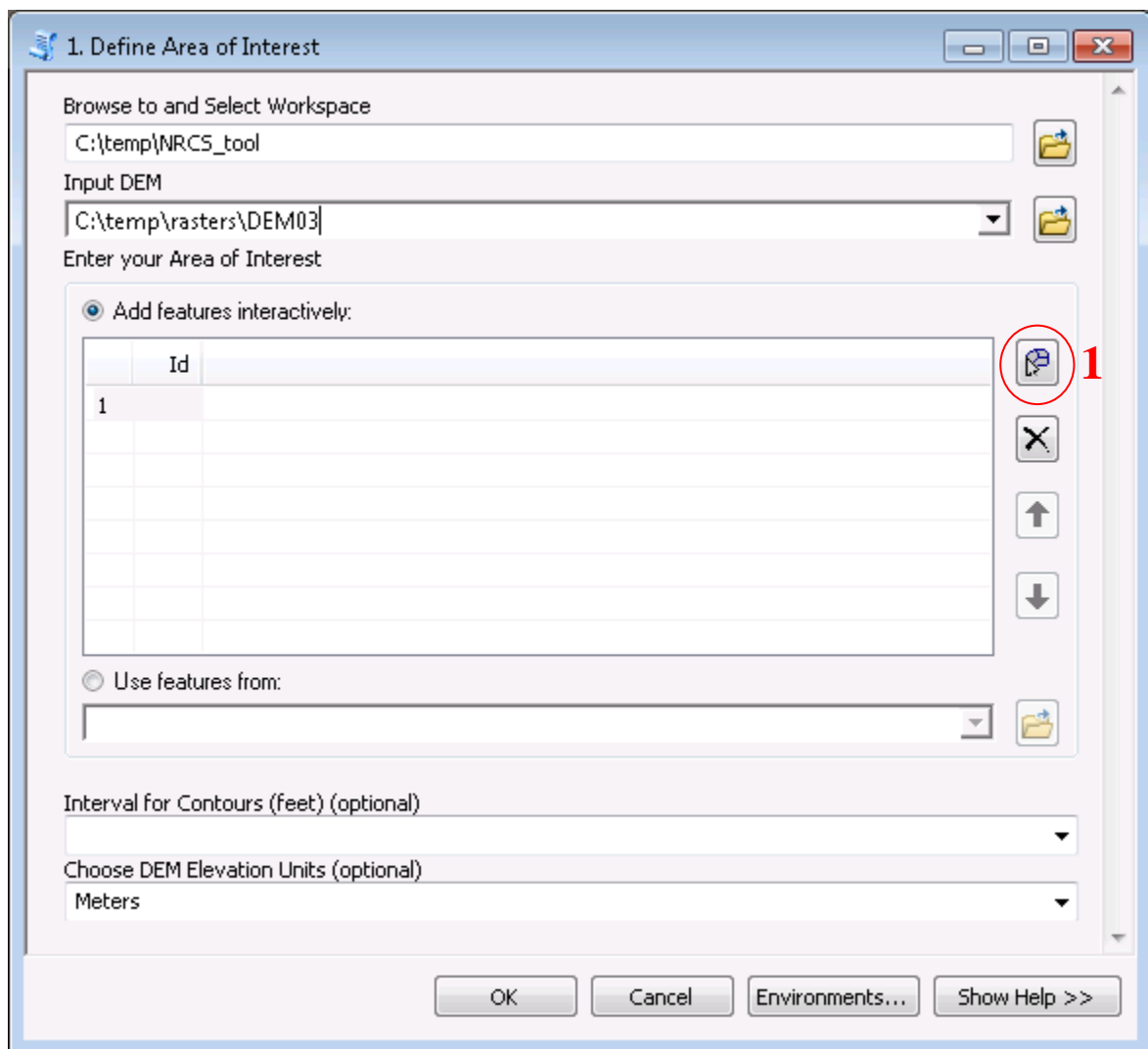
3. **Browse to and Select Workspace:** Choose your workspace folder where outputs will be stored. Select a destination directory without spaces and choose a name for the folder based on your project or area of interest

4. **Input DEM:** Your DEM, preferably a 3m LiDAR elevation dataset.

5. **Enter your Area of Interest:** Click the **Add feature** icon (#1 circled red in above image), then minimize the **Define Area of interest** window. The cursor should be a cross icon. The add feature tool works as a polygon editor, with each click creating a new vertex. The sketch is finished by double clicking to connect the first and last sketch vertices. Optionally, the **Use features from** field can be used with a compatible raster or vector file fitting you AOI

6. **Interval for Contours (feet) (optional):** Select desired contour foot contours. If left blank, no contours will be created

7. **Choose DEM Elevation Units (optional):** User preference

8. Click OK to run tool script. Several new layers will be added to your map

1. Open **NRCS Engineering Tools > Watershed Tools > Watershed Delineation > Create Stream Network**
   The **Create Stream Network** tool serves multiple purposes: it creates a stream network, it is used to burn culvert locations, and it creates a hydro-conditioned DEM all within the AOI established in the previous **Define Area of Interest** tool.
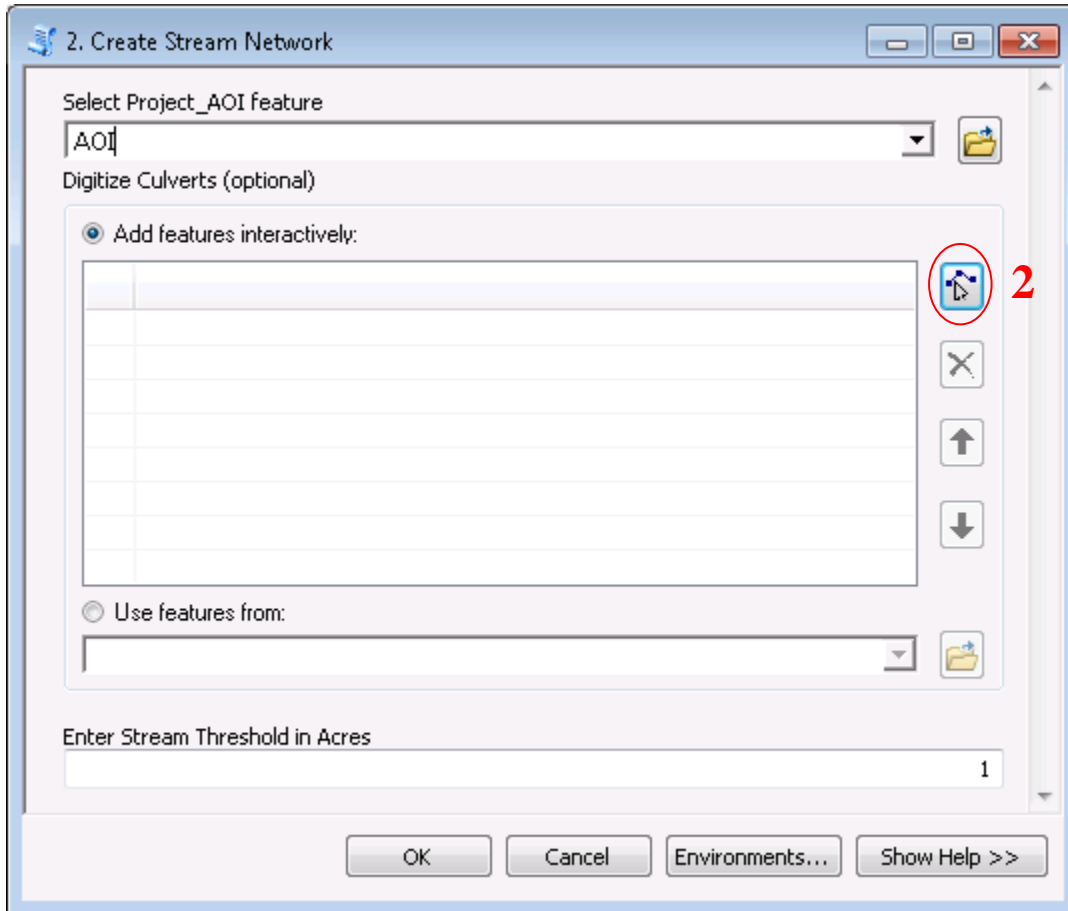
2. **Select Project_AOI feature:** Select the AOI that was created by the previous **Define Area of Interest** tool

3. **Digitize Culverts (optional):** Click the Add feature icon (#2 circled in red above) then minimize the current window. The add feature function works as a line sketch tool. Use the function to make a line that represents a culvert at any obvious or known locations where a culvert exists. The **DephthGrid** layer created by the previous tool **Define Area of Interest** can aid in showing where water backs up at impoundments such as road crossings (following figure). Culverts are likely to exist at these locations. Create as many digitized culverts as necessary to ensure an accurate stream network representation

4. **Enter Stream Threshold in Acres:** This value is the minimum contributing area required to form a stream. The default value of 1 is adequate in most situations and will form stream headwaters near catchment boundaries
5. Click OK to run tool script. Several new layers will be added to your map.
   o *Note:* The hydro-conditioned DEM will be created and called **hydroDEM** but will NOT be automatically added to your map. It is located in an auto-created file geodatabase within the workspace you selected in the first **Define Area of Interest** tool.

- Pit & Sink Filling

Along with hydro-conditioning, pit filling should also be considered before terrain attribute calculations are made. This procedure fills depressions with hypothetical water flow and forces drainage to the lowest possible outlet. These depressions can vary considerably in scale from an isolated single cell to hundreds of contiguous cells covering well over a thousand acres. The pit-filling process may not be appropriate for all areas, especially where water is held and evaporated in depressions or where extensive tile drainage exists (see Case Studies section for examples). It is, however, a more conservative approach than using a non-filled DEM because it tends to err on the side of overestimating flows (Galzki, et al. 2011) – SPI signatures created from pit filled DEMs are more analogous to saturation excess runoff flow paths produced from large storm events than unsaturated flows. For SPI creation, users may generally find filling pits most suitable for steep-sloping landscapes and less suitable for low relief areas, though it is highly advisable to experiment with various pit fill Z limits, including a "fill all" run and a run with no pit filling. This will allow comparisons to be made among the SPI layers and help determine which best represents the landscape.

For CTI layer creation, a 'fill all' routine should be used to accurately depict surface water storage.

1. Open **ArcToolbox > Spatial Analyst Tools > Hydrology > Fill**
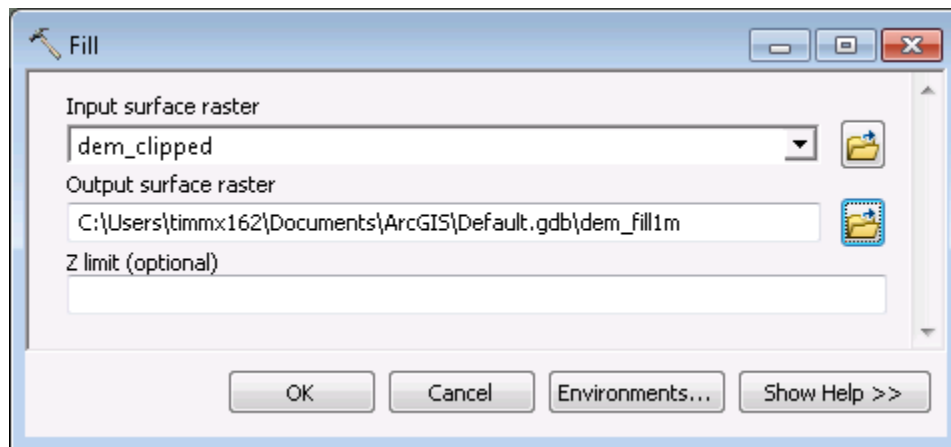
2. **Input surface raster**: Your DEM. If you used the NRCS Engineering tools previously, your **Input surface raster** will be **hydroDEM** for you hydro-conditioned DEM, or [**Your workspace folder name]_DEM** for your non-hydro-conditioned DEM. If you manually created a clipped subset of your original DEM, your **Input surface raster** will be the 'dem_clip' layer. To fill the tool fields, select layers from the drop-down, drag the layer to the blank field, or browse to the desired layer by clicking on the folder icon left of field.

3. **Output surface raster**: Browse to output workspace and name using it something you can remember, e.g. 'dem_fill'. It may be useful to add the unit amount used to fill the DEM so that users can identify each layer's Z limit when calculating multiple filled DEMs; e.g. 'dem_fill1m' or 'dem_fillall'

4. **Z limit**: The maximum elevation difference between a sink and its pour point to be filled. Units will be the same as the DEM's Z (vertical) axis, typically meters.
   Note: The default, which is achieved by leaving the Z limit field blank, will fill all sinks regardless of depth

5. Click OK to run. The output surface raster is added to your map as a new layer

- Filter

  At times, LiDAR data expressed in fine-resolution DEMs can contain either errors or spurious features which impede flow analysis and/or other terrain analysis, though these anomalies are becoming a non-issue with advancing technology in LiDAR acquisition along with improved quality control and assurance deliverables. The filter tool employs a low pass filter using a 3x3 moving window to "smooth" the raster and create a more contiguous dataset. Caution should be used when filtering, as it essentially 'dumbs down' the data by averaging out extreme outliers. Similar to pit filling, it is recommended to run terrain analysis with both filtered and non-filtered processes and determine which outputs best suit the terrain. The filter tool is typically run after pit filling.

 1. **ArcToolbox > Spatial Analyst Tools > Neighborhood > Filter**.
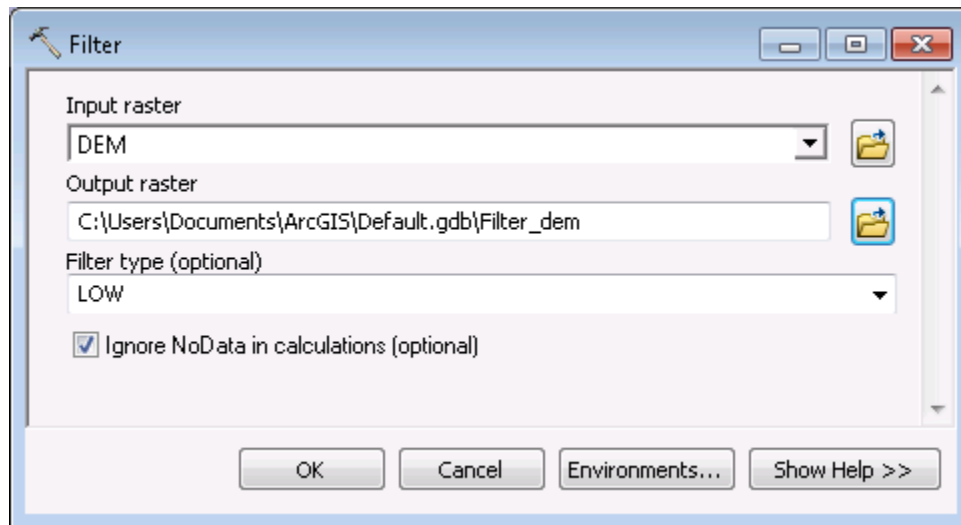
  2. **Input raster**: Your DEM. If pit filling was previously used, your **Input raster** will be 'dem_fill'. If pit filling was not used, but clipping was, your **Input raster** will be 'dem_clipped'. If NRCS tools were used, the **Input Raster** will be **hydroDEM** or [**Your workspace folder name]_DEM**
  3. **Output raster**: Browse to output workspace and name it, e.g. 'dem_filter'.
  4. **Filter type (optional):** the enhancement to be performed in the filter analysis.
     o *Note*: The default is "LOW" which is required to do the smoothing we seek.
  5. Click OK to run.
  6. The output raster is added to your map as a new layer.

Calculate primary attributes

Primary attributes are derived directly from the DEM. The slope, flow direction, and flow accumulation primary attributes will be used to calculate secondary attributes. Many of the other primary attributes created here will be used to visualize landscape surfaces and terrain attributes.
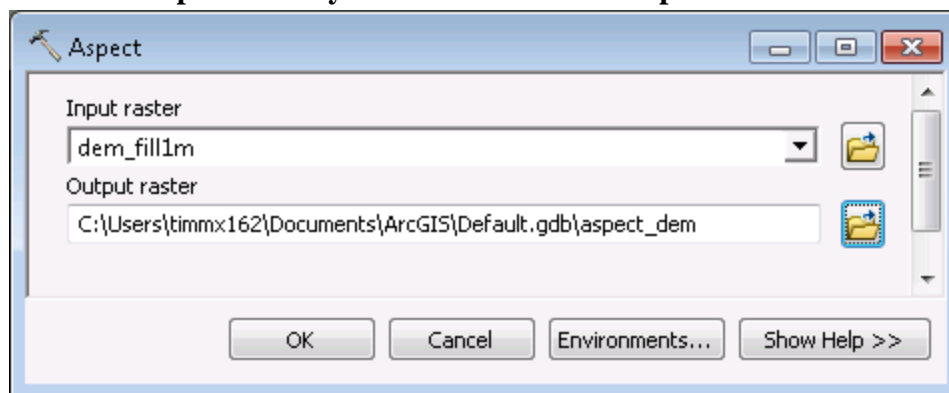
- Slope
  1. **ArcToolbox > Spatial Analyst Tools > Surface > Slope**
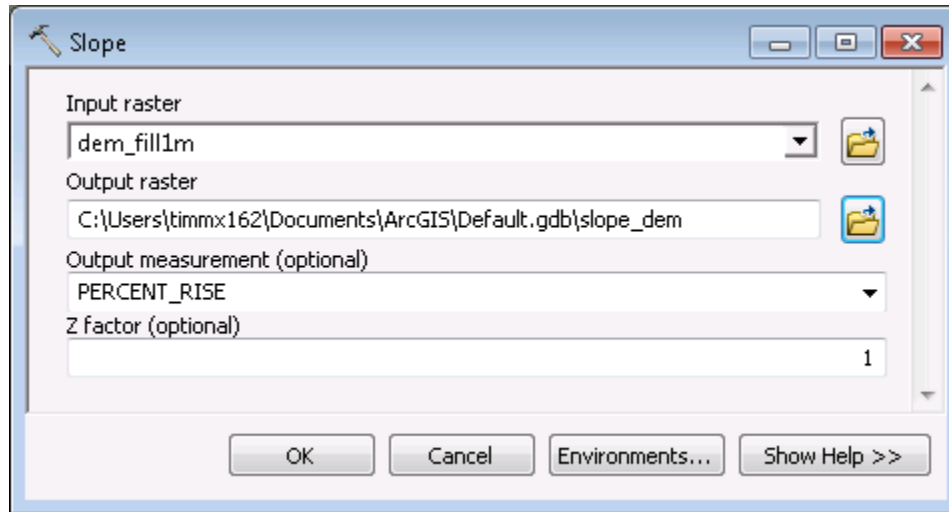
  2. **Input Raster**: Your DEM. If pre-processing was used, this should be the final DEM created, such as 'dem_fill' or 'dem_filter'.
  3. **Output raster**: Browse to output workspace and name output layer 'slope_dem'.
  4. **Output measurement (optional):** Select 'PERCENT_RISE'
     - *Note:* It is important for the rest of the analysis that you select PERCENT_RISE, even though the data will look the same.
  5. **Z factor (optional):** For DEMs with vertical (Z) units in meters, type 1, or else leave as default
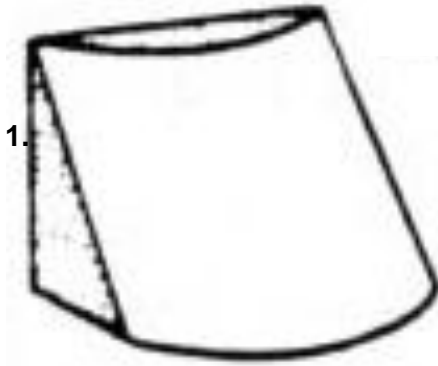 6. Click OK to run. The output raster is added to your map as a new layer.

- Aspect
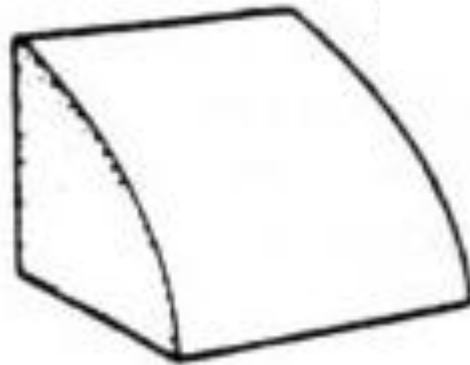 1. **ArcToolbox > Spatial Analyst Tools > Surface > Aspect**

  2. **Input Raster**: Your DEM. If pre-processing was used, this should be the final DEM calculated, such as 'dem_fill' or 'dem_filter'.
  3. **Output raster**: Browse to output workspace and name output layer 'aspect_dem'.
  4. Click OK to run. The output raster is added to your map as a new layer.

- Plan & Profile Curvature
  Plan curvature is measured perpendicular to the direction of descent and describes converging/diverging flow. It is well suited for describing soil water content and characteristics. Profile curvature is measured in the direction of maximum descent or aspect direction. It is a measure of flow acceleration and suited for erosion/deposition rate and geomorphology visualization.
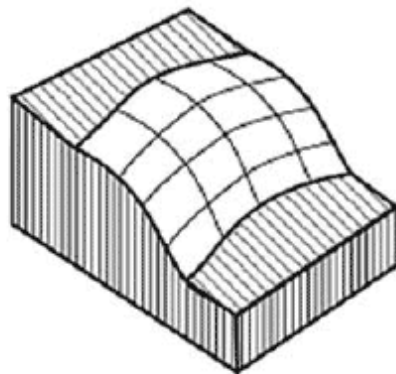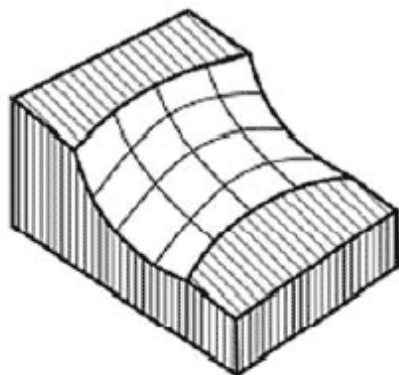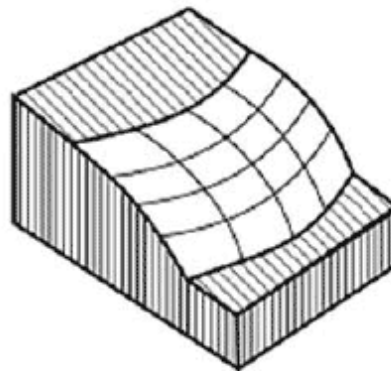
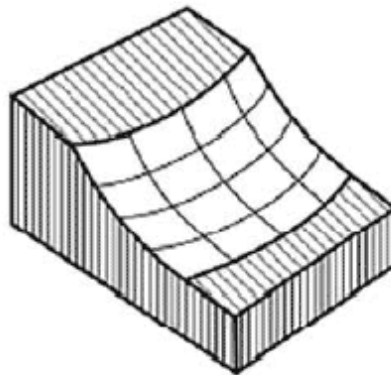**Plan curvature**   **Profile curvature**

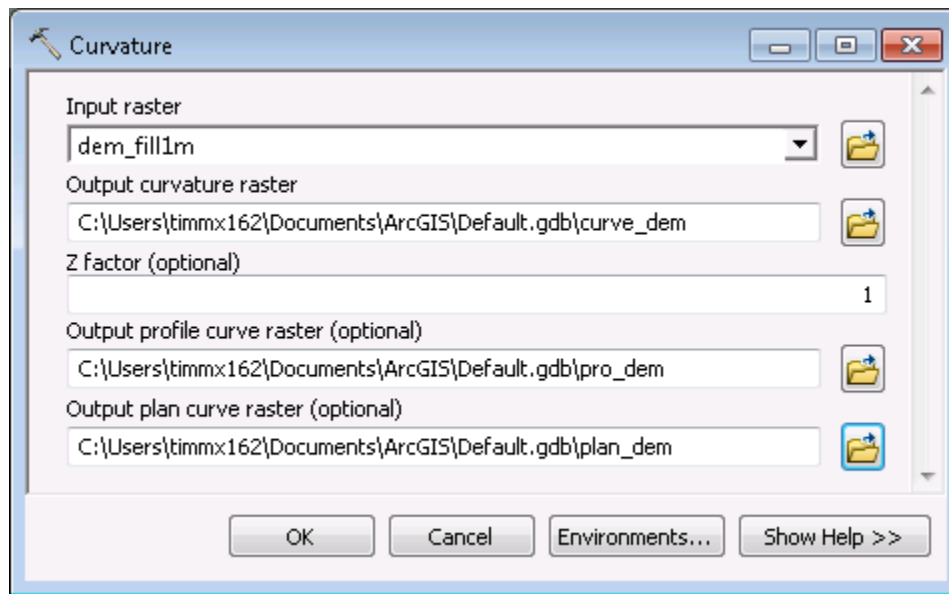Convergent - accelerating   Divergent - accelerating

Convergent - decelerating   Divergent - decelerating

1. **ArcToolbox > Spatial Analyst Tools > Surface > Curvature**

2. **Input Raster**: Your DEM. If pre-processing was used, this should be the final DEM calculated, such as 'dem_fill' or 'dem_filter'.
3. **Output curvature raster**: Browse to output workspace and name output layer 'curve_dem'.
4. **Output profile curve raster**: Browse to output workspace and name layer as 'pro_dem'.
5. **Output plan curve raster**: Browse to output workspace and name layer as 'plan_dem'.
6. Click OK to run. The 3 output rasters are added to the map as new layers.

- Hillshade
  The hillshade tool creates a shaded relief layer from a surface raster by considering the illumination source angle and shadows. The resulting hillshade raster creates a pseudo 3D display of topography.

  1. **ArcToolbox > Spatial Analyst Tools > Surface > Hillshade**
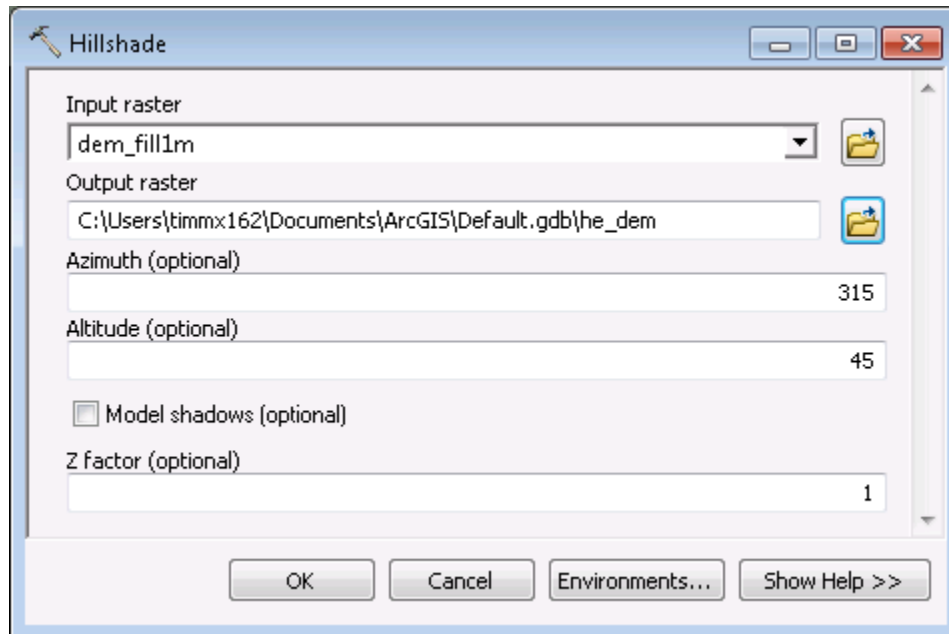

  2. **Input Raster**: Your DEM. If pre-processing was used, this should be the final DEM calculated, such as 'dem_fill' or 'dem_filter'.
  3. **Output raster**: Browse to output workspace and name output layer 'hs_dem'.
  4. Accept defaults for **Azimuth** and **Altitude**
     o *Note:* You can try checking on **Model Shadows**, it can be helpful in visualization, but in some cases it may make little difference.
  5. **Z factor (optional):** For DEMs with vertical (Z) units in meters, enter 1, or else leave as default
  6. Click OK to run. The output raster is added to your map as a new layer.

- Flow Direction
ArcMap's Flow Direction tool uses a calculation method called the 'D8' algorithm. This method is well suited to the identification of individual channels, channel networks and basin boundaries making it suitable for terrain analysis CSA identification. However, it is based on two simplifying assumptions that do not capture the geometry of divergent flow over hillslopes. The two simplifications are the use of 8 discrete flow angles, and each pixel has a single flow direction (Rivix, 2008). Due to these factors, the 'D-Infinite' algorithm was created to overcome D8 limitations and therefore provide an increased potential to improve terrain analysis results. Several software programs exist with dedicated DEM processing offering both D8 and D-Infinite calculations (e.g. TauDEM, RichDEM, RiverTools, etc.). The D8 method imbedded in the Flow Direction ArcTool is used in this manual, though users are encouraged to process DEMs with the D-Infinite method Flow Direction calculation if available.

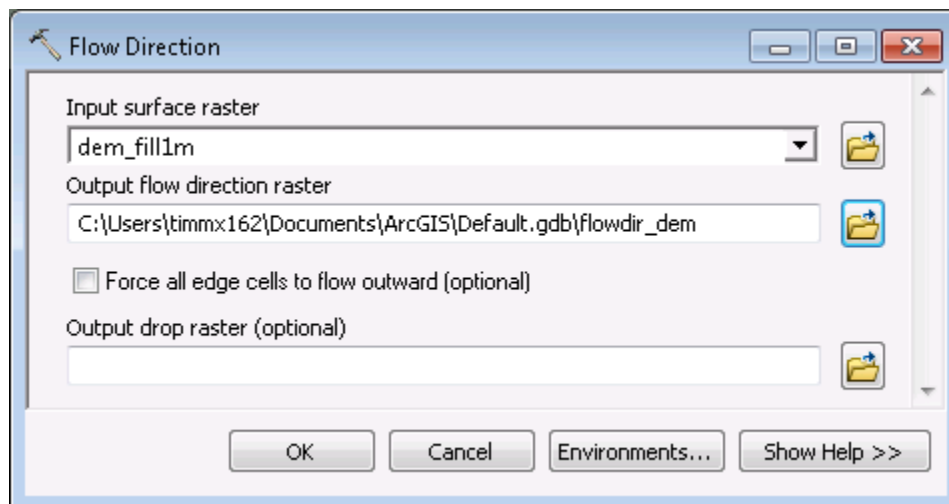1. **ArcToolbox > Spatial Analyst Tools > Hydrology > Flow Direction**

2. **Input Raster**: Your DEM. If pre-processing was used, this should be the final DEM calculated, such as 'dem_fill' or 'dem_filter'.
3. **Output flow direction raster**: Browse to output workspace and name output layer 'flowdir_dem'.
4. Click OK to run. The output raster is added to your map as a new layer.

- Flow Accumulation

    1. **ArcToolbox > Spatial Analyst Tools > Hydrology > Flow Accumulation**
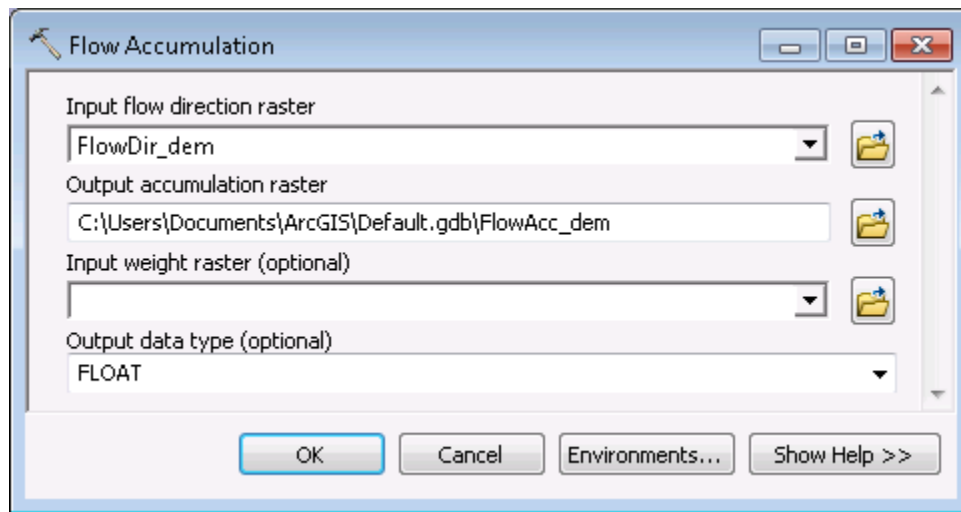

    2. For **Input Flow Direction Raster**, use the output of Flow Direction from earlier step. If you kept the suggested name, it will be 'flowdir_dem'.
    3. **Output accumulation raster**: Browse to output workspace and name output layer 'flowacc_dem'.
    4. Accept defaults for other parameters.
    5. Click OK to run. The output raster is added to your map as a new layer.

Calculate secondary attributes

- Stream Power Index (SPI)

1. Launch the **Raster Calculator** by clicking on **Spatial Analyst Tools > Map Algebra > Raster Calculator**
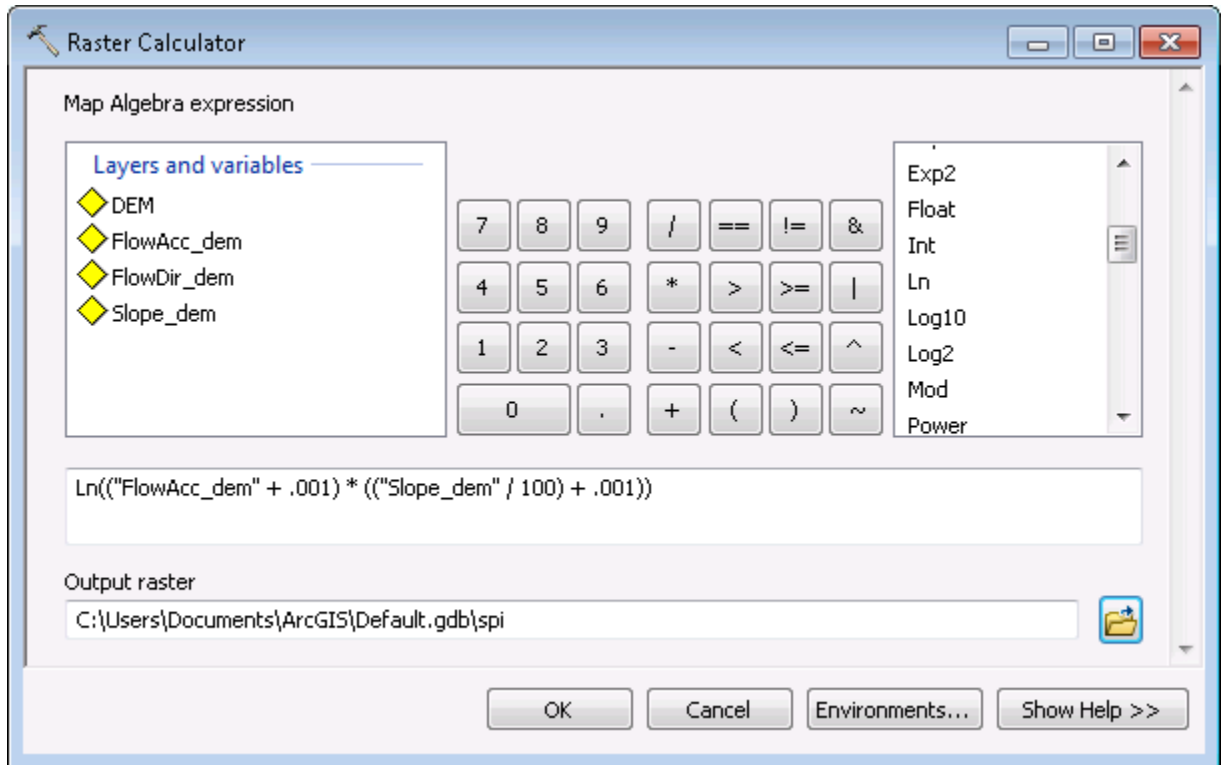
2. Enter formula so the Map Algebra expression looks exactly as follows: **Ln(("flowacc_dem" + 0.001) * (("slope_dem" / 100) + 0.001))**
   - *Note:* The spaces between operators are required for proper calculation
3. **Output raster**: Browse to output workspace and name output layer 'spi'.
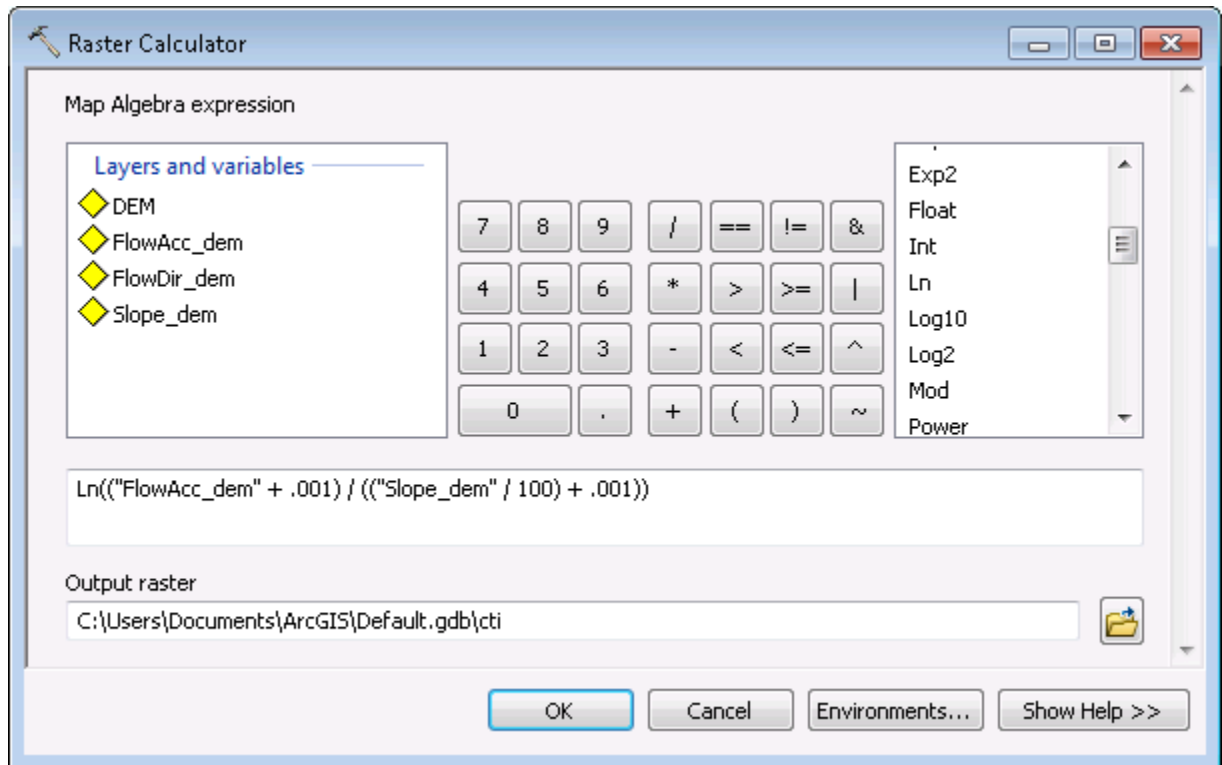4. Click OK to run calculation.

- • Compound Topographic Index (CTI)

    1. Launch the **Raster Calculator** by clicking on **Spatial Analyst Tools > Map Algebra > Raster Calculator**

    2. Enter formula so the Map Algebra expression looks exactly like: **Ln(("flowacc_dem" + 0.001) / (("slope_dem" / 100) + 0.001))**
       o *Note:* The formula above is the same as the SPI formula with the only difference being the division between Flow Accumulation and Slope.
    3. **Output raster**: Browse to output workspace and name output layer 'cti'.
    4. Click OK to run calculation.

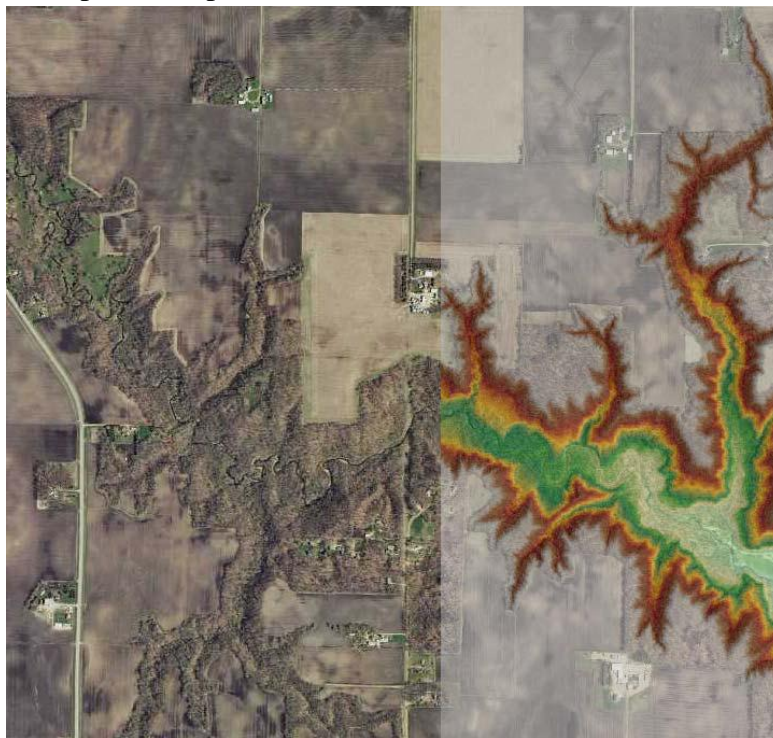## Visualizing terrain attributes

- Terrain Attribute Comparison – Often, the best way to understand differences in terrain attribute calculations is to view each layer in conjunction with one another. By paying careful attention to a specific portion of the landscape, one can overlay each of the terrain attributes to gain a better understanding of the relationships between each attribute.

- Aerial Photo Comparison - Utilizing aerial photography is a great way to better understand your landscape, and it may be possible to validate some of the largest features in your area of interest with aerial photos alone. While ground-truthing is the most effective way to determine the accuracy of terrain attribute-based predictions of critical source areas, this is not always possible – especially on privately-owned land. Furthermore, photos when used with flow accumulation and its associated secondary terrain attributes, often help in assessing whether or not further hydrologic conditioning is required for the task at hand.

- Swipe function
  1. To display the **Effects** toolbar, right-click anywhere in the toolbar and select Effects.
  2. Select the Swipe Tool to "wipe" a layer using a horizontal or vertical line across the screen.
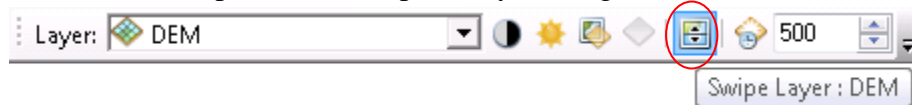
  3. Make sure the layer you want to "swipe" is shown in the "Layer:" box.
  4. Click on the map and drag to swipe *(do not release mouse button; the mouse must be depressed to get the swipe effect).*

  Example of swipe function:

- <u>Symbology for Terrain Attributes</u>
  Often this is a matter of personal preference, but there are a few tips/tricks in display used for specific terrain attributes:
    1. Slope - Colormap variations
    2. Flow Accumulation - Visualize upslope contributing area as if it were a watershed boundary.
    3. CTI – Blue/water – display highest values darkest
   4. SPI – Brown/sediment - display highest values darkest
- <u>SPI/CTI visualization</u> – Once calculated, the SPI and CTI layers are not very informative without first removing a majority of the cells that have low erosion (SPI) or ponding (CTI) risk. The layer histograms can be used to estimate a threshold for these unwanted values for quick display changes. More precise methods for determining how many cells to remove from the layers are discussed in the **Determining thresholds** section.
  To modify the original SPI and/or CTI layers to display percentile values:
    1. Double click on the layer in the Table of Contents window in ArcMap to open the layer's Properties menu.
    2. In Layer Properties, open the Symbology tab (**1**). On the right side under 'Show' click on 'Classified' (**2**) and in the classification box click 'Classify…' (**3**). The Classification window will open. At this point users can experiment with several different classification methods, classes, and threshold values. Keep in mind that any changes made here in Layer Property Symbology will not modify the data in anyway; it will only change the way the data is displayed in the active ArcMap data frame.
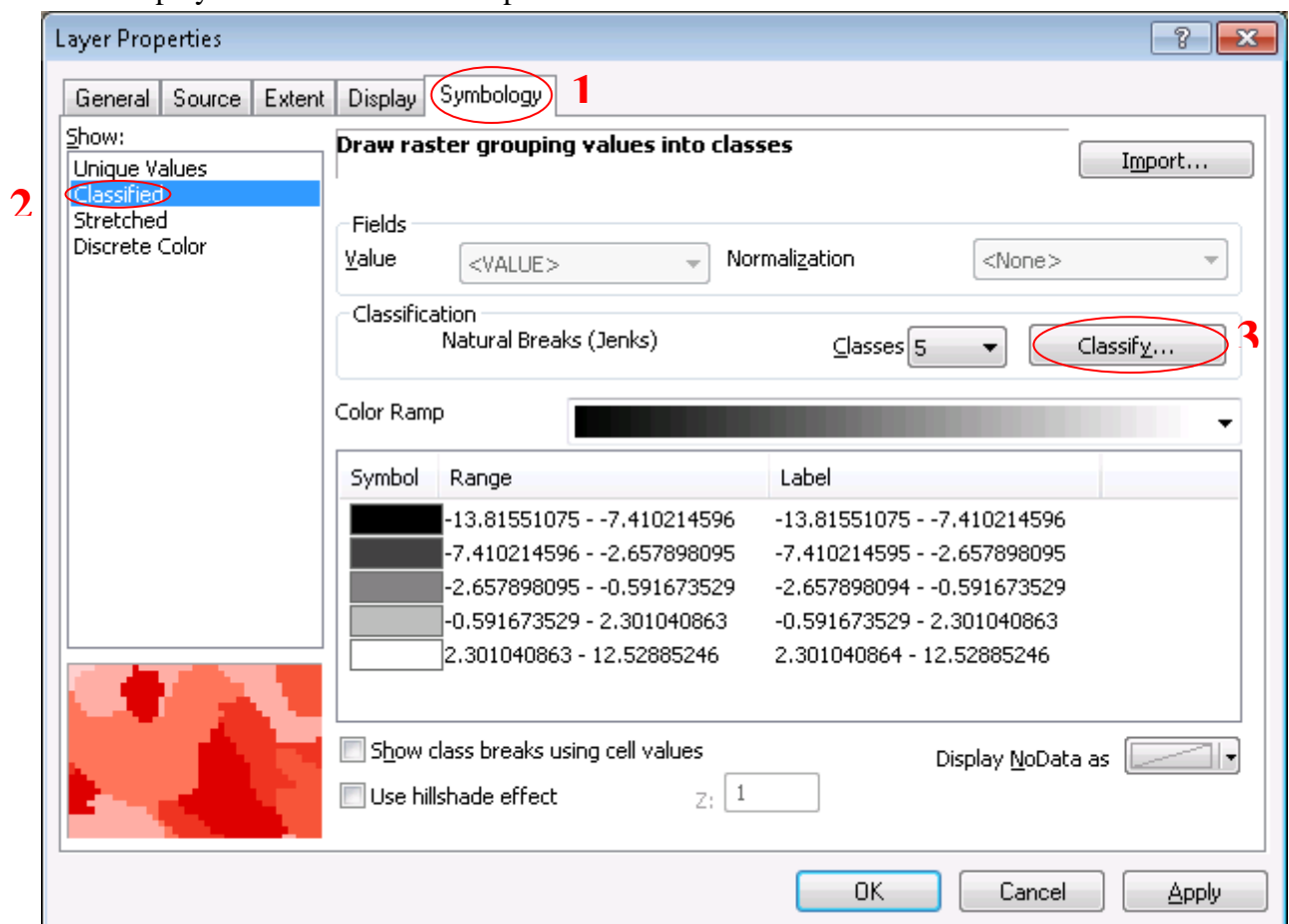
- o The Classes pull down menu allows for the user to select the number of class breaks to be calculated using the user defined classification method. Using class breaks between 1 and 10 should be appropriate for displays.
- o With the classification method, there is no right or wrong method to use, though the Quantile and Natural Breaks (Jenks) classification methods often match well with signature gradients. Esri provides the following descriptions for each classification method from their ArcGIS Help Resource Center:
  - ➢ Equal interval divides the range of attribute values into equal-sized sub-ranges. This allows you to specify the number of intervals, and ArcGIS will automatically determine the class breaks based on the value range.
  - ➢ Defined interval allows you to specify an interval size used to define a series of classes with the same value range.
  - ➢ With Quantile classification, each class contains an equal number of features. A quantile classification is well suited to linearly distributed data. Quantile assigns the same number of data values to each class. There are no empty classes or classes with too few or too many values.
  - ➢ Natural Breaks (Jenks) classes are based on natural groupings inherent in the data. Class breaks are identified that best group similar values and that maximize the differences between classes. The features are divided into classes whose boundaries are set where there are relatively big differences in the data values.
  - ➢ The Geometrical Interval classification scheme creates class breaks based on class intervals that have a geometrical series. The geometric coefficient in this classifier can change once (to its inverse) to optimize the class ranges. The algorithm creates geometric intervals by minimizing the sum of squares of the number of elements in each class. This ensures that each class range has approximately the same number of values with each class and that the change between intervals is fairly consistent.
  - ➢ The Standard deviation classification method shows you how much a feature's attribute value varies from the mean. Class breaks are created with equal value ranges that are a proportion of the standard deviation—usually at intervals of 1, ½, ⅓, or ¼ standard deviations using mean values and the standard deviations from the mean.
- o The Data Exclusion option can be used to exclude all data below or above any user determined threshold value.
3. The simplest method for display is to use two classes to represent all signatures over a certain threshold. This threshold value is at the users' discretion, though quantitative methods for calculating statistical thresholds are presented in the **Determining thresholds** section.
   - o For the simple method described here, set Classes to '2' and Classification Method to 'Manual' in that order. Two values will display in the Break Values column on right (see following figure). For this initial step, click and drag the lower break line to the approximate location shown in regards to the background histogram, or place it at the break value of ~2. This can be easily fine-tuned later. Click OK.
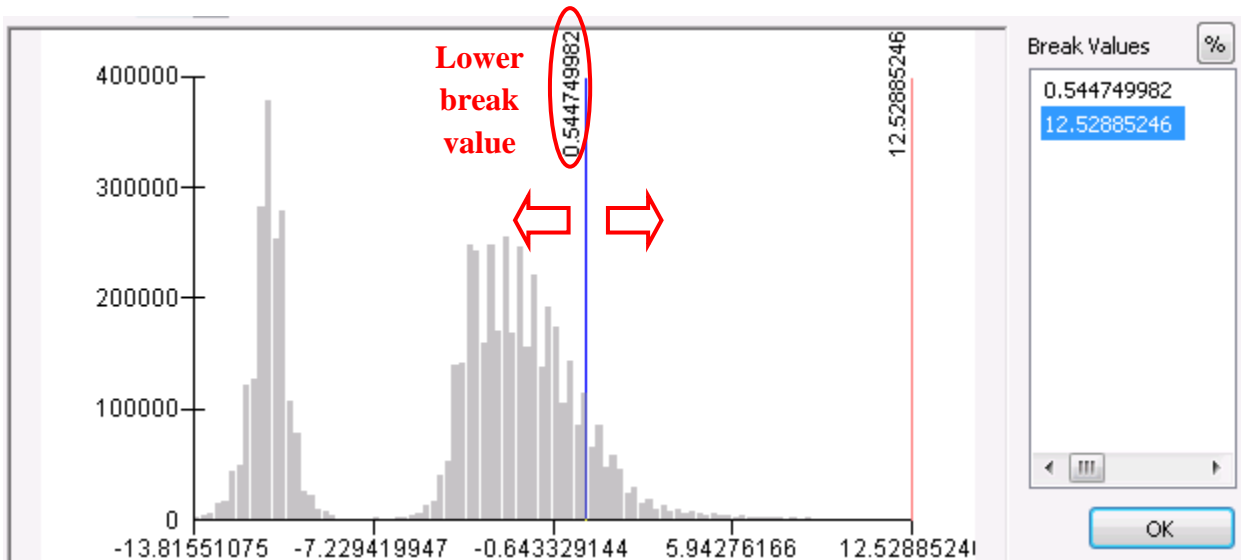
- o Back in the Symbology window, there will be two class symbols displayed – one black and one white – with the ranges associated with each to their right. The black symbol by default will contain all values below the threshold we chose, and the white contains the values above. Double-click the white rectangle symbol and a color palette will appear. Click any color you prefer that is highly visible, such as 'Mars Red'. Double-click the black rectangle and choose "No Color' at the top of the palette window. If the layer is active, you can click 'Apply' the see the changes behind the Layer Properties window instantly, otherwise click 'OK'.
- o Users will likely want to tweak the threshold value used to best represent the surface flow paths (SPI) or ponding (CTI) in their area of interest.
    - ➢ If the SPI signatures look too crowded or dense (example 1 below), the threshold values should be increased incrementally by clicking and dragging the vertical break line in the classification window until display results are satisfactory and vice versa for sparse SPI populations (example 2).
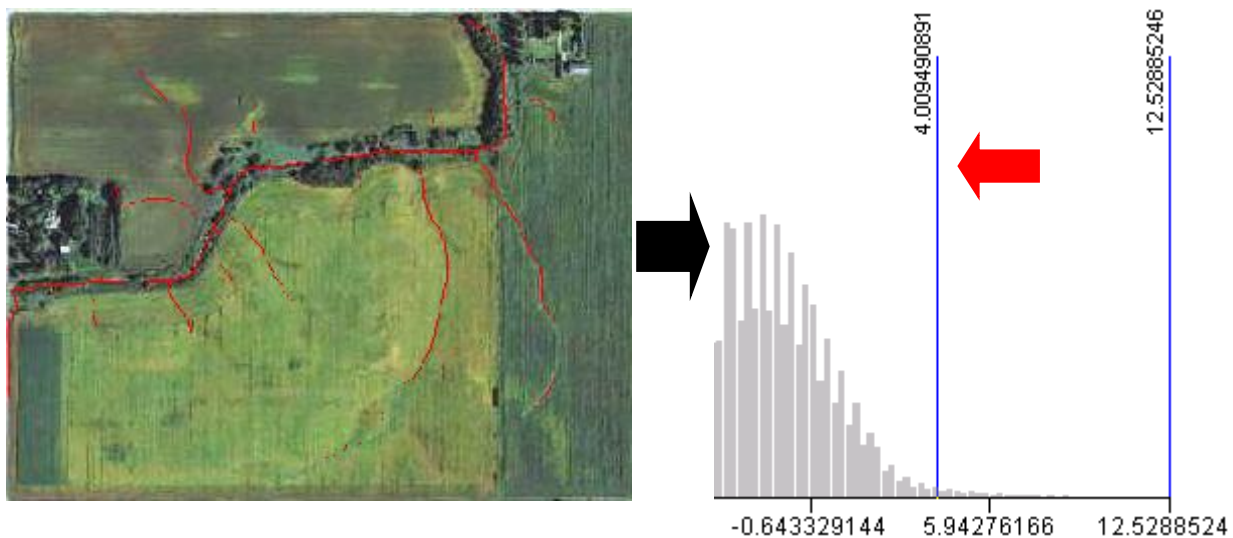   *Note:* The symbol colors will need to be changed again after each classification change.
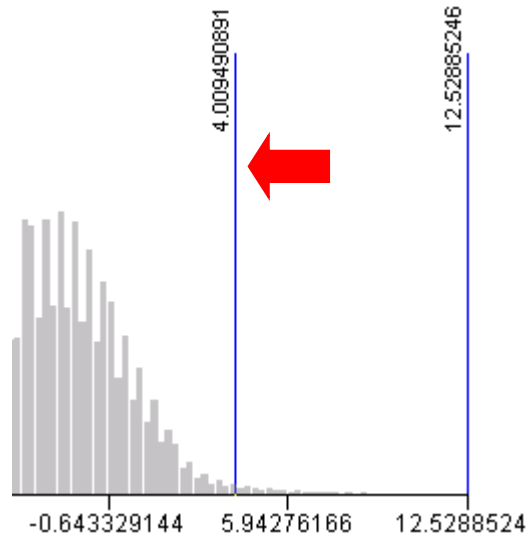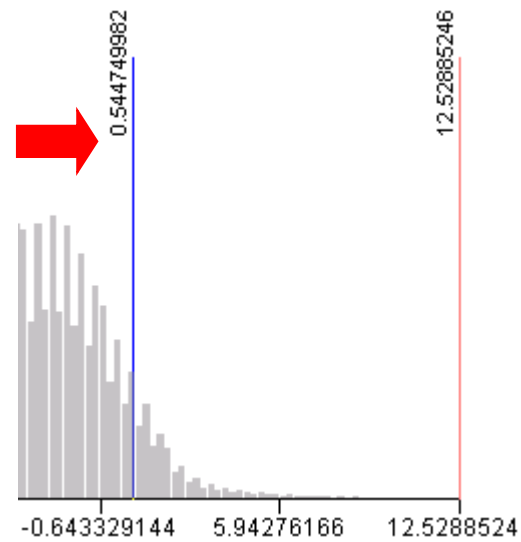
Ex. 1
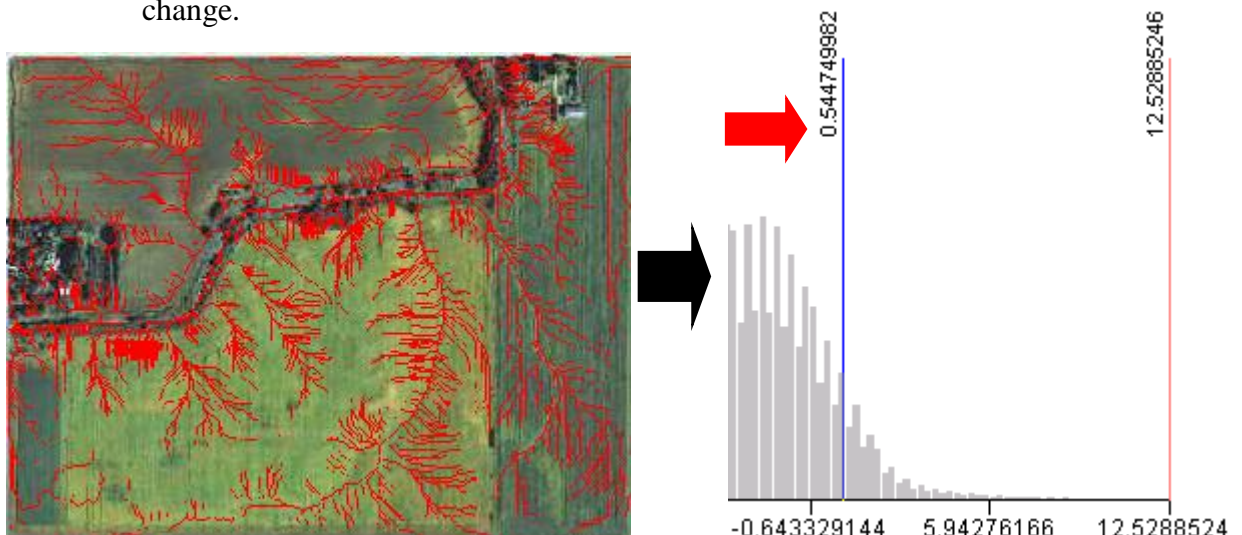
Ex. 2

> ➢ Treat the CTI layer using the same technique described in the previous step. A proper CTI threshold should display areas of impounded water if pit filling was used during DEM pre-processing.

o Often it is preferable to display SPI and CTI signatures with color gradients that represent high and low values within the same signature. For this purpose we can use the classification window with more than two classes.

➢ Under Classification Method, choose 'Quantile' or 'Natural Breaks (Jenks)' and Classes between 5 and 10 (user preference).

➢ We will use the Data Exclusion option to remove all values below a threshold. In the Classification window's Data Exclusion box, click "Exclusion…"
Under the Value tab, type your desired data exclusion range in the blank. For instance, to exclude all values below a threshold value of 2, and a minimum value range of -14, you would enter "-14 - 2" (without quotes). The minimum or maximum value used can be below or above the true value respectively to ensure full exclusion of data in the desired range.
Note: The range will be displayed in the underlying Classification window in the upper right, as Minimum and Maximum

➢ Click on the Apply button to see the changes in the underlying window's histogram to ensure it matches your exclusion range. If the results are satisfactory, click OK on both windows to return to the Layer Properties window.
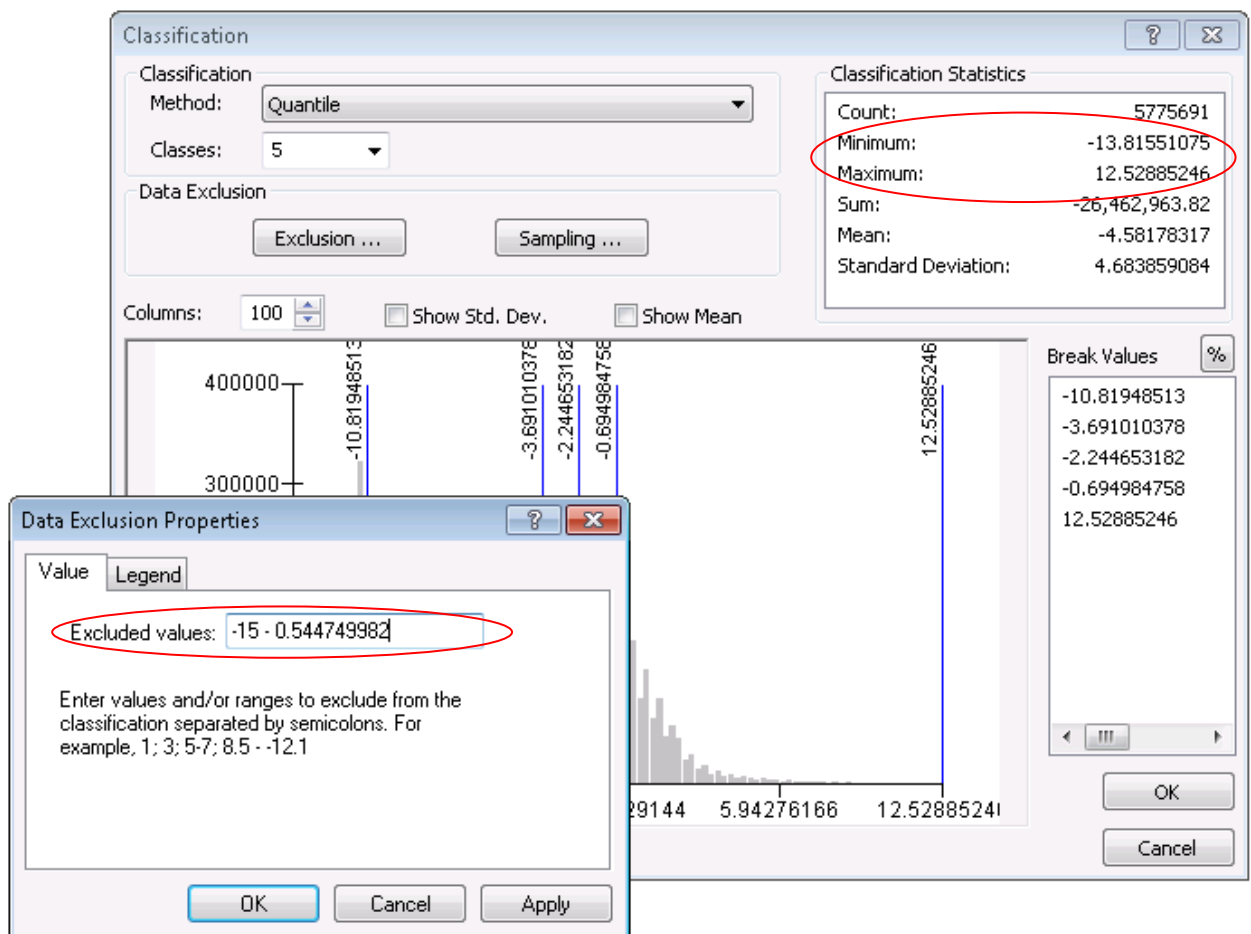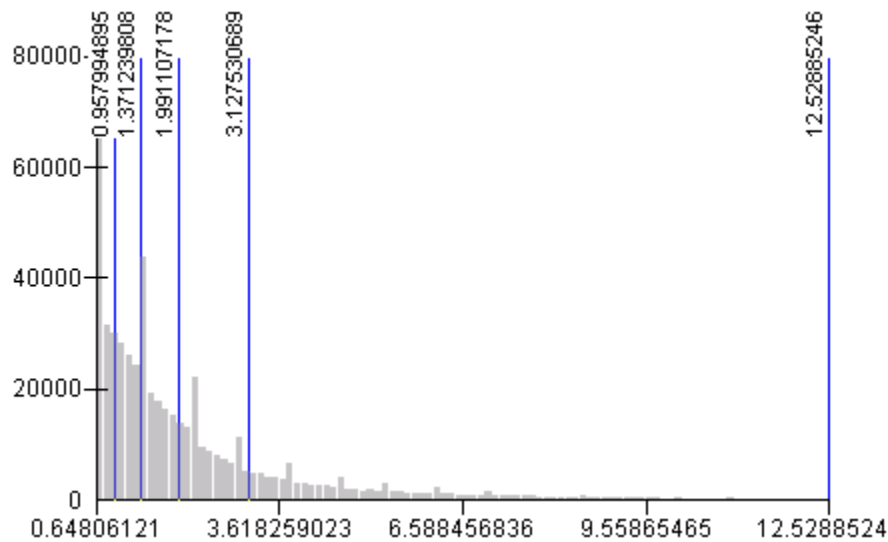
> ➢ In the layer properties window, you can set your preferred color ramp for pixel display by clicking on the Color Ramp pull down. It may be best to match the highest values with the darkest colors and lowest values with lightest.

Symbol	Range	Label
	0.64806121 - 0.957994895	0.64806121 - 0.957994895
	0.957994895 - 1.371239808	0.957994895 - 1.371239808
	1.371239808 - 1.991107178	1.371239809 - 1.991107178
	1.991107178 - 3.127530689	1.991107179 - 3.127530689
	3.127530689 - 12.52885246	3.12753069 - 12.52885246
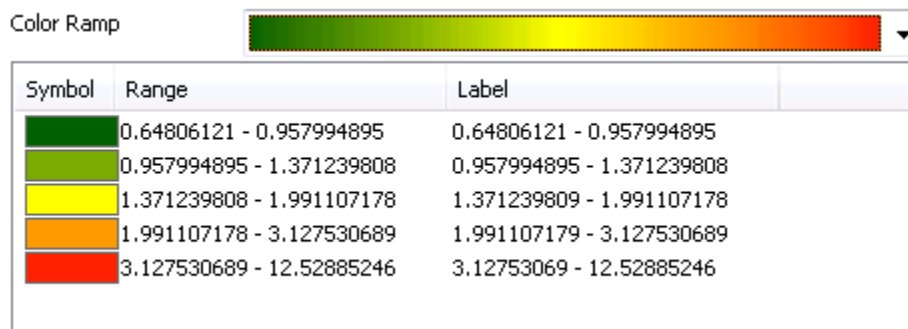
> ➢ As with the two class display approach, you may find that the exclusion range used allows too many or too few signatures for display. The method for correction is to change the threshold value in the data exclusion range. If the signatures are too crowded, increase the threshold value closer to your maximum value, and vice versa.

Determining thresholds

The SPI and CTI raster layers are most useful when displayed at a certain percentage of values above a threshold. The threshold depends mainly on local topography and overall slopes, and there is often a range of percentile values that will represent surface features sufficiently. Common thresholds are typically between the top 15% of values for flat areas to the top 1% of values for high relief areas.

Using estimation to visualize thresholds was previously described. This section will detail several methods for calculating exact percentile values from raster layers. Though not a necessary step for locating potential CSAs, the percent of SPI or CTI values displayed should be known to ensure consistency among users, or if following SOPs and/or publishing results. Methods for creating exportable SPI/CTI raster files with permanently-set thresholds will also be explained in this section.

When determining thresholds, the user must consider the spatial extent of the area being processed, as software has limited abilities to process large data sizes. For instance, if using Microsoft Excel, the maximum records affect ability to input LiDAR data:

Excel 2003 max records - 65,569
Excel 2007 max records - 1,048,575
Statistical Packages – Many around 10 million

If Excel maximum records become an issue, users may circumvent those limitations by creating random samples from the SPI raster at a 95% or better confidence interval. There are also many statistical software packages that can readily compute percentiles from large datasets, such as the free to use R program (CRAN, http://www.r-project.org/). Since those programs often have a learning curve for even basic functioning, using a more familiar program such as Microsoft Excel may be preferable. This manual will focus on using Excel for threshold calculations. A full explanation on using the R statistical software package for percentile calculations is presented in the appendix (see appendix section A.4).

Calculating thresholds using Excel:

When using Excel, first consider data size. Using 3m LiDAR derived attributes from an AOI of 2,332 acres or more will contain too many records to be contained in a single Excel 2007 sheet. As mentioned previously, there are ways to circumvent these limitations. Two methods for using Excel to calculate thresholds will be described in detail. One will use an exported text file (also known as ASCII file) from ArcMap to be opened directly in Excel, while the other method will first use a random sample from stream power index values to be opened in Excel.

- Raster to ASCII method
    1. Launch the **Raster to ASCII** tool by clicking on **Conversion Tools > From Raster > Raster to ASCII** in **ArcToolbox**
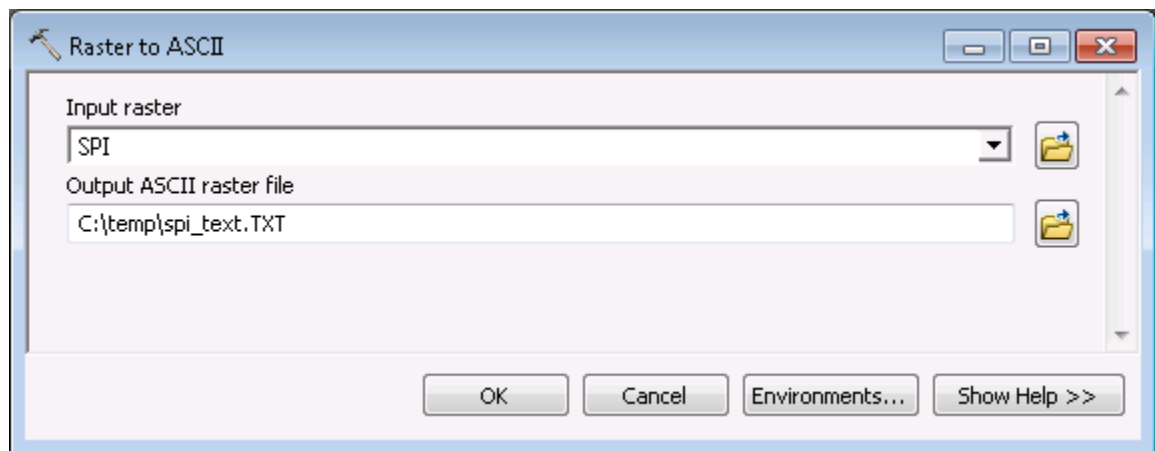
    a. **Input raster**: Your SPI raster layer.
    b. **Output ASCII raster file**: Any folder location of your choosing. Name the file 'spi_text'
    c. Click OK to run.
        o *Note:* If the output text file exceeds 250mb, users should consider proceeding with other percentile calculation methods described in this manual.

    2. Open Microsoft Excel with a blank workbook.
    3. In Excel 2007/2010, choose the **Data** tab, and click on **From Text** from the **Get External Data** group (pictured below).
    In Excel 2003 and earlier, navigate to the **Data** pull down menu and choose > **Import External Data > Import Data…**
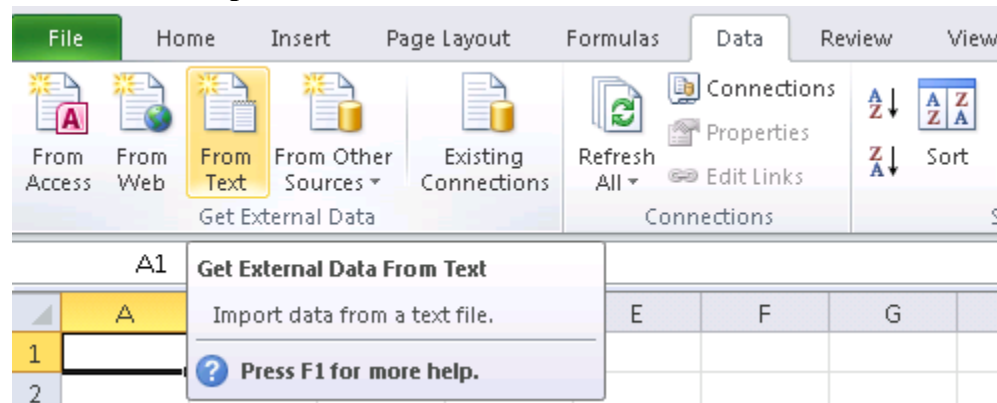
4. Browse to the saved 'spi_text' file created previously and click Import. The Text Import Wizard will open.

5. In the step 1 of 3 window, click the "Delimited" radio button and click Next.

Original data type
Choose the file type that best describes your data:
- ⦿ Delimited — Characters such as commas or tabs separate each field.
- ○ Fixed width — Fields are aligned in columns with spaces between each field.
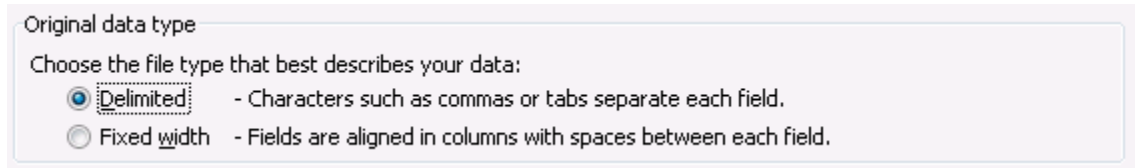
6. In step 2 of 3, under the Delimiters checkbox fields, un-select Tab, check the Space box and click Next.

Delimiters
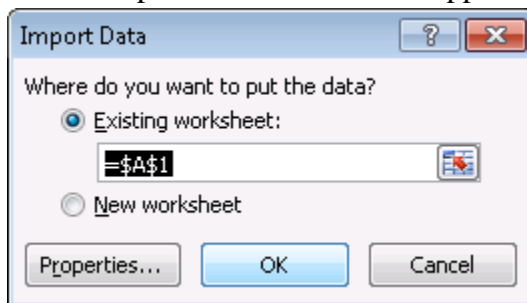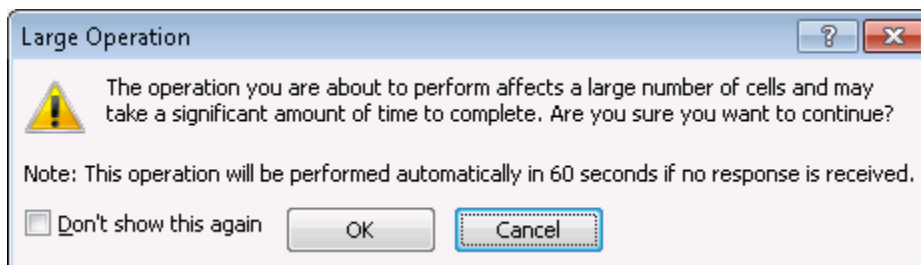- ☐ Tab
- ☐ Semicolon
- ☐ Comma
- ☑ Space
- ☐ Other: ____
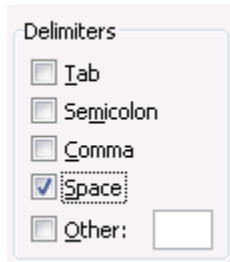
7. In step 3 of 3, leave the fields at default and click Finish.

8. In the new Import Data window that appears, click OK.

Import Data
Where do you want to put the data?
- ⦿ Existing worksheet:
  =A1
- ○ New worksheet
Properties...   OK   Cancel

9. The data from the text file is added to your current worksheet.

10. Notice that the first 6 rows of the sheet are populated with data properties. These should be deleted. Move your cursor over the 1st row header until the pointer turns into a right pointing arrow ➡ then click and drag down to the 6th row (fig. 2). Once the cells are highlighted, right click anywhere in the blue highlighted section and choose delete. Once the header cells are deleted, click any cell in the sheet to unselect the highlighted rows.
   o *Note:* If the following 'Large Operation' warning box appears, click OK.

Large Operation
⚠ The operation you are about to perform affects a large number of cells and may take a significant amount of time to complete. Are you sure you want to continue?
Note: This operation will be performed automatically in 60 seconds if no response is received.
- ☐ Don't show this again   OK   Cancel

Figure 2

11. Many of the cells will contain a value of -9999 which is ArcMap's default NoData value. All cells containing that value will need to be removed as they will affect the percentile calculation. The Find and Replace editing tool in Excel can be used for this purpose. In Excel 2007/2010, from the Home tab, find the editing group (far right) and click on the 'Find & Select' button and choose 'Replace…' (pictured below). The 'Find and Replace' dialog box will open.
Excel 2003 users should click the Edit pull down menu, then choose 'Find…' Select the 'Replace' tab after the tool opens.

o *Note:* The Find and Replace function can be quickly brought up by typing Crtl+F in all Excel versions.
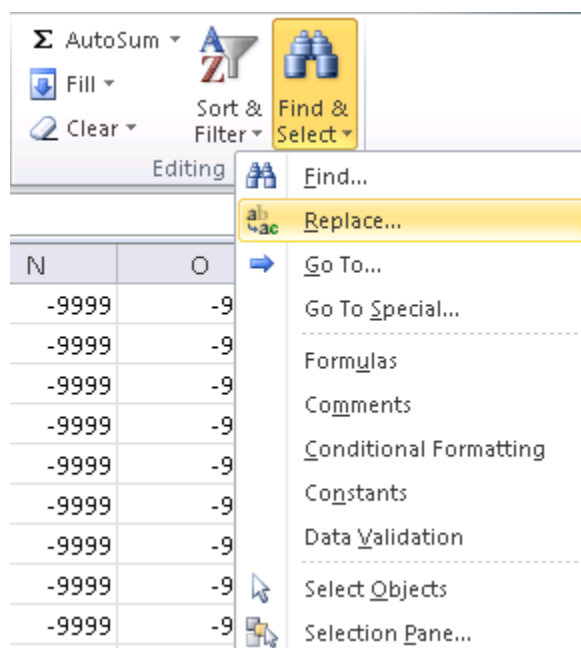
12. In the Find and Replace dialog box, type '-9999' into the 'Find what' field, and leave the 'Replace with' field empty. This will replace all -9999 NoData cells with a blank cell.
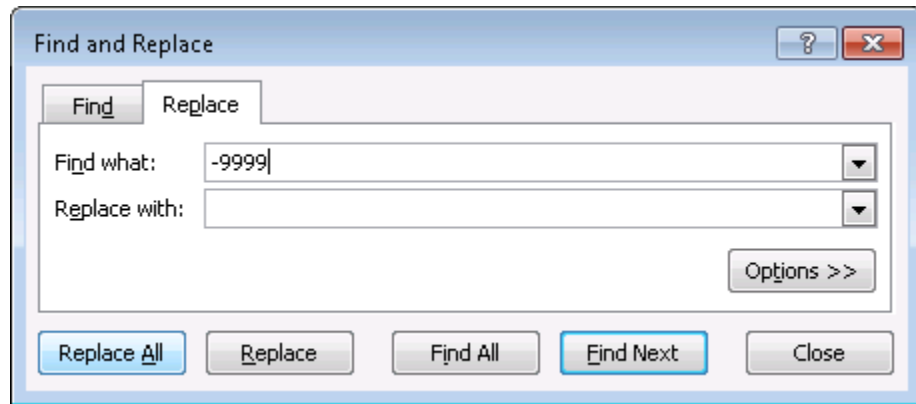
13. Click 'Replace All' to run the operation.
    o *Note:* During this operation, Excel may become unresponsive. This is normal, and the replace function may take several minutes to complete depending on data size.
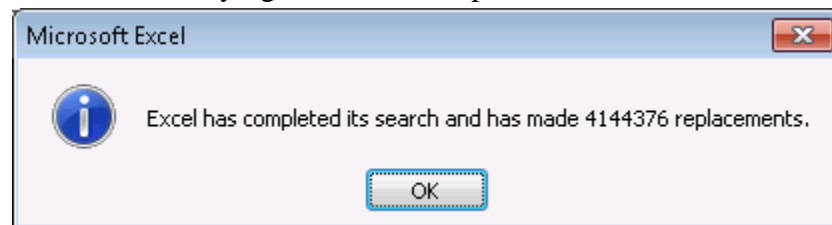
14. You should receive a notice saying Excel has completed its search. Click OK.

15. To calculate percentiles from the data, we will use the built-in Percentile function. The data range will first need to be determined. The easiest way is to click the first cell in the upper-right-most corner of the sheet (A1) and type Ctrl+Shift+End. All active cells in the worksheet will be highlighted. Make note of the row and column header extents, e.g. 'A1 to DFM2796' as they will be used for the percentile array.
16. Click a blank cell anywhere below the highlighted cells, and type '=percentile(' (without quotes) and the percentile function will become active with format (**array,** k).
17. For **array**, type in your data range from the previous step as the array using the format 'top left cell:lower right cell' e.g. 'A1:DEF200' then type a comma.
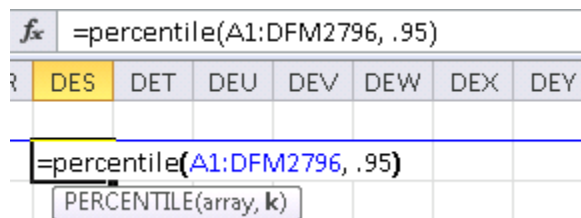
18. For the k parameter, enter your percentile value, such as .95 for the 95th percentile threshold value. Finish the function by ending with a closing parentheses and hit enter. The function will calculate the threshold of acceptance value from your original range of SPI or CTI values.

- Random point method
  1. In ArcGIS 9.x, Open **ArcToolbox > Data Management Tools > Feature Class > Tools > Create Random Points**
  In ArcGIS 10.x, Open **ArcToolbox > Data Management Tools > Feature Class > Create Random Points**
     - *Note:* The Spatial Analyst or 3D Analyst extension is required to use Create Random Points with both ArcView and ArcEditor licenses.

a. **Output Location**: Choose a geodatabase workspace as the output location. The Random Point tool requires an existing geodatabase, either file or personal, for output compatibility. Folders will not be accepted by this tool.
b. **Output Point Feature Class**: Name the output file 'random_points'
c. **Constraining Feature Class (optional)**: This is the boundary of your SPI and/or CTI layer(s). It must be vector format (shapefile, coverage, or feature class). It is often easiest to use the same **Output Extent** vector layer when clipping the original DEM to your area of interest. If clipping was not used, a polygon can be created around your SPI layer for use as the **Constraining Feature Class**.
d. **Number of Points [value or field] (optional)**: Click the radio button next to **Long**, and use the blank to input the desired number of random points. Users should create enough sample points from the population size to ensure at least a 95% confidence interval with a 1% margin of error. Table 1 can be used to this purpose.
   o *Note:* For determining population size of your SPI raster, see appendix section A.5.
e. Leave the rest of the fields as default and click OK to run. The output feature class is added to your map as a new layer.

2. Open **ArcToolbox > Spatial Analyst Tools > Extraction > Extract Values to Points**
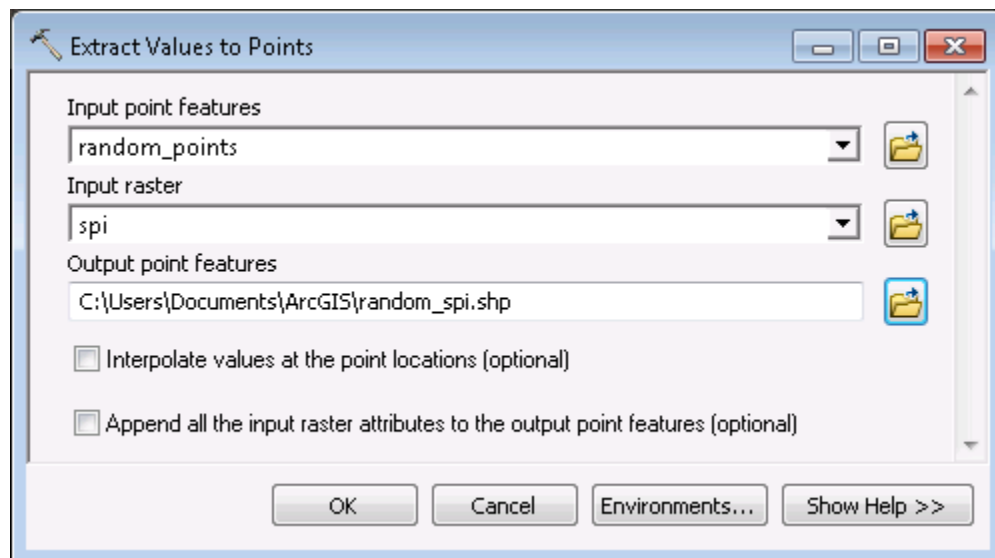
a. **Input point features**: Your 'random_points' layer created in previous step.
b. **Input raster**: Your SPI or CTI raster layer.
c. **Output point features**: Browse to output workspace and name output layer 'random_spi'
d. Click OK to run. The output shapefile is added to your map as a new layer.

Table 1

Required Sample Size[†]

Population Size	Confidence = 95%				Confidence = 99%			
	Margin of Error				Margin of Error			
	5.0%	3.5%	2.5%	1.0%	5.0%	3.5%	2.5%	1.0%
10	10	10	10	10	10	10	10	10
20	19	20	20	20	19	20	20	20
30	28	29	29	30	29	29	30	30
50	44	47	48	50	47	48	49	50
75	63	69	72	74	67	71	73	75
100	80	89	94	99	87	93	96	99
150	108	126	137	148	122	135	142	149
200	132	160	177	196	154	174	186	198
250	152	190	215	244	182	211	229	246
300	169	217	251	291	207	246	270	295
400	196	265	318	384	250	309	348	391
500	217	306	377	475	285	365	421	485
600	234	340	432	565	315	416	490	579
700	248	370	481	653	341	462	554	672
800	260	396	526	739	363	503	615	763
1,000	278	440	606	906	399	575	727	943
1,200	291	474	674	1067	427	636	827	1119
1,500	306	515	759	1297	460	712	959	1376
2,000	322	563	869	1655	498	808	1141	1785
2,500	333	597	952	1984	524	879	1288	2173
3,500	346	641	1068	2565	558	977	1510	2890
5,000	357	678	1176	3288	586	1066	1734	3842
7,500	365	710	1275	4211	610	1147	1960	5165
10,000	370	727	1332	4899	622	1193	2098	6239
25,000	378	760	1448	6939	646	1285	2399	9972
50,000	381	772	1491	8056	655	1318	2520	12455
75,000	382	776	1506	8514	658	1330	2563	13583
100,000	383	778	1513	8762	659	1336	2585	14227
250,000	384	782	1527	9248	662	1347	2626	15555
500,000	384	783	1532	9423	663	1350	2640	16055
1,000,000	384	783	1534	9512	663	1352	2647	16317
2,500,000	384	784	1536	9567	663	1353	2651	16478
10,000,000	384	784	1536	9594	663	1354	2653	16560
100,000,000	384	784	1537	9603	663	1354	2654	16584
300,000,000	384	784	1537	9603	663	1354	2654	16586

3. Microsoft Excel cannot open the .dbf file format so the 'random_points' shapefile's table will need to be exported as a text (ASCII) file.
   a. Right click on the new 'random_spi' layer in the table on contents window, and choose 'Open Attribute Table'
   b. Click the upper left pull down menu button (table options) and choose the 'Export…' option.
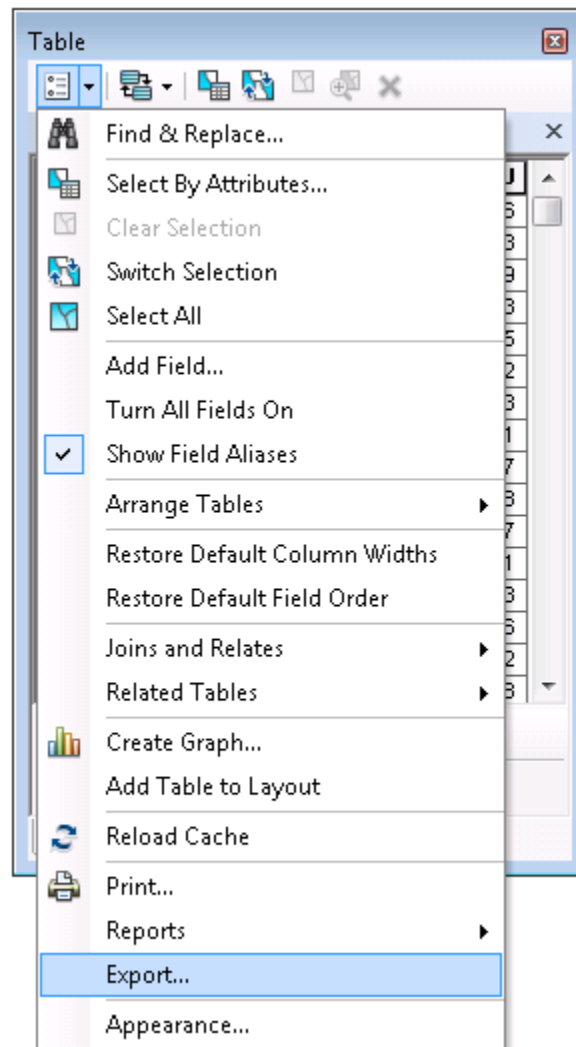
   c. In the Export Data window, click on the browse button to the right of the 'Output table' field.
   d. Save the file in a folder (not a geodatabase), naming it spi_points.txt or cti_points.txt. Make sure to save the file as **Text File** under the 'Save as type' pull down and click Save (fig. 3).
   e. Back in the Export Data window, make sure 'All Records' is selected in the Export pull down, and click OK.
   f. When the process has completed, you can select No when prompted to add to the current map.
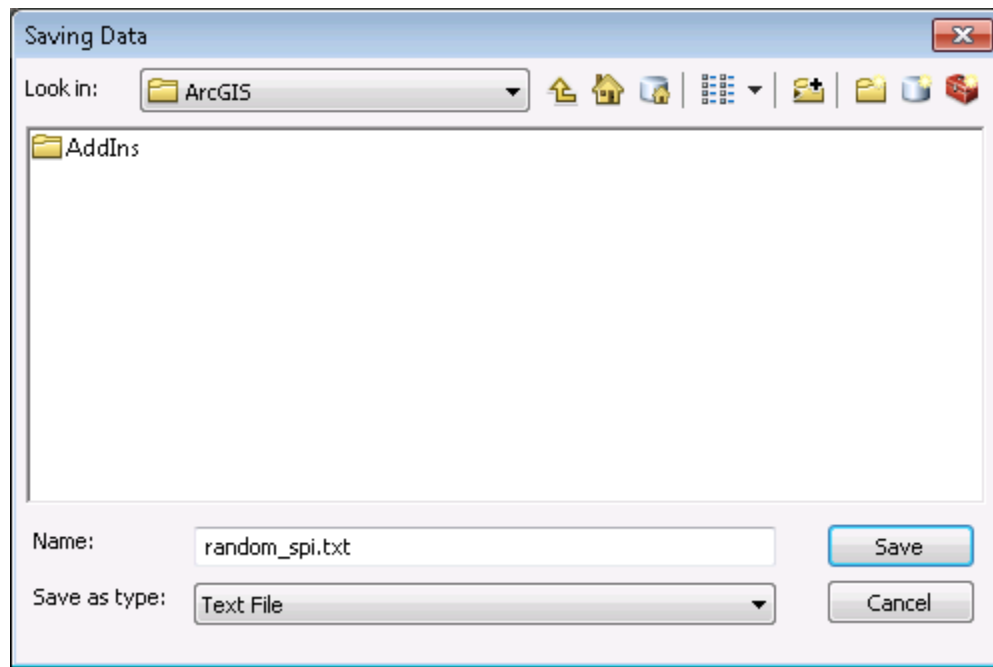
Figure 3

4. Open Microsoft Excel with a blank workbook.
   a. In Excel 2007/2010, choose the **Data** tab, and click on **From Text** from the **Get External Data** group (pictured below).
   In Excel 2003 and earlier, navigate to the **Data** pull down menu and choose > **Import External Data > Import Data…**
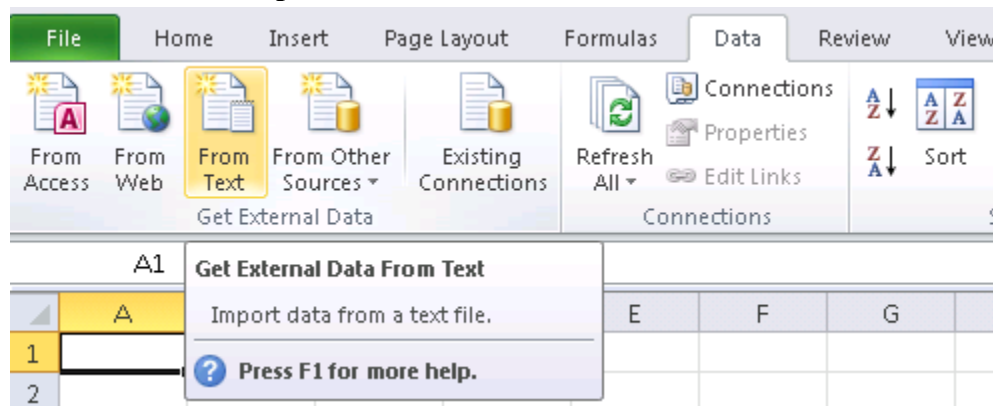
   b. Browse to the saved text file created in the steps above and click Import and the Text Import Wizard will open.
   c. In the step 1 of 3 window, click the "Delimited" radio button and click Next.
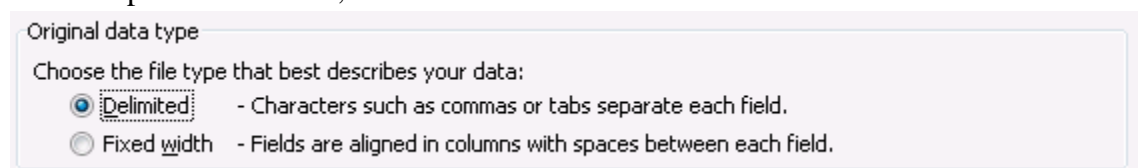
d. In step 2 of 3, under the Delimiters checkbox fields, un-select Tab, and check the Comma box and click Next.
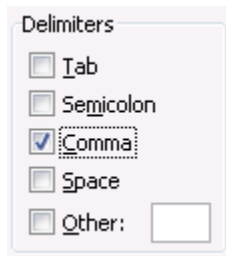
e. In step 3 of 3, leave the fields at default and click Finish.
f. In the new Import Data window that appears, click OK.
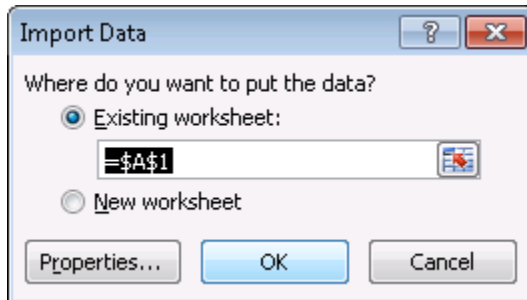
g. The data from the text file is added to your current worksheet.

5. Several columns may be currently displayed in the Excel worksheet – we are only interested in the column named RASTERVALU. We will now calculate the threshold value using the percentile function in Excel.
    a. Click on a blank cell in the sheet and type '=percentile(' (without quotes) and the percentile function will become active with format (**array,** k).

    b. For **array**, select all cells in the column named 'RASTERVALU' by clicking on the alphabetic character above that column, then type a comma.
        o   *Note:* Including the cell with the text 'RASTERVALU' in the **array** will not affect the percentile calculation.
    c. For the k parameter, enter your percentile value such as .95 for the 95th percentile threshold value. Finish the function by ending with a closing parentheses and hit enter. The function will calculate the threshold of acceptance value from your original range of SPI or CTI values.

Rank secondary attributes

Once the percentile thresholds are known, they can be used with the SPI and CTI layers in ArcMap. The percentile values will be used to display all cell pixels above those thresholds. If additional display detail is desired, those cells can then be further ranked with color gradients using reclassification techniques. Refer to the **Visualize terrain attributes** 'SPI visualization' section for detailed instructions on when to use those percentile thresholds.

Often, it is desirable to have multiple SPI layers each set to display different percentiles. For this purpose, separate SPI or CTI raster layers can be created each with permanently set percentile thresholds by using the **Reclassify** tool.

    a.   In ArcMap, open **ArcToolbox > Spatial Analyst Tools > Reclass > Reclassify**

    b. **Input raster:** Your original SPI or CTI layer.
    c. **Reclass field:** This should default to "Value"
    d. The **Reclassification** is done using the same procedure as outlined previously and initiated by clicking the "Classify…" button.
        o *Note:* Make sure to use your desired threshold value in the data exclusion range.
    e. **Output raster:** Browse to output workspace and name output layer spi or cti followed by the percentile threshold used, e.g. "spi_95"
    f. Check the box next to **Change missing values to NoData (optional).**
    g. Click OK to run. The output raster is added to your map as a new layer.
        o *Note:* You may have to enter Layer Properties and set the new SPI or CTI layer's symbology to "Stretched" for a smooth display color gradient.

Locate and prioritize potential CSAs

The data acquired earlier will now be used to assist in CSA placement.
1. Start a new ArcMap session with a blank map. Start populating your map with a base layer consisting of orthophoto(s) from the area of interest and the data layers collected in the Data Acquisition section. The layers in the table of contents should be generally organized so that orthophotos are on bottom, followed by raster layers, then polygon, polyline, and point vectors layers on top in that order.
    o *Note:* Some layers may benefit from using lowered display transparencies, such as the hillshade layer. This will allow base layers to still be visible. Layer transparency can be adjusted through the effects toolbar (**1**) or the layer properties display tab (**2**).
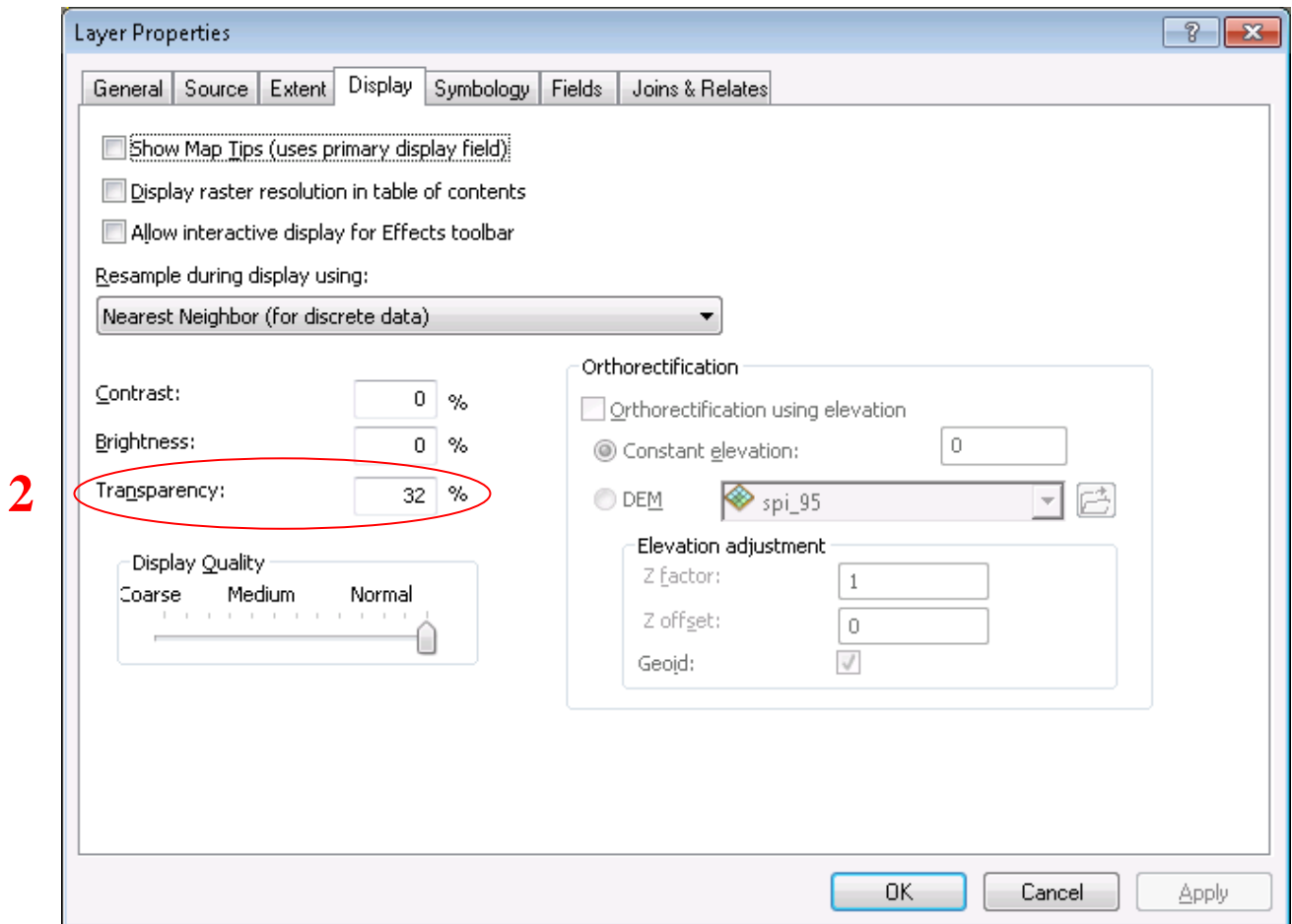
2. Create a new point shapefile or feature class to use for CSA placement.
    a. To create a new shapefile, open ArcCatalog either though ArcMap (version 10.x) or the separate ArcCatalog application.
    b. Browse to your preferred workspace folder or geodatabase using the catalog tree, right-click on your folder and select New, then "Shapefile…", or right-click on your geodatabase and select New then "Feature Class…" The **Create New Shapefile** or **New Feature Class** window will open.

- o **Create New Shapefile:** Choose a name for the shapefile, such as "CSA points". Make sure 'Feature Type' is set to **Point**. You should set the spatial reference to match the spatial coordinate system used in your other data layers. For data acquired from many Minnesota government sources, including MN DNR and MNGeo, the coordinate system used will often be "NAD 1983 UTM Zone 15N" but could differ, including UTM Zone 14N or 16N if using data from the far eastern or western parts of the state. Figure 4 shows Minnesota UTM zone grids, with zone numbers circled in red.

  An easy way to select the coordinate system is to use the Import option. From the **Create New Shapefile** window, click the 'Edit…' button in the Spatial Reference box. The Spatial Reference Properties window will open. Click the 'Import…' button. Browse to any vector of raster file currently being used in your active ArcMap session, select it and click Add. The coordinate system should be the North American Datum 1983 UTM system. Click OK. Back in the **Create New Shapefile** window, click OK and the new shapefile will be added to your chosen folder.

  - *Note:* When importing coordinate systems, some layers may not have spatial references set. ArcMap will still display those layers by automatically using the first coordinate system seen in the active data frame.

  - o <u>OR</u> create **New Feature Class:** Choose a Name and Alias for the new feature class. The Name must not have spaces – instead use underscores for spaces. The Alias can contain spaces. In the Type pull down menu, select 'Point Features'. Click 'Next >'. The second step involves choosing a coordinate system for the new Feature Class. Follow the steps from the **Create New Shapefile** process above using the 'Import…' button to select NAD 1983 UTM system. Click 'Next >' on the next three windows to create the new feature class.

c. Add the new shapefile or feature class to your active ArcMap session by either dragging the file from ArcCatalog onto the map, or using the Add Data button.

d. Before new points can be placed, an editing session must be started. Right click on the new shapefile or feature class point layer and choose 'Edit Features' then 'Start Editing'. If a window appears with warnings, click Continue. You are now able to place new points on the map using the editing functions.
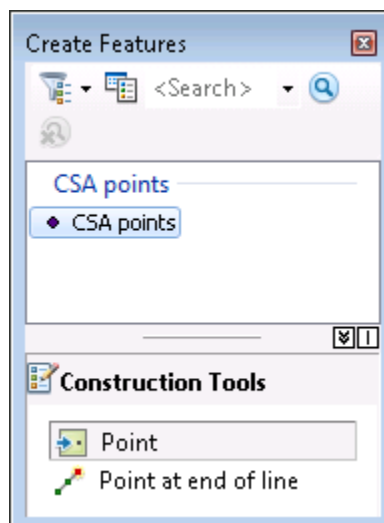
MINNESOTA DEPARTMENT OF TRANSPORTATION

Universal Transverse Mercator (UTM) Zones, Minnesota State Plane Zones, and Minnesota County Coordinate Projections

For more information, see: http://www.dot.state.mn.us/surveying/toolstech/mapproj.html

UTM PROJECTIONS

In Minnesota, UTM Zone 15 is usually extended to cover the entire state and is then denoted as Zone 15E.

STATE PLANE PROJECTIONS

The three zones are Lambert Conic Conformal Projections.

Zone boundaries are coincident with specific county boundaries.

COUNTY PROJECTIONS

Lambert Conic Conformal

Transverse Mercator

Oblique Mercator

Notes: Lighter–weight county lines indicate identical projections in adjacent counties.
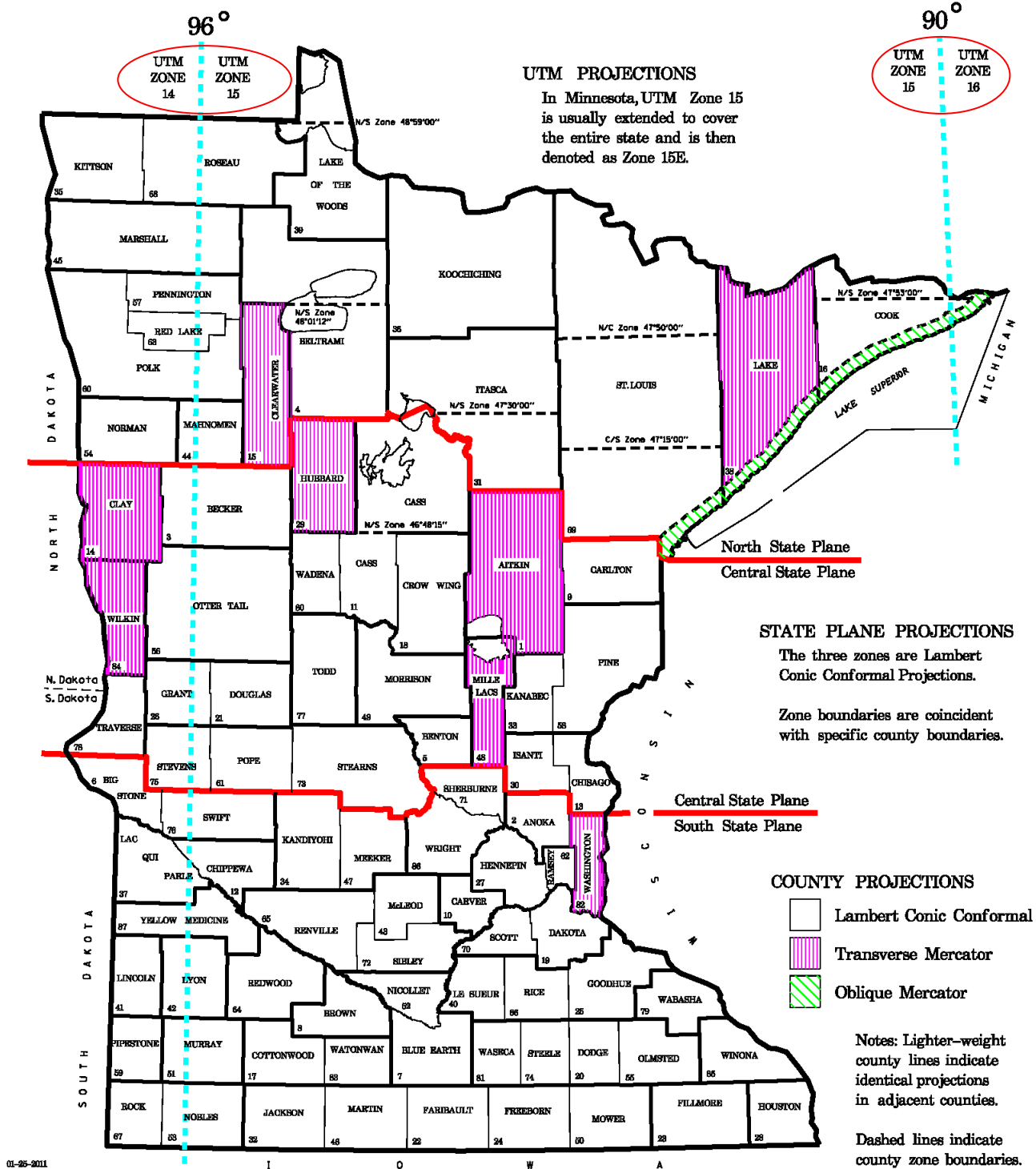
Dashed lines indicate county zone boundaries.

Figure 4

CSA Placement and Prioritization

Critical Source Areas (CSAs) are defined as portions of the landscape that combine high pollutant loading with a high propensity to deliver runoff to surface waters, either by an overland flow path or by sub-surface drainage. These areas have a higher likelihood of conveying more pollutants to surface waters than other portions of the landscape and thus coincide well with high SPI value characteristics. Features that could be associated with CSAs include culverts, drop structures, gullies, ravines, grassed waterways, bank slumping and erosion, in-stream vehicle/livestock crossings, tile drain outlets and side-inlets, exposed tile, and open intakes. CSA features can be placed anywhere on the landscape but users should focus targeting efforts to certain areas, depending on project goals.

A set of criteria were developed that facilitates systematic assessment of the factors involved in critical area identification. The ideal criteria incorporate the inherent characteristics associated with SPI, efficiency of the hydrologic system in pollutant transport, magnitude of the source, and type of pollutant into guidelines that can be applied throughout the watershed. Critical area criteria should be applied consistently throughout the project watershed. This ensures that the study area does not receive biased identification and also that landowners do not feel singled out or excluded from the selection process depending on whether areas of their land met the criteria or not (Line & Spooner, 1995).

Criteria for placement and prioritization of CSAs include:
- Magnitude of the pollutant source
  - Contributing area
  - Average SPI value
  - SPI signature length
- Hydraulic transport of pollutants and proximity to the water resource
- Land use/land cover
- Sub-watershed soil characteristics
- Existing conservation practices
- Crop productivity indices

Terrain analysis users should select these CSA sites for field visits and evaluation based on:
- GIS analysis results
- In-house knowledge
- Available resources (e.g., funding, staff time, etc.)

Time commitments should be factored in when determining how many points to place, as creating a potential CSA at each hydrologically connected SPI signature could involve substantial validation time spent in the field. It may be preferable to only place CSAs at the locations where signature lengths are longest and in close proximity to surface water, the average SPI signature(s) value is high, no BMPs exist, and soil characteristics show high potential risk for soil erosion. It is also important to note any regional-specific factors that may exist in the area of interest, such as sinkholes, feedlots and/or cattle grazing operations, and their proximity and contribution to any potential CSAs.

1. Using your orthophoto and surface water layers in ArcMap, activate the SPI layer previously set with your desired threshold display, then zoom into your area of interest. The SPI signatures should resemble surface runoff flow paths on the map (fig. 5).
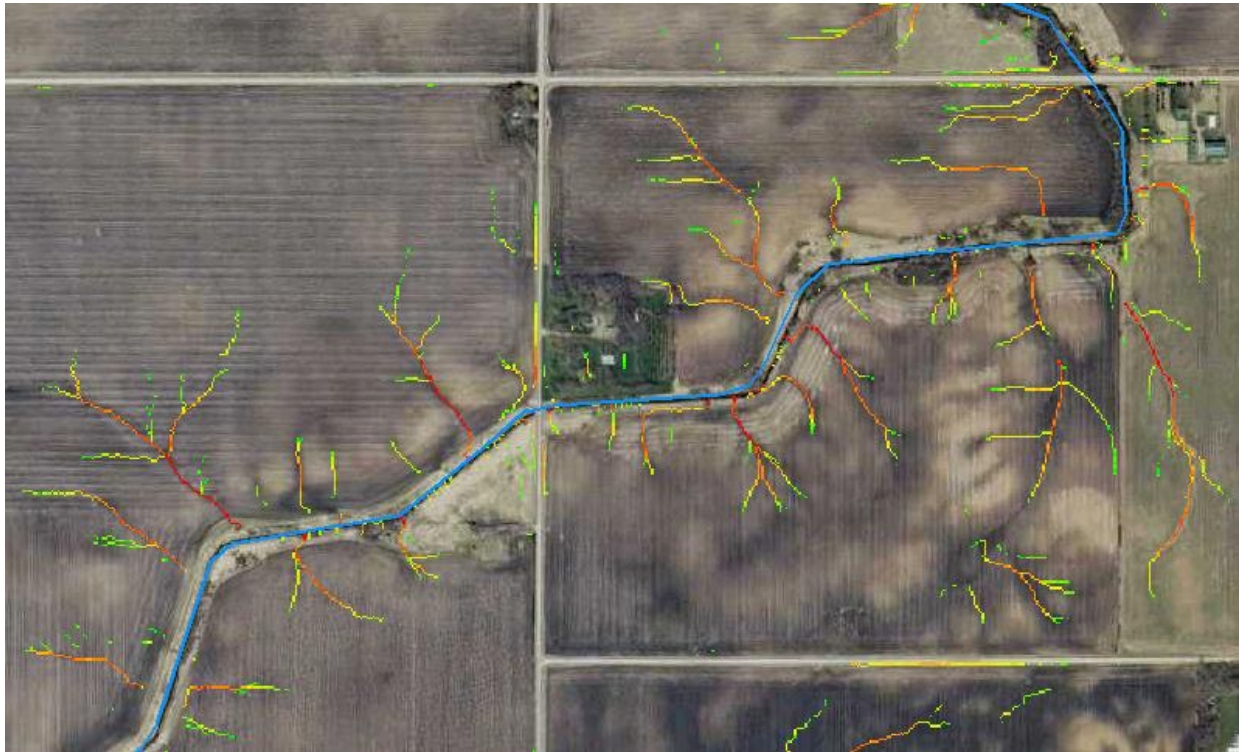

Figure 5. The above images depict how an SPI signature can be visualized as a flow path. The arrows represent flow direction

2. The following metrics should be considered for each potential CSA. They are not listed in order of importance – the weight of each metric should be tailored to fit project goals.

   - Identification by aerial photography – High resolution orthorectified aerial photos play an important role in the CSA identification process. The orthorectification process geometrically corrects aerial imagery such that the scale of the image is uniform. In GIS, orthophotos help match SPI and CTI signatures to physical features on the landscape. Though some large features can be identified using only aerial photos, they are most useful when overlain with SPI or CTI signatures. The layers can then be turned on and off for photo comparisons, or the swipe function can be used for the same purpose. When land cover type cannot be distinguished from aerial photography, land cover/land use layers can be used with the swipe function in a similar fashion.

     If multiple aerial photos are available for your area of interest, consider date, time of year, and surface moisture conditions present at the time of photo acquisition. Common orthophotos available from Minnesota Geospatial Information Office include Spring, Summer and Fall series. The most recently available leaf-off imagery taken during Springtime is often most preferable for CSA identification, as soil moisture and areas prone to ponding are most evident, and surface erosional features have not yet been worked through in the field.
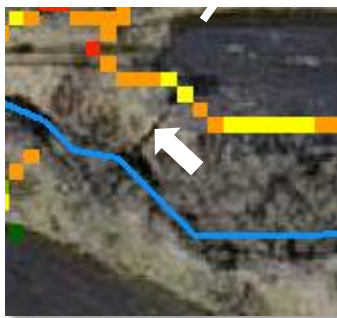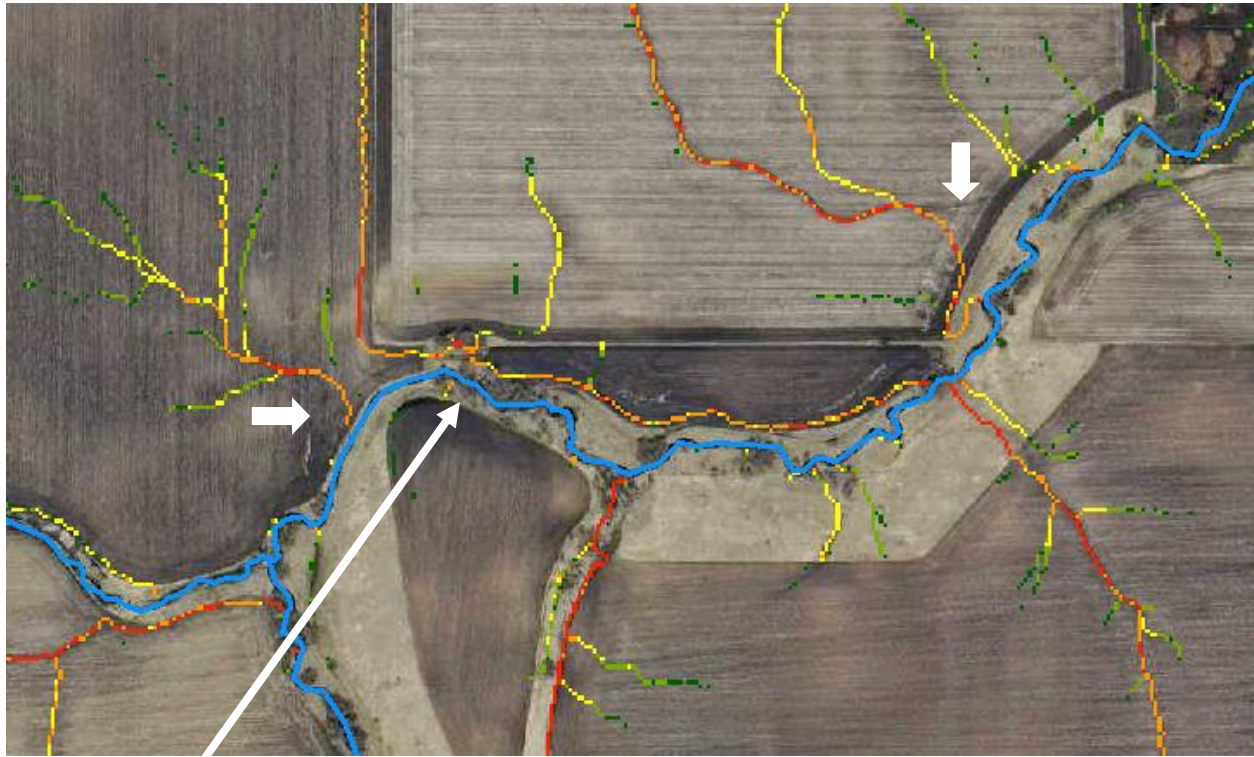
The first image (previous page) is an orthophoto taken in the spring of 2011 with several gullies evident, followed by the same photo with an SPI layer overlain (above). The SPI signatures closely match the surface erosion where flows concentrate. Note the white arrows highlight differences between apparent erosion on the photo vs SPI signatures, likely explained by the gap between date of LiDAR flown (11/27/2008) and aerial photo acquisition (mid-April, 2011).

- Signature length – SPI signature lengths are representative of their associated contributing areas. Longer SPI signatures will typically have larger upland contributing areas and therefore increased risk of sediment and nutrient volume conveyance. The length should be considered in relation to other signatures in close proximity in order to ignore threshold bias. Slope must also be considered in relation to signature length, as short signatures occurring over an area of high relief can exhibit considerable surface erosion vs. a short signature over flat topography.
  - *Note:* Signature lengths can be easily calculated when using line vector data in lieu of a raster SPI dataset [see Average SPI value metric below].
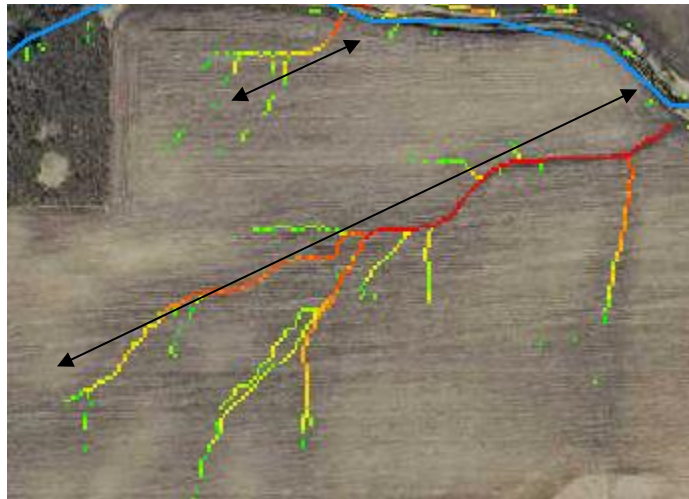
- Average SPI value – The portions of a signature with the highest SPI values have the greatest potential to erode the landscape. The overall SPI value of a signature flow path can be visualized using a smoothed or "stretched" color gradient.
  - *Note:* Advanced GIS users may prefer a quantitative approach over this qualitative visualized one by converting a reclassed SPI raster to either point or line vector data. Individual SPI statistics can then be calculated for each signature. The mean, minimum, maximum, sum, and standard deviation can be particularly useful for prioritization purposes. Signature length can also be easily calculated if using line vectors.
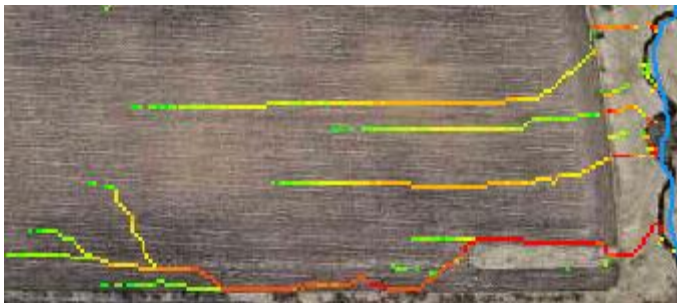

The figure on left shows differences between signatures of different average SPI values. The signature on the bottom has a noticeably higher overall SPI value than the top three signatures.

- Contributing area – The contributing area upland of CSAs can be used to estimate the amount of potential sediment and nutrient delivery at those pour points. Contributing areas can be manually created by "heads-up" digitization using elevation contours, or by using third party software to automatically create catchments. A free-to-use ArcToolbox set is available from the Natural Resource Conservation Service (NRCS) named 'NRCS GIS Engineering Tools v1.17' which allows creation of contributing area catchments from a user defined point (along with many other great scripts). The image on right shows an example of the NRCS tool's Watershed Delineation toolset over an SPI layer and orthophoto. The acres and average slope are automatically calculated as shown.

  See Appendix section A.6 for step-by-step instructions for watershed creation using the NCRS tool.
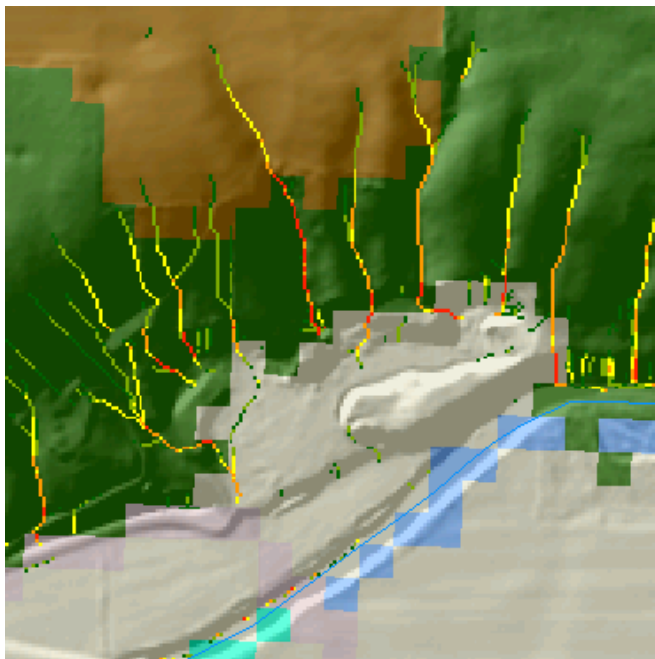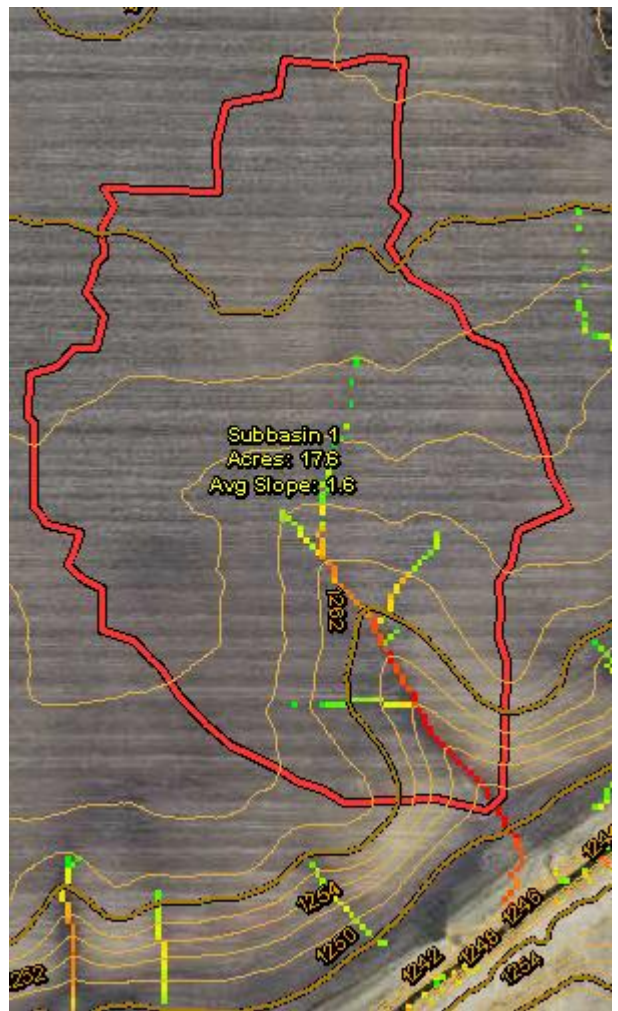
- Land use/land cover – land cover information can aid initial large-scale screenings for CSAs and be used to filter out use types that are of low priority. Historical land use information combined with historic aerial photos can also be a great asset for checking crop rotation practices at the field scale. For instance, priorities can be targeted to fields identified as implementing sequential seasons of continuous corn (corn on corn without legumes).

  The image on left shows land cover in several colors – brown/cultivated crop; green/forest; white/grassland; and blue/water. In this example, the three SPI signatures advancing into the cropland may be of higher priority than the surrounding signatures confined to forestland.

- Proximity to water – Signatures that terminate in or near surface waters are typically of highest concern, though the exact location of the CSA point placement may vary depending on project goals. For instance, if agricultural funds are to be used to install BMPs in upland areas, users might only target upland field SPI signatures and place points at field edges, whereas TMDL concerns may shift user focus to riparian areas and signatures entering waterways.
  - *Note:* Advanced users may wish to create an SPI layer clipped from a stream corridor buffer for riparian-only CSA identification, and vice versa for upland-only identification.
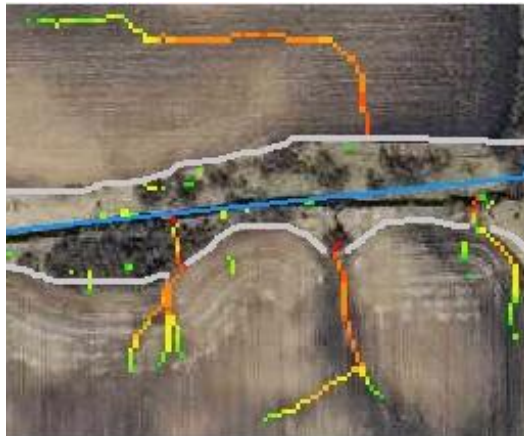
The grey horizontal lines represent the extent of the stream buffer. The top signature terminates at the buffer-field edge. The lower signatures terminate at the stream edge. *Note:* the bottom middle signature terminates just past the buffer. A field visit verified a steep knick point drop to water level at the signature terminus.
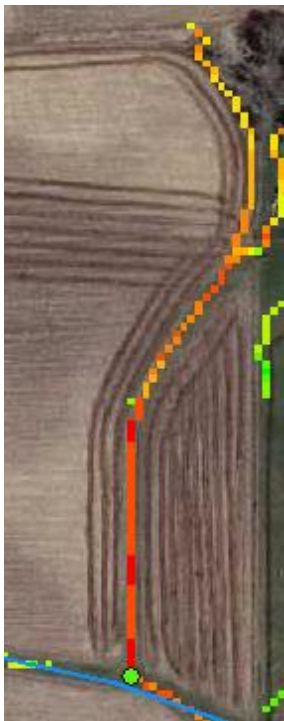
- Existing conservation – Conservation practices (CPs) may already exist that address located CSAs, some of which may be evident using high resolution aerial photos. Local knowledge of existing best management practices and conditions should be used when locating CSAs. It should be noted that the presence of CPs shouldn't necessarily eliminate the placement of a CSA unless the condition of the practice is known. All CPs have a useful lifespan, and their condition cannot always be ascertained from GIS and remotely sensed data.

The three images, starting from the furthest left, show an SPI signature leading to an intermittent stream. The middle image shows conservation practices exist under the SPI signature, in this case a grassed waterway. Using color infrared (CIR) orthophotos, shown in the right image, can also greatly aid in detecting vegetated areas. CIR photos show vegetation as red and bare soil as green color.
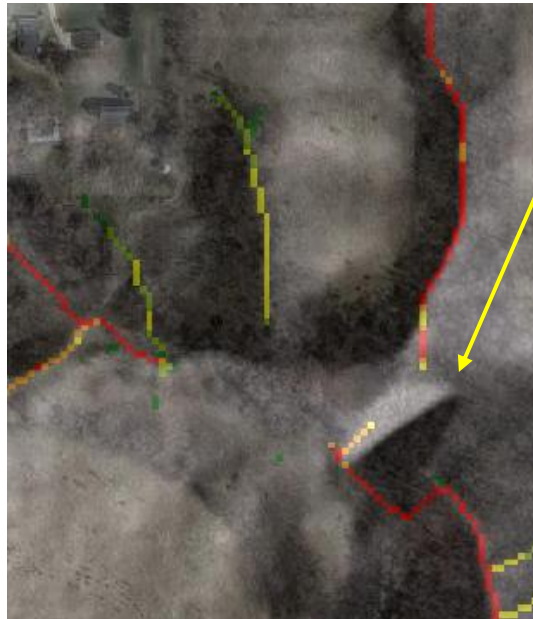
The hillshade layer can aid in locating existing topological conservation practice features, such as the water and sediment control basin pictured above and middle. These features can be hard if not impossible to spot with just aerial photos and SPI signatures (far left image).

- Sub-catchment soil characteristics – A Soil Erosion Risk raster layer can be used to display areas with high soil sheet and rill erosion risk. The raster layer is available as part of the Minnesota Environmental Benefits Index (EBI) series from the Minnesota Board of Water & Soil Resources (BWSR) website (see 'Data acquisition' section for link). Based off the Universal Soil Loss Equation (USLE), the 30 meter spatial resolution raster was calculated using rainfall erosivity (R), soil erodibility (K), and topographic length and slope factors (LS). The cropping management (C) and conservation practice (P) factors were omitted (CP=1) as they would warrant field specific data that is not readily available.

The Soil Erosion Risk raster layer, much like SPI/CTI layer(s), is most useful when displayed with values above a certain threshold. These can be created in the same manner as the percentile thresholds calculated previously with SPI and/or CTI layers. Common thresholds used to display areas of elevated soil erosion risk can range from the top 30% of values and up, though with inherent USLE factor and source data variability, users may find useful thresholds significantly below that range.

The image on left shows a series of small SPI signatures originating in an upland cultivated crop field. The large, tan colored shape represents the top 15% of the Soil Erosion Risk values (30 meter pixels) within the Pelican Lake HUC12 catchment (Stearns Co., MN). A field visit confirmed slight erosion occurring from the signature nearest the high Soil Erosion Risk percentile values (circled in white).

- SSURGO soils data – The NRCS Soil Survey Geographic Database (SSURGO) is a large collection of soil-related data that can be used to inform CSA identification. The SSURGO nationwide database contains a multitude of information sorted within unique soil map units. SSURGO data can also be integrated within the ArcGIS environment by use of the NRCS Soil Data Viewer extension which provides the ability to visually map each individual criterion with matching attributes. Available data range from physical soil properties to construction, development, and planning suitabilities (see next image). Several criteria within the database can be of particular use for CSA identification, including depth to water table, ponding and flooding frequency, crop productivity index, drainage class, and hydric rating, among others.
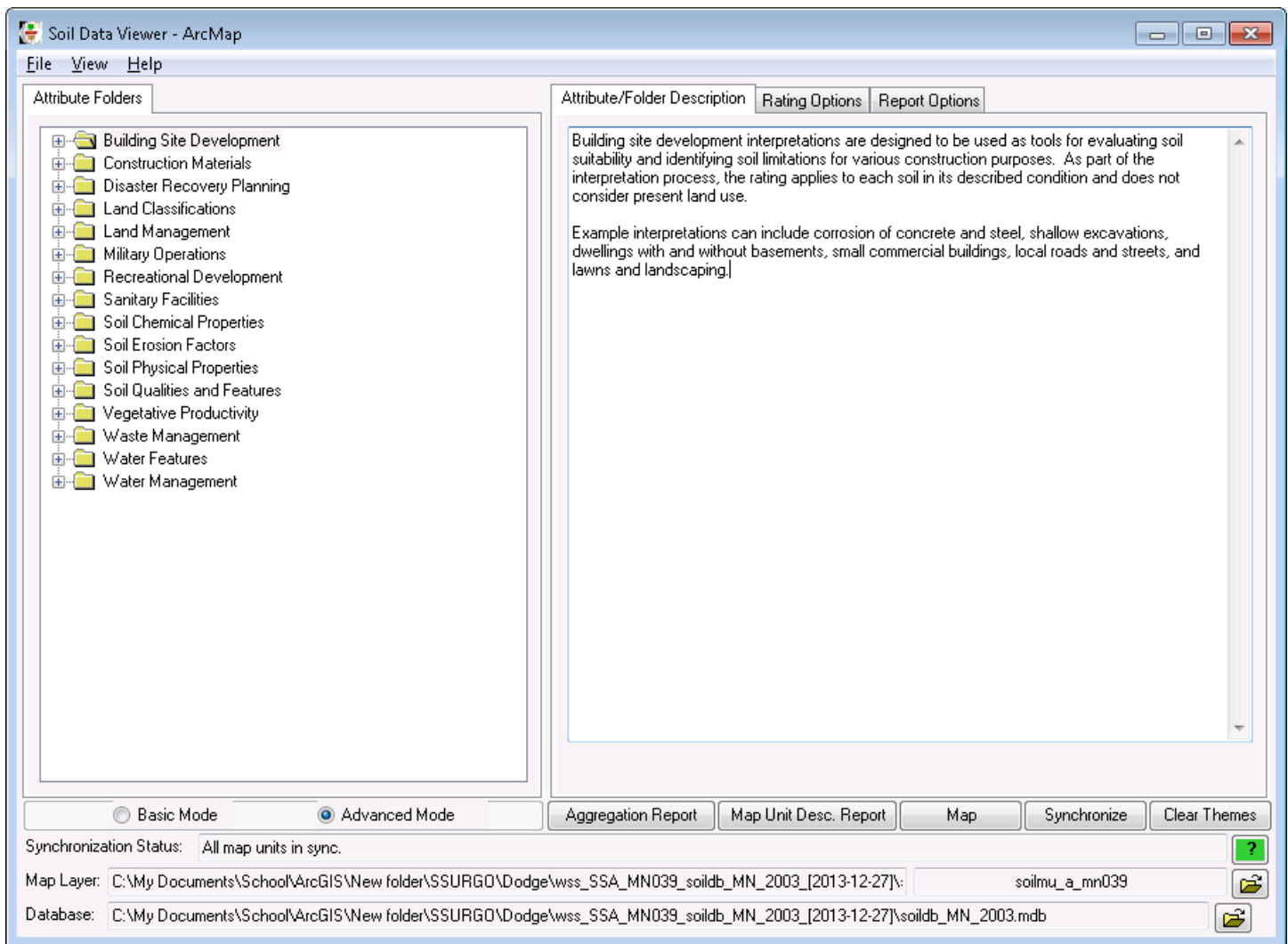
3. When suitable locations have been identified for CSA placement, start editing on your CSA point shapefile/feature class.

- **ArcGIS ver. 9.**x: Using the editor toolbar:

Set the Task pull down to "Create New Features" and the Target to your CSA point layer. Use the Sketch function (the pencil-shaped icon) to place a single geographic CSA point on the map with each click.

Note: You can use the Undo button or press Ctrl+Z to remove the last point placed while editing.

- **ArcGIS ver. 10.**x: Start an editing session with the CSA point layer and the Create Features window will open. Select the CSA point layer in the Create Feature window. At the bottom of the window under **Construction Tools**, click the Point button.
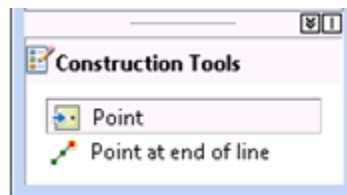
The cursor will turn into a point editor, and each click on the map will place a geographical point at that location.

4. When finished creating new features, save your edits, and stop editing using the Editor toolbar pull down menu.
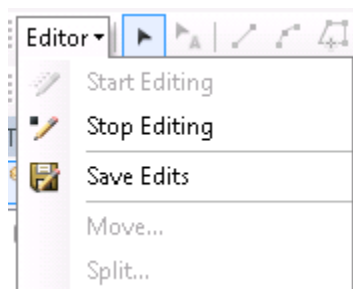
CSA output and evaluation

Once the Critical Source Area point layer has been completed, it can be used to create physical and digital maps, and exported into a variety of mobile devices to guide field work. Common mobile devices include:

- Tablets with ArcGIS for Windows Mobile installed (one mobile deployment license is included with each ArcGIS Desktop license)
- iPad with ArcGIS free app
- Handheld GPS units with a Windows mobile operating system installed

The accompanying Field Assessment Manual can aid in data collection and evaluation during field visits. An overall determination of site status at each CSA should be made, e.g.:

- Where appropriate conservation measures are in place, recognize good site management
- Where improvements could be made, suggest possible conservation measures
- Where CSA tools were in error, record the findings (tracking errors will improve both the GIS protocols and a GIS professional's judgment that is required during evaluation)

<u>Case Studies</u>

Digital terrain analysis has been used in several capacities stemming from initial research to practical application throughout the world. Much of the work has recently taken place in the State of Minnesota, thus providing several relevant case studies showcasing the tool's strengths and limitations. Each case study is organized by location and watershed, and they describe the agroecoregion, landscape and scale of the study area, known impairments, types of critical source areas identified in both GIS and field, the type of field validation preformed, and observations and lessons learned.

An agroecoregion is a concept stemming from an extensive multi-disciplined research project conducted at the University of Minnesota. The idea of agroecoregions was created to define regions with relatively homogenous physical characteristics in agriculturally impaired Minnesota watersheds. Minnesota has 39 distinct agroecoregions which are landscape units that share relatively uniform crop productivity, climate, geologic parent material, soil drainage, and slope steepness. The researchers found that the variance in soil erosion, stream biotic habitat, stream water quality, lake water quality, and ground water quality was smaller within agroecoregion boundaries than within watershed boundaries, and that through linked biophysical and economic modeling, the economic costs of reducing phosphorus loads to streams were lower when best management practices (BMPs) were targeted to specific agroecoregions compared with an untargeted strategy involving entire watersheds (Hatch et. al., 2001). Thus agroecoregions provide a nice complement to Critical Source Area identification and remediation.

The following site provides a link to download the Minnesota agroecoregion layer as a polygon feature class within and outside a file geodatabase (either can be directly accessed within ArcGIS software): http://devel.gisdata.mn.gov/da_DK/dataset/agri-agroecoregions/resource/f53059b9-8339-4528-a8b4-b291551062de

The Zumbro River watershed was the focus of a study involving digital terrain analysis and critical source area identification; several locations in the watershed were visited between 2012 and 2013 and excerpts from those findings are highlighted in the following sections.

Level Plains

The Level Plains agroecoregion is located in Southeast MN and composed of fine-textured, soils with row crop production on relatively flat to moderately steep topography without sinkholes. The majority of soils are poorly drained, while a significant portion is well drained. This agroecoregion has a very high density of intermittent streams and a moderate density of permanent streams. Water erosion potentials are high, while wind erosion potentials are low. Practices to control soil erosion by water and sediment delivery to streams are important. These include conservation tillage, and grassed filter strips along streams. Tile intakes at the base of steep slopes should be replaced with French drains or blind inlets (Olmsted[1]).

<u>Case Study #1</u>

Case study #1 is located in Dodge County, MN in the headwaters of the Middle Fork of the Zumbro River near West Concord, MN. A 1¼ mile long ditched stream section was walked on Nov. 18th, 2012.

November weather in 2012 as monitored at the Dodge County Municipal Airport had a mean temperature of 37°F and a total of only 0.19 inches of precipitation compared to a 30+ year average of 1.76 inches (NOAA archives). The region was considered to be in moderate drought at the time (droughtmonitor.unl.edu). The stream section walked has a turbidity impairment.

Several critical source areas were identified in the field, nearly all of which were gullies and a few instances of bank slumping and tile outlet erosion. Length, width, and depth measurements were taken at each identified erosional feature.

The ephemeral gully shown in these images is entrenched starting approximately 185 yards from the pour point and drains an area of 43 acres with average slope of 3.9%. The bottom left image displays the top soil erosion risk raster values – the yellow corresponds to the top 3%, and red the top 1% within the HUC12 catchment. The bottom right image shows the SPI signature associated with the erosional feature, created using 1 meter pit fill z-limit. The picture on left was taken from the opposite (northern) bank looking south-southwest.
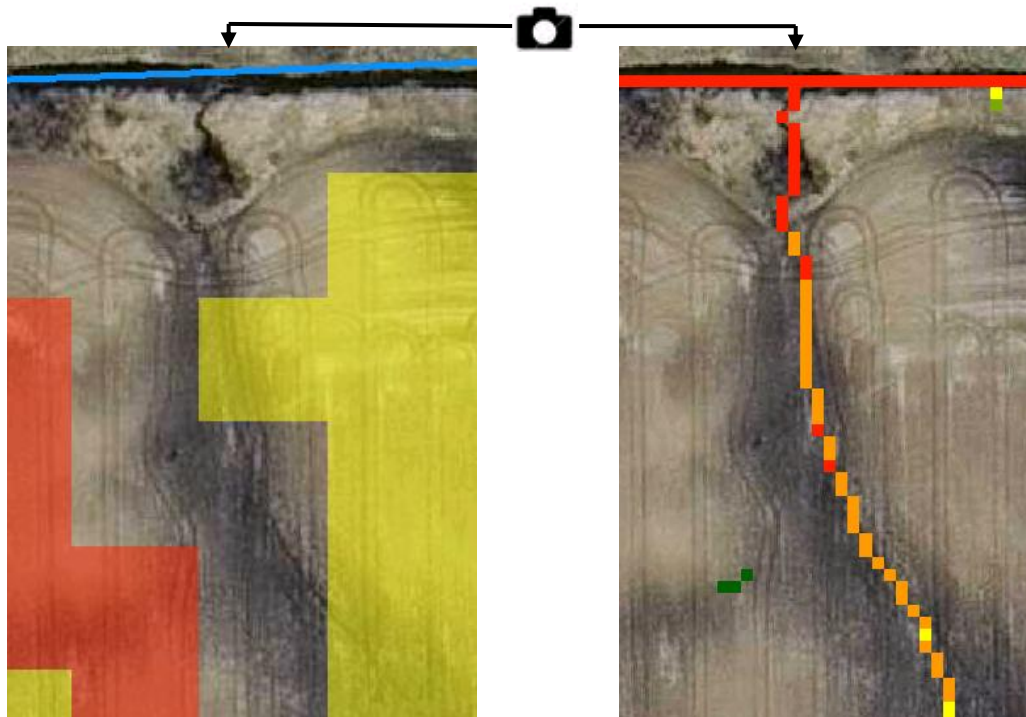
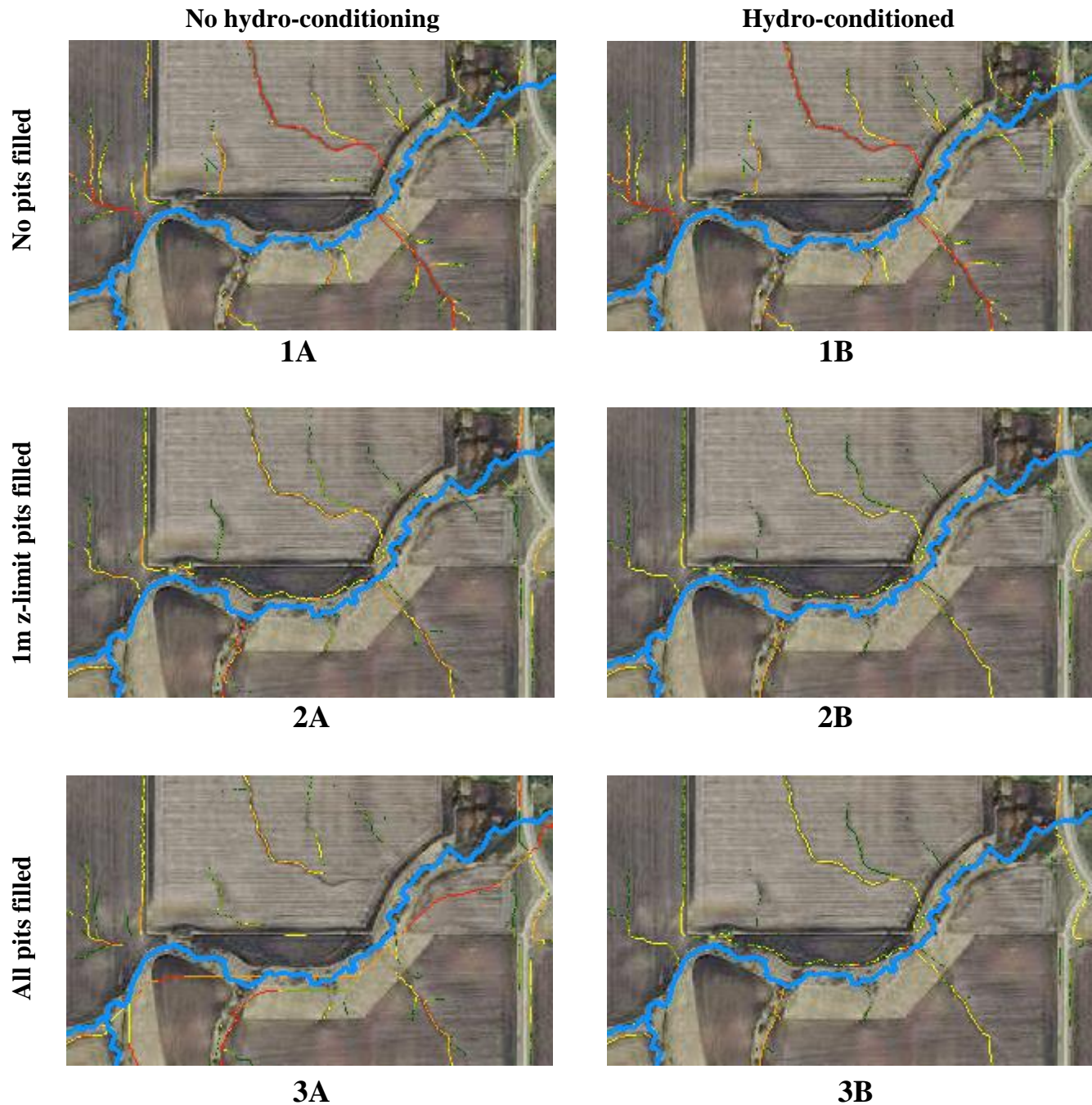Observations and lessons learned: In ditched stream sections with steep, high walls, an SPI signature as short as one to two pixels (depending on threshold used) can often coincide with significant erosion in the field as compared to the same length signature along flat riparian areas. When using short SPI signatures to identify and rank potential CSAs, it is especially important to consider contributing area and soil erosion risk characteristics for each point.

Several SPI layers were calculated in the study area to show how both pit filling and hydro-conditioning affect signatures. The site shown in the following images was chosen for the presence of a large culvert road crossing and a high concentration of stream flow. Sites with those two characteristics tend to produce erroneous SPI signatures when pit filling without hydro-conditioning is used (**3A**). Note the signature that parallels the buffer just north of the stream, which doesn't exist in the non-pit filled images. Also note the signature that starts at top of images and either terminates at buffer (non-pit filled) or stream (pit-filled).

No hydro-conditioning   **Hydro-conditioned**

No pits filled

1A   **1B**

1m z-limit pits filled

2A   **2B**

All pits filled

3A   **3B**

The above figures show SPI signatures calculated from a 3 meter DEM with varying degrees of pre-processing performed. All SPI signatures are from the 97.5th percentile within the extent shown (~136 acres). Figures in the left column were not hydro-conditioned, while figures in right column were – the DEM was hydro-conditioned by burning the stream (blue line) through the north-south oriented road crossing culvert in the top-right of image.

1A & 1B – Not pit filled. The results are essentially identical.

2A & 2B – Pit filled using a 1 meter z-limit. The displays are nearly identical with only slight color gradient variation between the two. Note the new signatures near the buffer just north of stream that didn't exist in **1A & 1B**. These additions can influence CSA predictions.

3A & 3B – Pit filled with no maximum z-limit, meaning all pits were completely filled. In this example, **2B** and **3B** are nearly identical. This is not always the case [see case study #5 – Steep Dryer Moraine]. Note the straight signature somewhat paralleling the stream in **3A**. This can be used to estimate where main channel flow will exist during flooding or culvert blockage. Caution should be used when identifying potential CSAs from those seemingly "erroneous" signatures.

Rochester Plateau

The Rochester Plateau agroecoregion is located in Southeast MN and composed of well-drained, fine-textured loessial soils developed on moderate to steep slopes in karst with a high density of intermittent streams and sinkholes, and a mixture of row crop, livestock operations, and dairy production systems. Water erosion potentials are extreme, while wind erosion potentials are low. Stream water quality ranges from fair to poor. Phosphorus transport risks to surface waters are high to severe. Major resource concerns in this agroecoregion are soil erosion by water, cattle and hog operation management, nutrient management from manure and fertilizer, and rapid leaching or seepage of pollutants to ground water in areas with karst topography and sinkholes. Soil erosion should be controlled by any or all of the following practices where applicable: conservation tillage, contour farming, stripcropping, terracing, grassed waterways, and sediment detention basins. Riparian buffer strips are recommended along streams. Best management practices for cattle include livestock exclusion from streams, and practices to reduce feedlot runoff (Olmsted[1]).

Case Study #2

Case study #2 focuses on a small tributary to the Middle Fork of the Zumbro River in northeast Dodge County, MN approximately 5 miles from Pine Island, MN. The naturally meandering stream contains a Soil Conservation Service grade stabilization pond structure (Fig. 6) that was constructed in the 1967 for controlling gully erosion in the draw and was the site for several sedimentation surveys over the years. Several disjointed sections of the stream were field verified by walking along the stream corridor on October 15th, 2012, including the 1.2 mile section containing the pond.

Figure 6. 5 acre surface area SCS Grade Stabilization Structure on un-named creek, Dodge Co., MN.

October weather in 2012 as monitored at the Dodge County Municipal Airport had a mean temperature of 46°F and 1.28 inches of precipitation compared to an historical average of 2.24 inches. The region was considered to be in moderate drought at the time.

Critical source areas identified were mostly gullies along with some bank slumping and tile outlet erosion. Some areas were worsened by cattle grazing operations in and near the stream. Length, width, and depth measurements were taken at each identified erosional feature.

The gully shown in picture #1 near Berne, MN was the result of concentrated flow from a corrugated 6 in. drain tile outlet (picture #2), and further exacerbated by cattle livestock in and near stream. Forest canopy cover at the pour point reduced chance for vegetated filter establishment. The lower right image shows the SPI signature associated with this gully (all pits filled), which contains a lower average value compared to several surrounding signatures. The semi-transparent white pixels represent this HUC12's top 5% of values from the soil erosion risk raster [see Locate potential CSAs - Sub-catchment soil characteristics section].

Picture #1

Picture #2
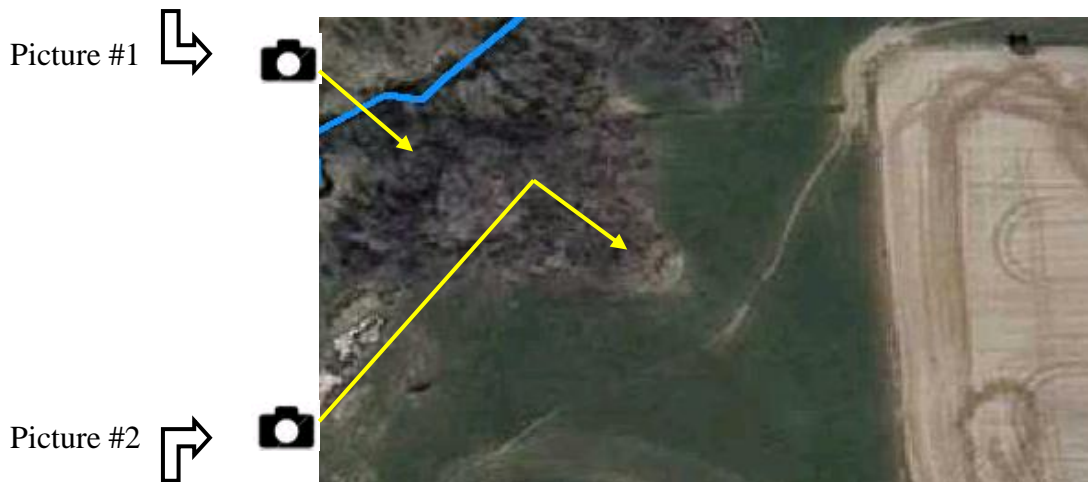
Observations and lessons learned: Most of the larger gullies near case study #2 flowed through riparian forestland where little underbrush was present and were formed from tile outlets located near the fluvial terrace.

Erosional features on the south side of the stabilization structure were expected to be verified in field due to the presence of multiple long SPI signatures, though none were located – possibly due to cattle exclusion in forested areas both north and south of the pond.
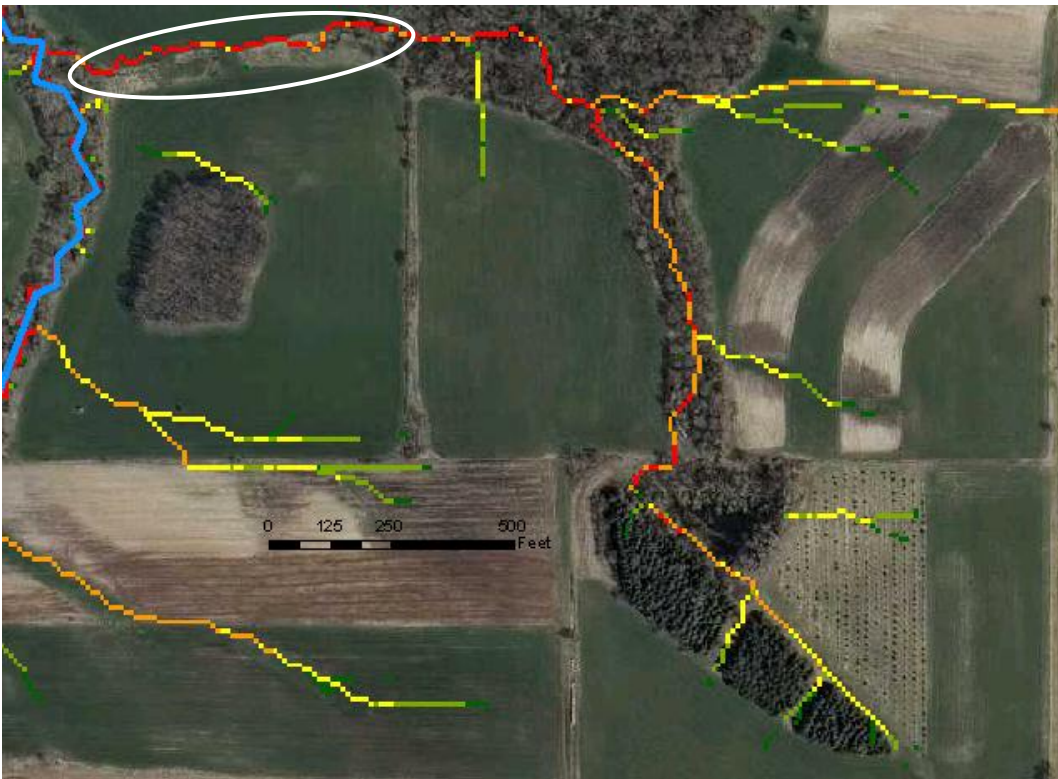
The image on left shows a long (~1/2 mile) SPI signature with several high SPI values following a forested ravine. Users would typically expect to see surface erosion associated with such an SPI, though a field visit showed very little erosion and soil deposition evident from the upslope tree line to the pour point due to a well maintained filter strip (circled in white).

Blufflands

The Blufflands agroecoregion in SE MN has well drained, fine-textured soils on very steep to extremely steep slopes in karst topography. Sinkholes can occur near incised stream drainage networks. This agroecoregion has a very high density of intermittent streams and a moderate density of forested perennial stream networks. Water erosion potentials are extreme, while wind erosion potentials are low. The risk of phosphorus transport to surface waters is moderate to high. On steep lands, practices to control water erosion are important. These include avoiding row crops on steep lands, or if they must be grown on steep lands, using a combination of conservation tillage, strip-cropping, and terracing. Buffers, along with practices that provide stable conveyances of flow, should be provided for ravines and gullies (Olmsted[1]).

Case Study #3

Cold Spring Brook is a designated trout stream in western Wabasha County and drains into the Zumbro River at Zumbro Falls, MN. The stream is located in the Bluffland agroecoregion where forested ravines are commonly found. Sedimentation from upland and in-stream sources have caused Cold Spring Brook to be the target of several in-stream trout habitat improvement and bank stabilization projects over the last several years, with Trout Unlimited funding and conducting much of the work.

Approximately five miles of Cold Spring Brook and its surrounding tributary stream corridors were walked in early to mid-June of 2013 for CSA field validation. The preceding winter at the Rochester International Airport (26 miles south of Zumbro Falls) recorded above average snowfall amounts totaling 73.1" from July 2012 to June 2013. The average annual snowfall for Rochester, MN is 48". The area also received record snowfalls in the first week of May, with Zumbro Falls reporting over 14 inches on May 2nd and 3rd (NOAA). The spring of that year was especially wet in Southeast MN, with April and May receiving precipitation well above average. April and May precipitation totals were 6.33" and 11.04" respectively, with average values of 3.24" and 3.63" respectively (as reported at the Rochester International Airport). Observations during the June field visits noted few crop fields around Zumbro Falls had worked fields due to very wet soils.

Several critical areas were identified in the field – ravines were the most commonly identified feature followed by edge of field gullies and bank erosion. Landowner attempts at remediating erosion were evident at many of the sites. The most common practice was rip-rap placement at head cuts/knick points to control gully erosion and felled trees in ravine channels to reduce flows. Length, width, and depth measurements were taken at each identified erosional feature.

Forested ravines with multiple branches are common in bluffland agroecoregions. Many of the ravine branches were actively advancing into upland fields (pictured). Hillshade layers can aid in identifying these ravines and existing conservation practices such as the grade stabilization structure shown (bottom right). The 98th percentile SPI threshold was found to best represent the flow paths during field verification of this bluffland agroecoregion. The SPI layer shown here was created using a 1 meter pit fill z-limit.
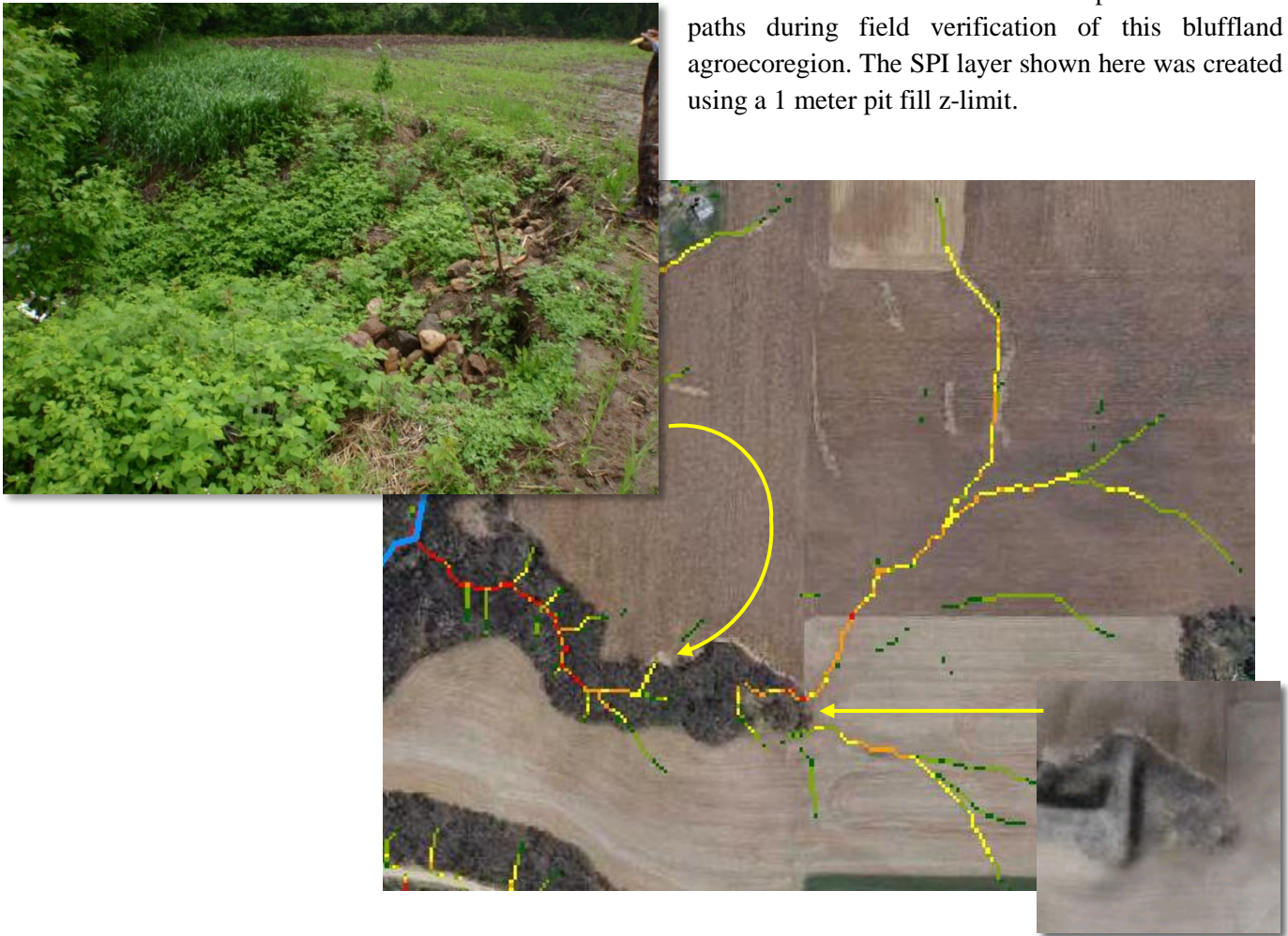
The image below shows a steep bluff near Cold Spring Brook. The bluff had a slope of ~50% (160ft high by 320ft wide). The hillshade layers help to visualize the area, and most SPI signatures can be seen terminating near the bluff's toe. During a field visit, one site along the bluff was found to have considerable active erosion. The gully had a near-vertical head cut of ~10 ft. The SPI signature associated with the feature was the only signature originating from the bluff with connectivity to the stream. This section of bluff was also within the top 10% of soil erosion risk raster values contained within this HUC12 catchment.

Observations and lessons learned: Despite the above average precipitation in spring, Cold Spring Brook – which is nearly 15 river miles long from headwaters to outlet – lost surface flow only 2 river miles from its outlet to the Zumbro River (as observed on June 5th). This changed the priority of any CSAs upstream in dry runs as they presented lower risk of moving sediment downstream. This example emphasized the need for current stream data that includes both perennial and intermittent classifications.

Steep Wetter Moraine

The Steep Wetter Moraine agroecoregion, located in east-central Minnesota, consists of dissected till plain and outwash valleys with ravines commonly occurring along steeply incised river channels, and with a mix of row crops and pasture land.

Case Study #4

The case study #4 site is located in a HUC12 catchment adjacent to the St. Croix River near Basswood Grove, MN. The site was visited to field verify the existence of a potential CSA that was located with GIS digital terrain analysis techniques. The site was selected due to the presence of a long SPI signature with a high mean value (top 1% of SPI from the HUC12) and flow through elevated soil erosion risk values (top 5% in HUC12, white areas in top right image). The SPI shown was created using no pit filling. Field verification showed no erosion present due to active landowner management of several conservation practices, such as the filter strip pictured bottom left and many grassed waterways. Color infrared ortho-imagery (bottom right image) can be used to locate these conservation practices and give a rough evaluation on their condition and density.

Steep Dryer Moraine

The Minnesota Pollution Control Agency (MPCA) assembled a set of BMP implementation strategies for TMDL turbidity reduction compliance in the Chippewa River Watershed in central Minnesota and provided the following descriptions of the Steep Dryer Moraine and Central Till (following section) agroecoregions:

The [Steep Dryer Moraine located in Central to NW MN] agroecoregion consists of loamy soils such as the Chapett, Langhei, and Barnes series developed from glacial moraines. Soils are located on very steep slopes, and are well-drained. Water erosion rates can be severe to extreme, while wind erosion can be moderate to severe. The risk of phosphorus losses to streams and lakes by runoff and erosion is moderate. There are numerous lakes in this agroecoregion, and a moderate density of intermittent streams. Stream water quality is generally poor in this agroecoregion, while lake water quality is threatened. Drinking water wells have a median depth of 80 ft.

Original vegetation was prairie, aspen-oak, oak openings and barrens, and big woods - hardwoods. Protection of lake water quality is a high priority in this agroecoregion. Conservation tillage systems that leave crop residue and maintain soil surface roughness are important. Contour farming and strip cropping are recommended where feasible. Highly erodible land should be placed in permanent grass easements. Restoration of wetlands is encouraged.

Case Study #5

The Pelican Lake watershed, located 15 miles SW of St. Cloud, is a 28.5 sq. mi. catchment that is part of a current TMDL study focused on reducing phosphorus in the lake.

Saint Cloud, MN received 78.5" of snowfall between July 2012 and June 2013 which was above the average annual of 47". The spring precipitation amounts for March, April and May were above average with totals of 2.63", 2.90", and 4.98" respectively compared to averages of 1.55", 2.57", and 2.95" respectively.

SPI layers were created in the watershed to locate potential sediment/nutrient erosion sources, followed with CSA predictions along the streams that discharge into the lake. Field visits to the area in mid-May of 2013 did not reveal significant sources of non-point source pollution adjacent to surface waters as most areas had wide buffers with thick perennial vegetation in combination with well drained soils.
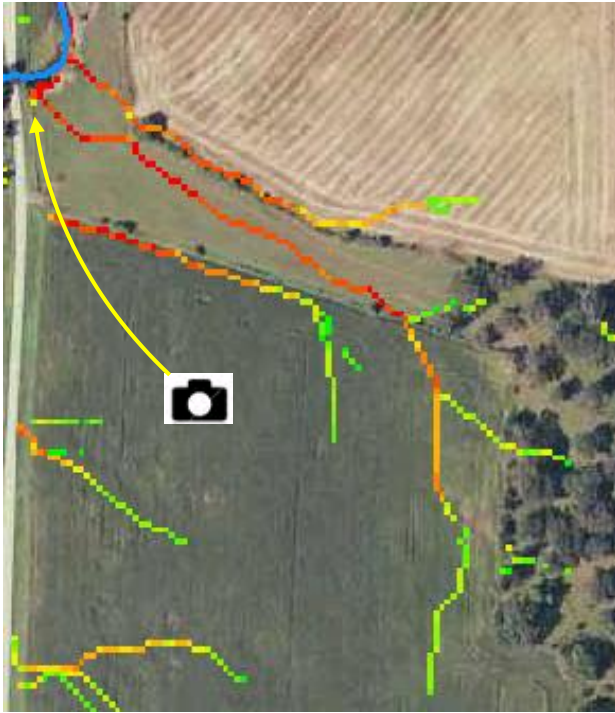
The longest hydrologically connected SPI signature of the top 1% of values in the study area was along Mill Creek (pictured above left). The accompanying field photo shows signs of slumping in the small pasture (foreground) and the landowner had installed rip-rap along the stream bank for stabilization. There was no further evidence of erosion upland of the slumping.

Observations and lessons learned: Similar to the 1st case study from the Level Plains agroecoregion, several SPI calculations were also made throughout the Pelican watershed with varying amounts of DEM pre-processing occurring for each run, specifically pit filled and hydro-conditioning (see following figures). One particular location showed what appeared to be spurious signatures when pit filling with no hydro-conditioning was employed (following figure **3A**), though the flow was confirmed by the landowner stating that ice breakup frequently blocks flow at the road crossing culvert during spring melt and the SPI signature was actually where flow diverts. Out of the six figures shown, the SPI signatures displayed in figure **2B** created from a 1m z-limit pit filled and hydro-conditioned DEM was confirmed to most closely resemble surface runoff during periods of normal stream flow in the Pelican watershed.

No hydro-conditioning   **Hydro-conditioned**
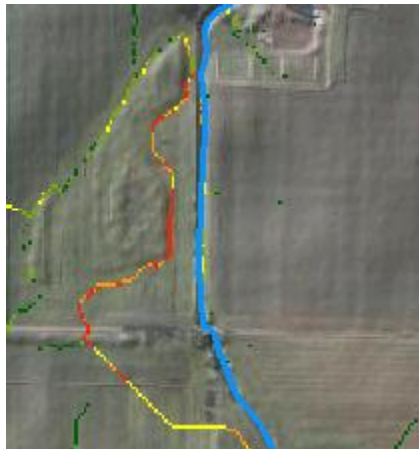
No pits filled
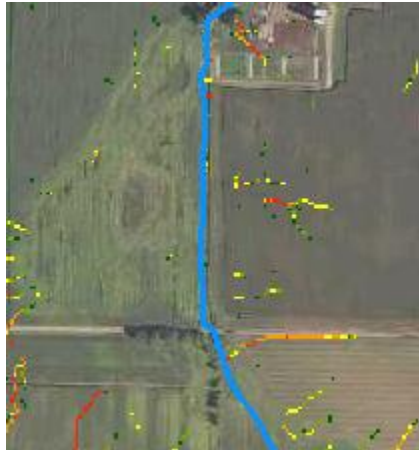
1A

1B

The six figures on left display SPI signatures calculated from a 3 meter DEM with varying degrees of pre-processing performed. All SPI signatures are from the 97.5[th] percentile within the extent shown (~41 acres). Figures in the left column (**A**) were not hydro-conditioned, while figures in right column (**B**) were – the DEM was hydro-conditioned by burning the stream (blue line) through the east-west oriented road crossing culvert.

1A & 1B were not pit filled. The results are essentially identical.

1m z-limit pits filled

2A

2B

2A & 2B were pit filled using a 1 meter z-limit.

3A & 3B were pit filled with no maximum z-limit, meaning all pits were completely filled.

All pits filled

3A

3B

Central Till

This agroecoregion in central Minnesota consists of well-drained, moderately steep to steep landscapes with fine textured soils of the Ahmeek, Greenwood, and Mora series. Water erosion potentials can be high. Stream and lake water quality are generally fair. Ground water quality is generally fair. Original vegetation was big woods - hardwoods, conifer bogs and swamps, aspen-birch, and prairie (MPCA Chippewa River Watershed Draft TMDL BMP strategies).

<u>Case Study #6</u>

The study area in case study #6 is near Spring Hill, MN in central Minnesota. The site was visited in mid-April of 2012 to field verify Critical Source Area predictions made using terrain analysis attributes. Factors that led to choosing the site include the presence of long SPI signatures with high average cell values through steep upland slopes.

The field visit did not verify considerable erosion present in the upland field containing the SPI signatures possibly due to the field being recently tilled. The downstream area from the pour point relating to the highest ranked SPI signature at the site had in-channel sedimentation evident. That particular SPI was found to terminate at an in-stream vehicle crossing built with course gravel and no buffer.

St. Cloud winter snowfall total received between July 2011 and June 2012 was 27.4" (http://climate.umn.edu/) – well below the average of 46.1". March and April precipitation totals were near average for those months.
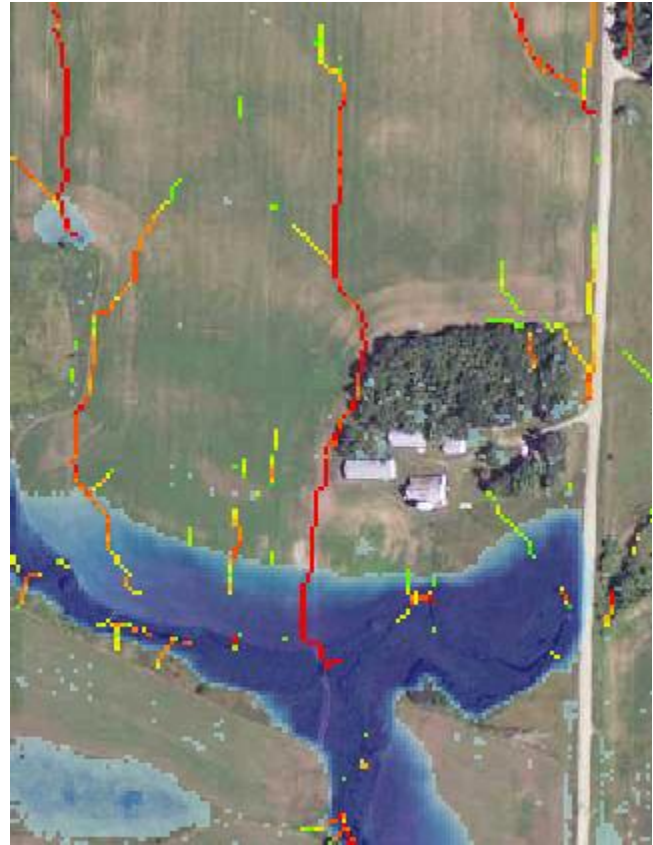
This example near Spring Hill, MN shows a long SPI signature with a high average value (centered, upper right photo) containing the top 1% of values in a 16.5 sq. mi. HUC12 catchment. A newly built concrete culvert was installed at the downstream road crossing (circled in yellow). A modified CTI raster was used in the top right image (blue pixels) to show the potential ponding if the culvert was to fail, or jam with ice, which could create additional hydrologic connections to several nearby SPI signatures.

The ponding raster also aided in locating a nearby sinkhole depression, shown in the right image with the sink circled in yellow.

Wetter Clays & Silts

The Wetter Clays & Silts agroecoregion is located in south-central Minnesota and is a vast, flat fertile plain of poorly drained deep soils dominated by row cropping with low erosion rates and high nitrate losses. The region has had a dramatic increase of drain tile installation within the last two decades and the majority of fields now take advantage of artificial drainage.

Case Study #7

Case study #7 focuses on the small 8.6 mi^2 Beauford Watershed in Blue Earth County, MN – part of the larger HUC8 La Sueur Watershed in the Minnesota River Basin near Mankato, MN. All the ditched streams in the Beauford watershed were walked along as part of a project to both identify upland erosion and assess the cost and time involved in doing so. Side inlets were the most commonly identified erosional feature along ditched waterways in the watershed. Side inlets are a form of artificial drainage common in the Minnesota River Basin and other regions with very flat terrain. A bermed ridge is formed parallel to the ditch, and a depression and drain pipe are installed perpendicular to drain ponded water to the ditch. Gullies were also identified during the survey.
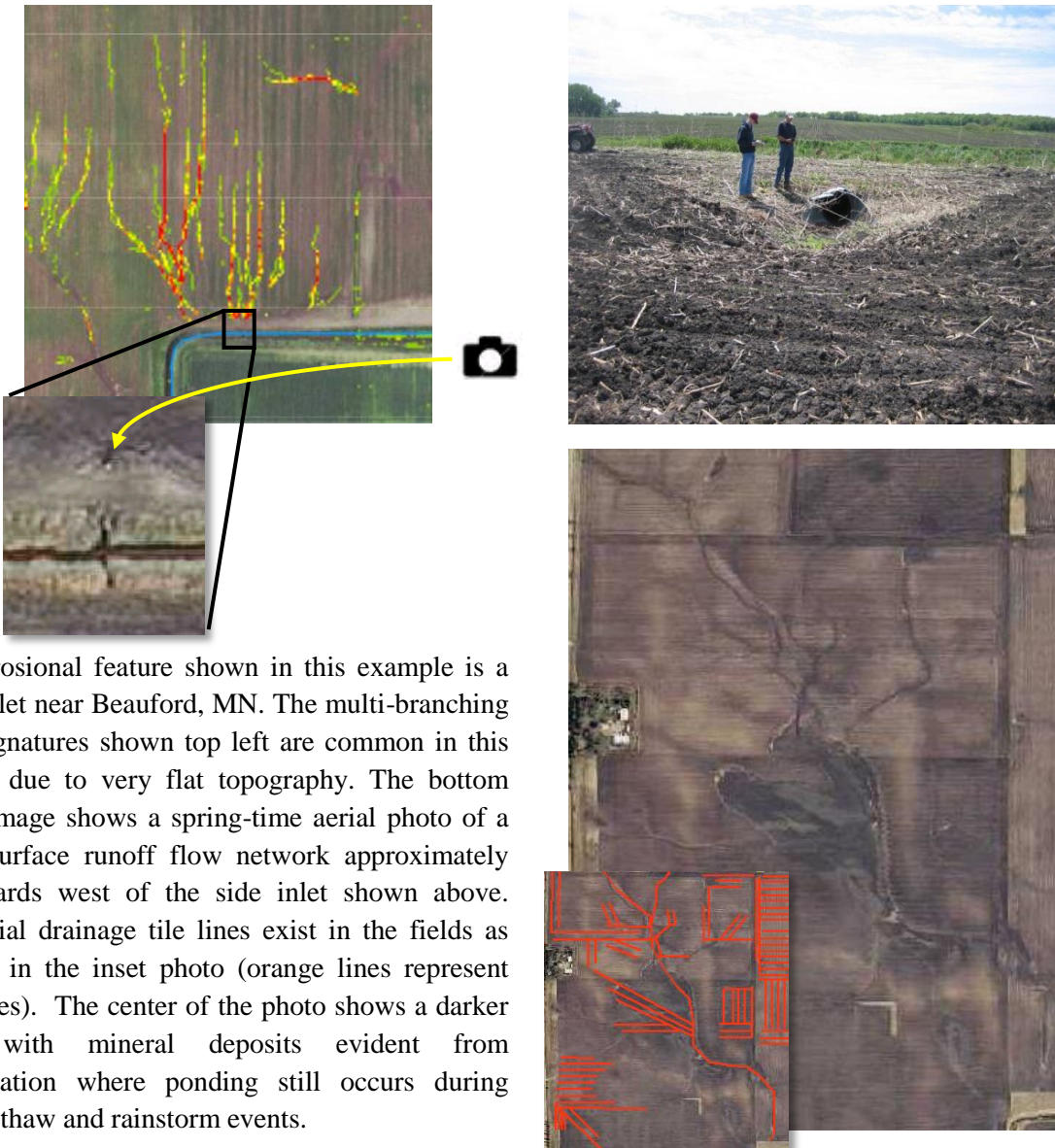
The erosional feature shown in this example is a side inlet near Beauford, MN. The multi-branching SPI signatures shown top left are common in this region due to very flat topography. The bottom right image shows a spring-time aerial photo of a long surface runoff flow network approximately 500 yards west of the side inlet shown above. Artificial drainage tile lines exist in the fields as shown in the inset photo (orange lines represent tile lines). The center of the photo shows a darker area with mineral deposits evident from evaporation where ponding still occurs during spring thaw and rainstorm events.

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Appendix

A.1 Digital terrain analysis accuracy results

Table 2 shows comparisons between the Sediment Delivery Potential (SDP) of erosional features identified or not identified in several Dodge Co., MN study areas using the GIS–based validation survey technique and a 97.5[th] percentile threshold calculated from each HUC12 study area.

SDP scores consist of three incremental values of risk: low, medium, and high (1, 2, and 3 respectively). The score was determined by a field technician's best professional judgment. Some of the factors that influenced the SDP score include general size and position of the feature in the landscape, the size of the drainage contributing area, and obvious indicators of sediment delivery, such as active alluvial fans. Although subjective, these SDP scores provide qualitative categories that can be used to compare the relative impact of gullies on potential water quality degradation (Galzki et. al., 2011).

Table 2

SDP value of erosional features	Validation result		Total erosional features identified	Accuracy (%)	Commission errors
	Features identified	Features not identified			
1 (Low)	44	15	59	75%	N/A
2 (Medium)	23	6	29	79%	N/A
3 (High)	8	0	8	100%	N/A
Total	75	21 (omission errors)	96	78%	74 of 139 pts

In total, 96 features (gullies, ravines, tile outlets, bank slumps, grassed waterways) were identified in the field.

21 out of 96 (22%) field surveyed points were not closely related to a 97.5[th] percentile SPI signature (errors of omission). 15 of these points had sediment delivery potentials (SDP) of 1 (lowest risk) and the remaining 6 had SDPs of 2 (medium risk).

74 out of 139 (53%) CSA prediction points combined in all study areas were not closely related to an erosional feature during the field survey (commission errors or false positives).

The 'Total' row is showing that out of the 96 features identified, 75 were closely associated with an SPI signature from GIS terrain analysis, and 21 were not (omission errors). The commission errors, also known as false positives, are predicted CSA points (there were 139 in total) placed using preliminary GIS analysis that were not closely associated with a field surveyed location.

The following two figures contain boxplots using data from the same Dodge Co. study areas. Figure 7 compares a 1-10 SPI rank to erosional feature SDP assigned values. The lower limit of the box represents the 1st quartile, the top limit is the 3rd quartile, and the middle solid line is the median value of the data. The whiskers are 1.5x the inner quantile range, with dots representing outliers. Figure 8 shows the same boxplot

configuration with a comparison made between field verified points vs. an equal number of randomly generated points.
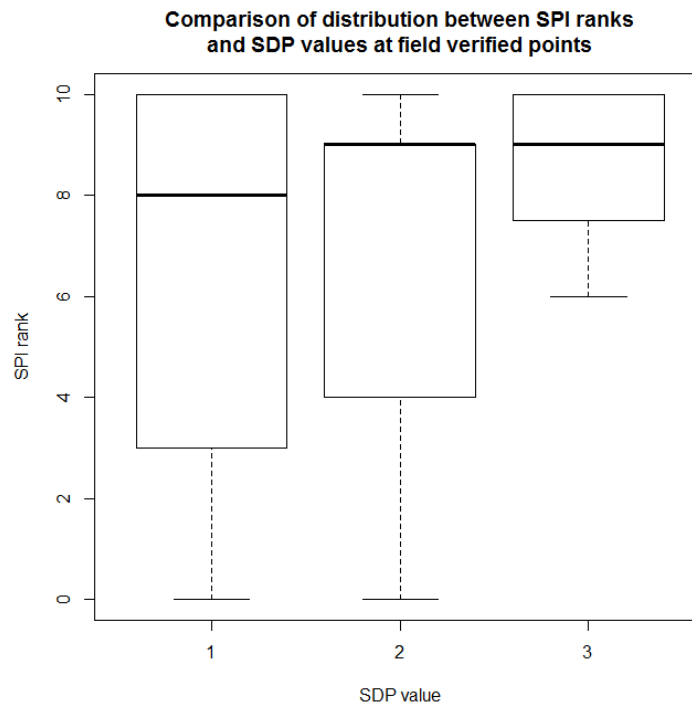
Figure 7
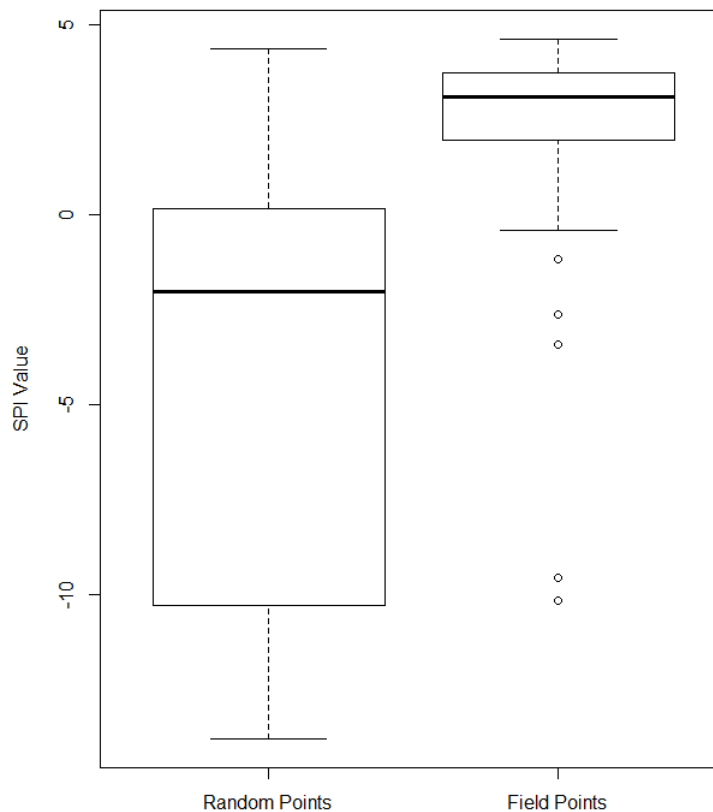
Figure 8

Table 3 shows comparisons between the Sediment Delivery Potential (SDP) of erosional features identified or not identified in several Wabasha Co., MN study areas using the GIS–based validation survey technique with a 97.5th percentile threshold.

Table 3

SDP value of erosional features	Validation result		Total erosional features identified	Accuracy (%)	Commission errors
	Features identified	Features not identified			
1 (Low)	12	1	13	92%	N/A
2 (Medium)	15	3	18	83%	N/A
3 (High)	3	0	3	100%	N/A
Total	30	4 (omission errors)	34	88%	12 of 34 pts

In total, 34 features (gullies, ravines, tile outlets, bank slumps, grassed waterways) were identified in the field.

4 out of 34 (12%) field surveyed points were not closely related to a 97.5th percentile SPI signature (errors of omission). One of the points had an SDP of 1, and three had SDPs of 2 – one of which was a slumping feature which typically do not have SPI signatures relating to them.

10 out of 34 (29%) field surveyed points were not closely related to a 99th percentile SPI signature (errors of omission). The majority of these points had estimated SDPs of 2. *This is not shown in the above table*.

12 out of 34 (35%) CSA prediction points were not closely related to an erosional feature during the field survey (commission errors or false positives).

The 'Total' row is showing that out of the 34 features identified, 30 were closely associated with an SPI signature from GIS terrain analysis, and 4 were not (omission errors). The commission errors, also known as false positives, are predicted CSA points (there were 34 in total, it was a coincidence that there were also 34 field points) placed using preliminary GIS analysis that were not closely associated with a field surveyed location.

The following two figures contain boxplots using data from the same Wabasha Co. study areas. Figure 9 compares a 1-10 SPI rank to erosional feature SDP assigned values. The lower limit of the box represents the 1st quartile, the top limit is the 3rd quartile, and the middle solid line is the median of the data. The whiskers are 1.5x the inner quantile range, with dots representing outliers. Figure 10 shows the same boxplot configuration with a comparison made between field verified points vs. an equal number of randomly generated points.
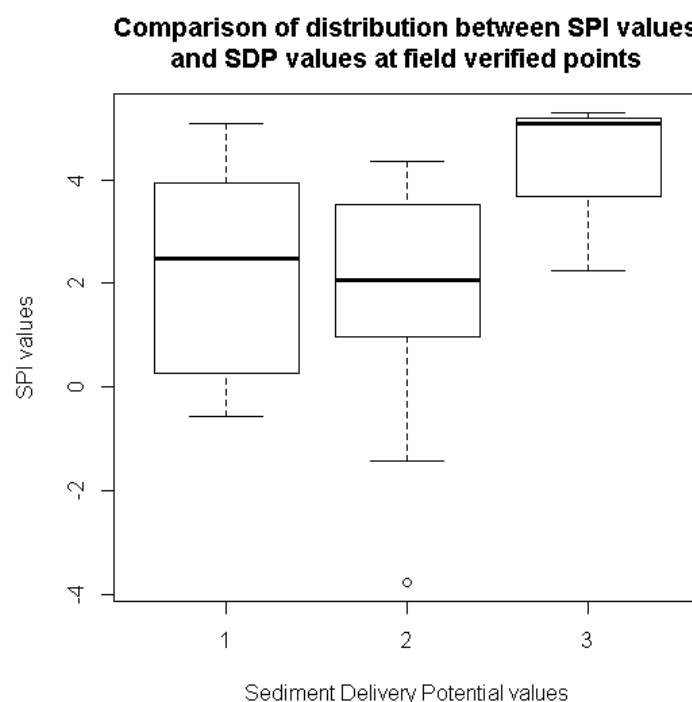
Figure 9
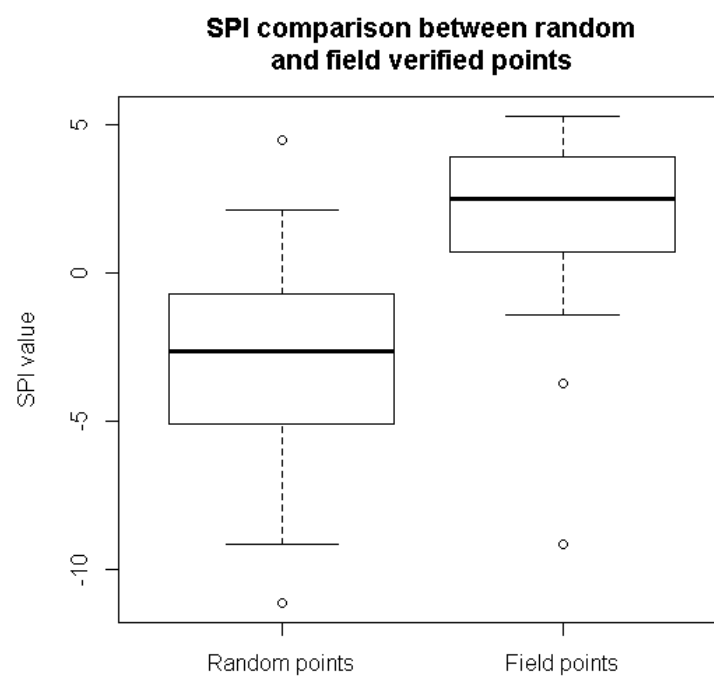
Figure 10

The following table and figure (Table 4 and Figure 11) were taken from the 2011 Galzki, et. al. paper, published in the Journal of Soil and Water Conservation. They show terrain analysis accuracy results in the same format presented in the two proceeding examples. Galzki's study was conducted in two watersheds, named Beauford and Seven Mile Creek, within the Minnesota River basin, near Mankato, MN.

Table 4

Comparison between gully features identified or not identified in Seven Mile Creek watershed using the geographic information system–based validation survey technique with an 85th percentile threshold.

Feature*	Validation result		Total features present
	Identified	Not identified	
SDP 3 gully	31	1	32
SDP 2 gully	17	5	22
SDP 1 gully	17	12	29
Total	65	18 (omission errors)	83
False positive	43 (comission errors)	—	—

Notes: SDP = sediment delivery potential. — = not applicable.

* A lower value of SDP indicates lower sediment delivery potential and a smaller catchment area.

Figure 11

Comparison of flow accumulation (FA) and stream power index (SPI) for random points versus field-sampled gully points in the Seven Mile Creek watershed. The whisker ends represent the 99% confidence interval.
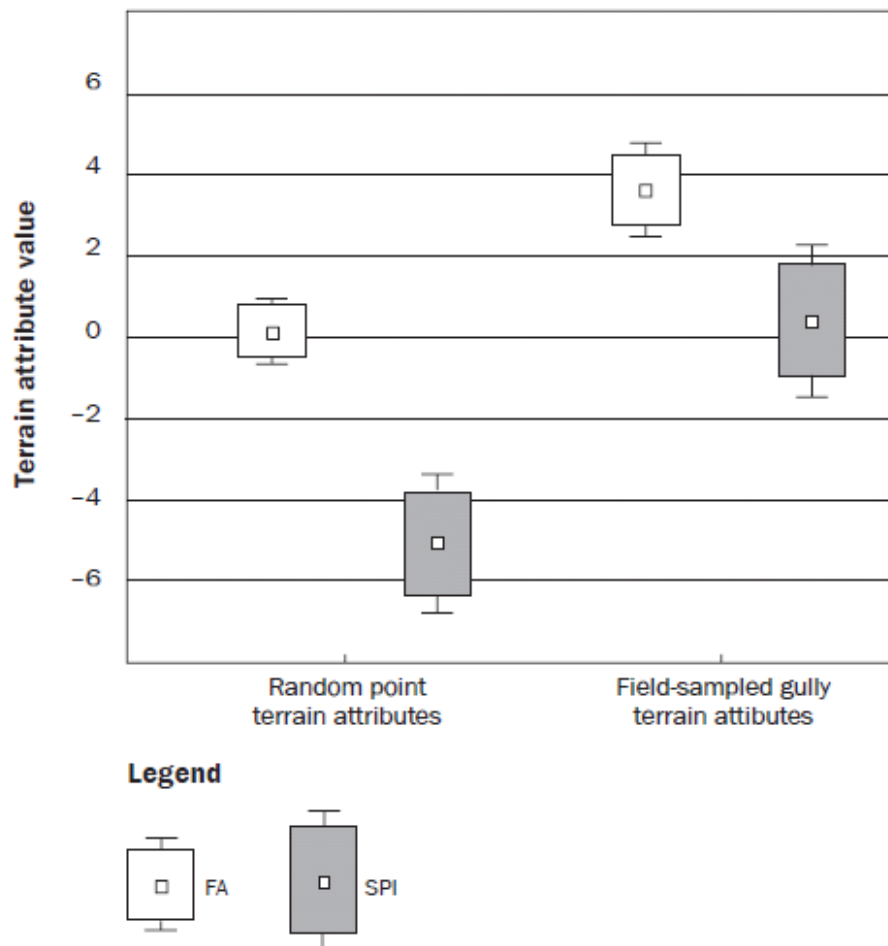
A.2 Create Area of Interest DEM manually using Clip

- Clip DEM Raster

  Minnesota LiDAR data acquired at the county level can contain very large file sizes. It is therefore important to minimize the spatial area to be processed to reduce output files sizes and increase processing times. The **Clip** ArcMap tool creates a subset of a raster dataset and will be used for this purpose.
  - *Note:* There are two **Clip** tools in the ArcToolbox – only one of which will create a subset of raster data.

1. Open **Data Management Tools > Raster** > **Raster Processing** > **Clip**
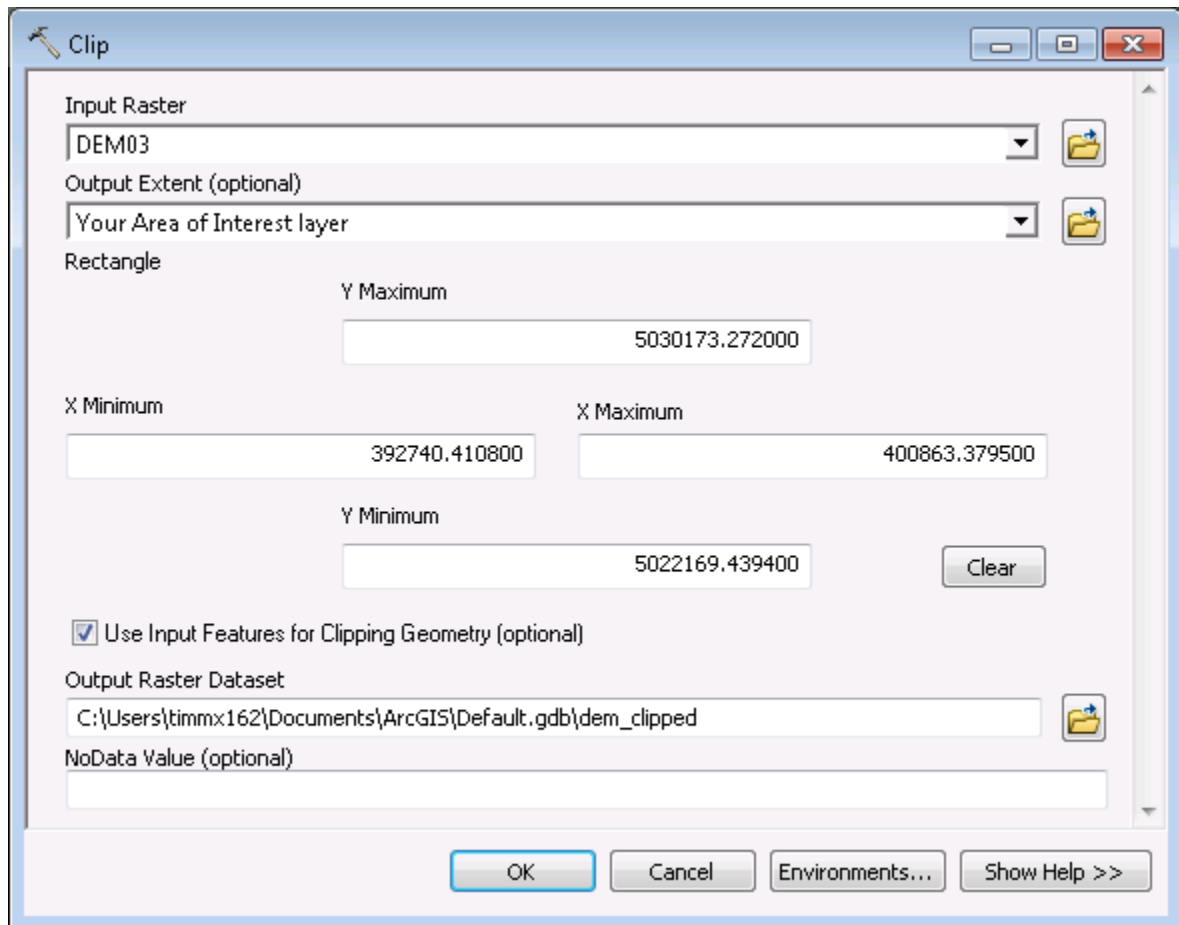
2. **Input Raster**: Your DEM
3. **Output Extent (optional)**: A raster or vector (point, line, or polygon) layer that covers the full extent of you AOI. For example, this could be a shapefile/feature class that you created yourself, HUC12 catchment(s), any digitized landscape feature, etc.
4. Check the box next to **Use Input Features for Clipping Geometry (optional)**.
5. **Output Raster Dataset**: Browse to output workspace and name with something you can remember, e.g. 'dem_clipped'.
6. Click OK to run. The clipped output surface raster is added to your map as a new layer.

A.3 Create Stream Power Index for ravine identification

A ravine is defined as a small, narrow and deep depression, smaller than a valley, and larger than a gully (Bates and Jackson, 1984). Ravines grow by head cutting action, but unlike gullies, are too large to be transversed by farm equipment.

Researchers in the UMN Dept. of Soil, Climate & Water developed an algorithm to aid in ravine identification while working in the Minnesota River Basin. The algorithm output is a topographic indice similar to the Stream Power Index, but includes aspect information which takes concave ravine profiles into account. This algorithm consisits of slope steepness greater than 7%, standard deviation of aspect greater than 40%, and a flow accumulation threshold between 200 and 7400 cells, depending on topography.

Starting from the procedures outlined in the Digitial Terrain Analysis Manual, the ravine algorithm will begin with a Digital Elevation Model.

The algorithm output generally displays best results when pit filling is included during DEM pre-processing. This is explained in the 'Pre-process DEM' section.

The Slope and Aspect raster layers are calculated directly from the DEM as shown in the 'Calculate primary attributes' section. Remember to use 'PERCENT_RISE' in the arctool output measeurment. The Flow Accmulation raster is also used for the algorithm, and thus a Flow Direction raster will need to be created before Flow Accumulation.

1. The **Reclassify** tool will be used to set the raster layer parameters for the ravine algorithm. Starting with the **Slope** raster layer, open the **Reclassify** Tool:
    a. In ArcMap, open **ArcToolbox > Spatial Analyst Tools > Reclass > Reclassify**
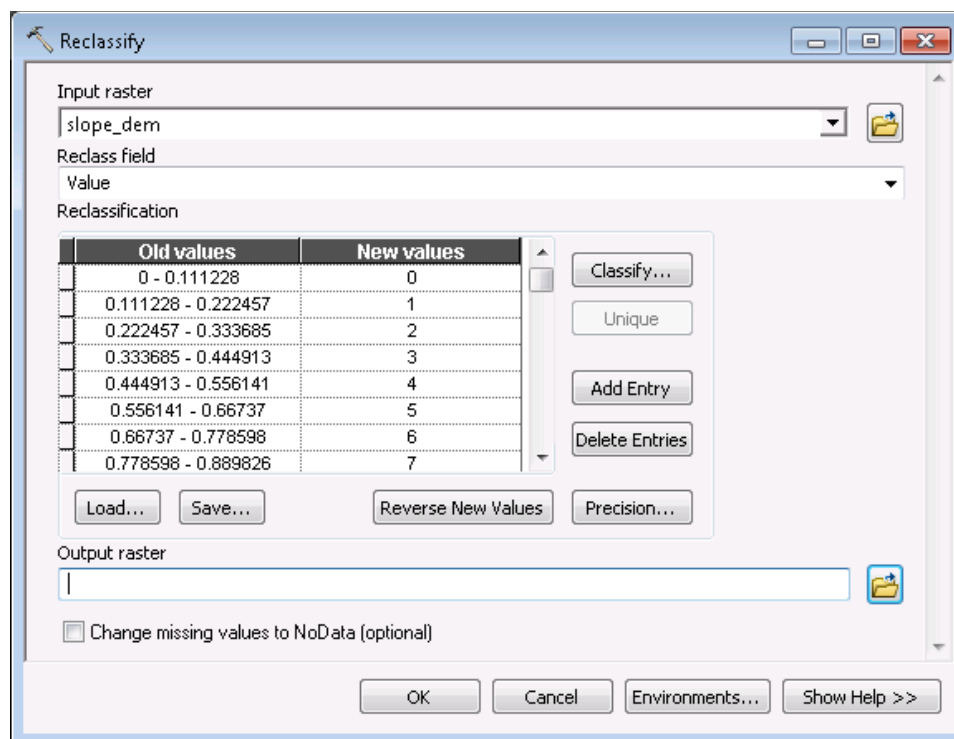
b. **Input raster:** Your Slope (slope_dem) layer.
c. **Reclass field:** This should default to 'Value'
d. **Reclassification:** Click on the 'Classify…' button.
   o Using the classification method pull down, select Equal Interval, and select 1 from the Classes pull down.
   o Click the 'Exclusion…' button and type '0-7' (without quotes) in the exclusion value field, and then click OK.
   o Click OK at the bottom right of the Classification window to return to the Reclassify tool.
e. **Output raster:** Browse to output workspace and name output layer 'slope_ravine'
f. Check the box next to **Change missing values to NoData (optional)**
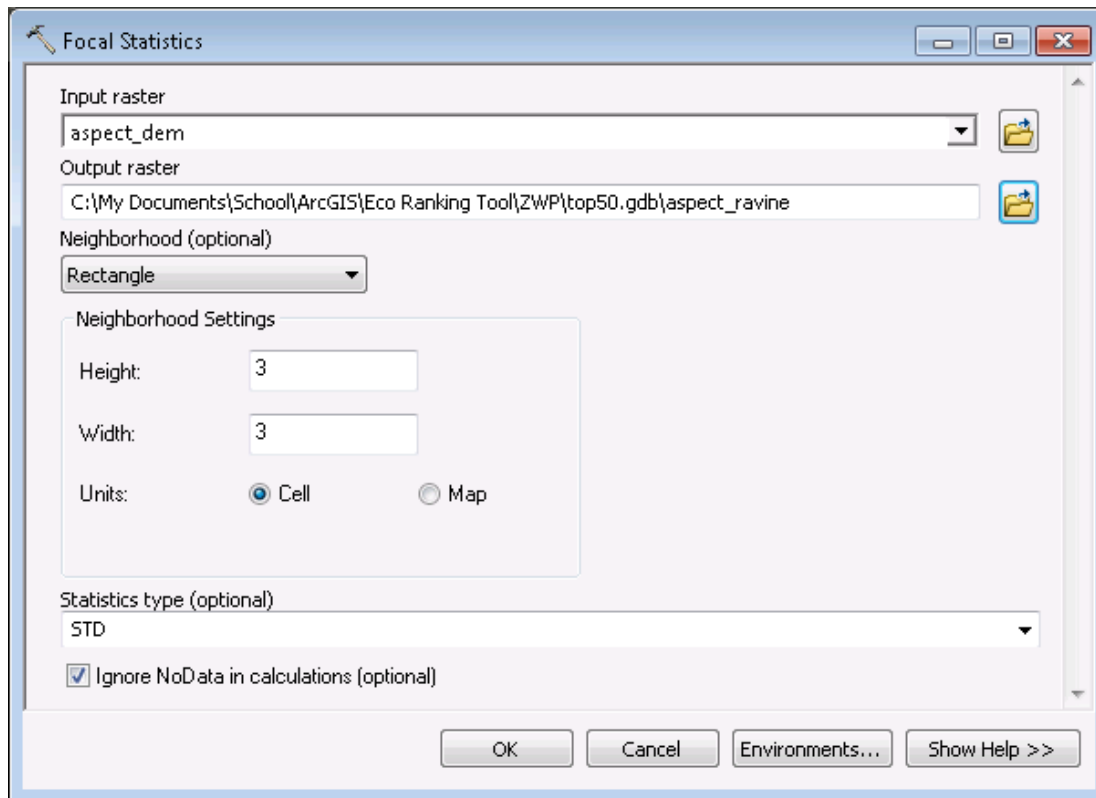g. Click OK to run. The output raster is added to your map as a new layer
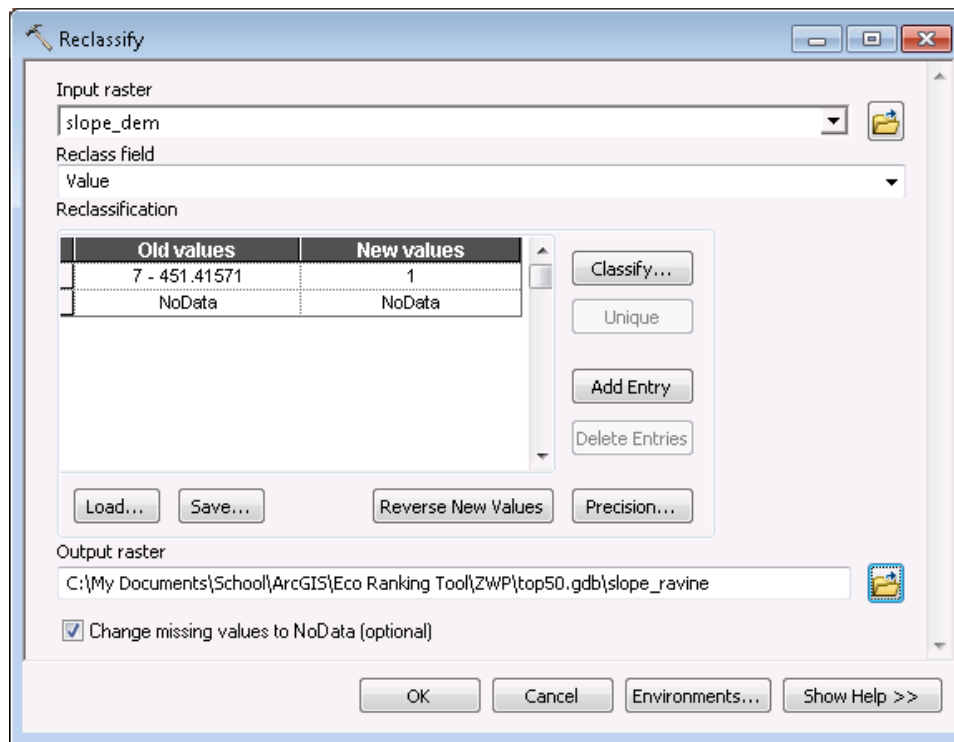
2. Open the **Reclassify** tool again to process the **Flow Accumulation** raster layer:
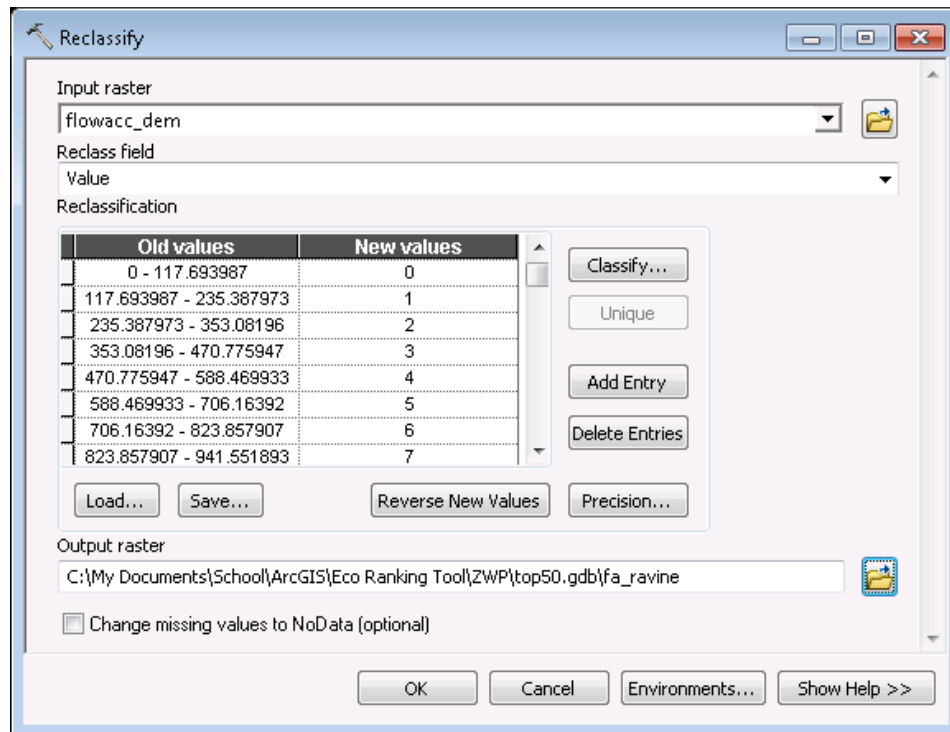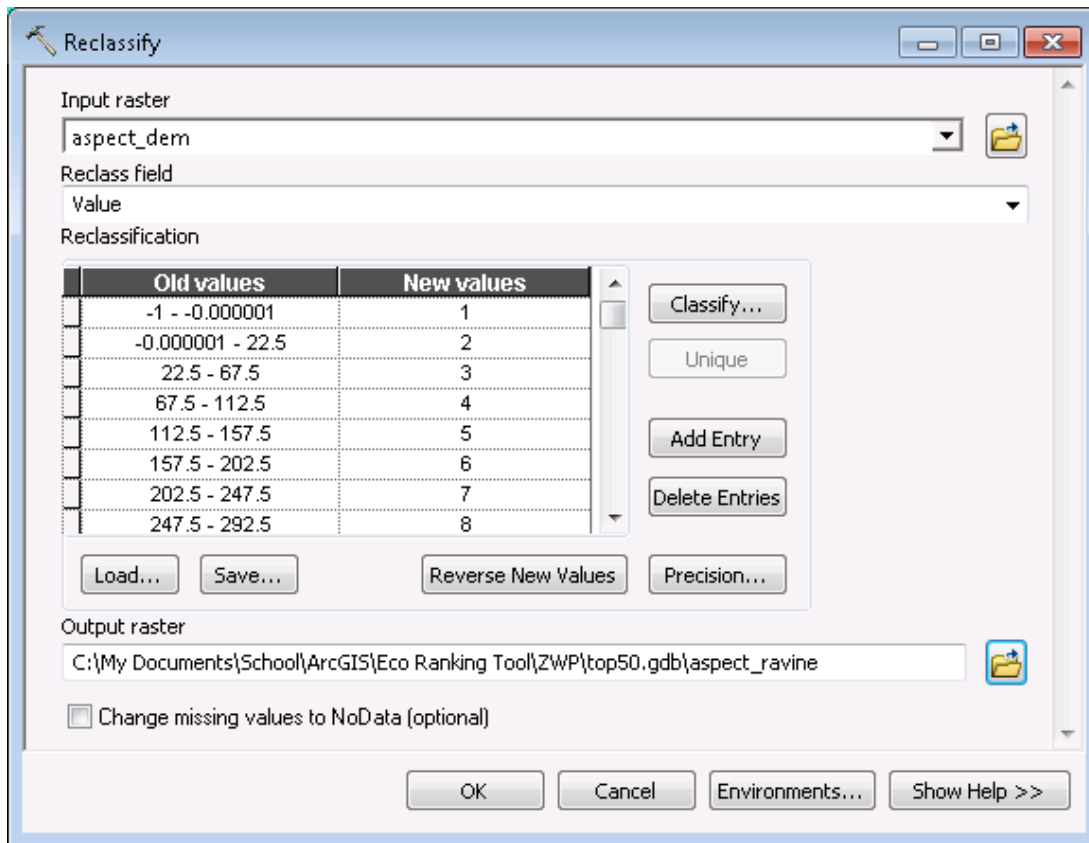

a. **Input raster:** Your Flow Accumulation (flowacc_dem) layer.
b. **Reclass field:** This should default to 'Value'
c. **Reclassification:** Click on the 'Classify…' button.
    o   Using the classification method pull down, select Equal Interval, and select 1 from the Classes pull down.
    o   Click the 'Exclusion…' button. The best exclusion range used here will vary depending on the overall topography steepness. As a general guideline: for steepest slopes, type '0-7400' in the exclusion range (without quotes), and for shallow slopes, type '0-200'.
    o   Click OK at the bottom right of the Classification window to return to the Reclassify tool.
d. **Output raster:** Browse to output workspace and name output layer 'fa_ravine'
e. Check the box next to **Change missing values to NoData (optional)**
f. Click OK to run. The output raster is added to your map as a new layer

3. The **Aspect** raster layer is first processed using the **Focal Statistics** arctool before being reclassified. To begin processing the **Aspect** raster:

    a. In ArcMap, open **ArcToolbox > Spatial Analyst Tools > Neighborhood > Focal Statistics**

    b. **Input raster:** Your Aspect (aspect_dem) layer
    c. **Output raster:** Browse to output workspace and name output layer 'aspect_FS'
    d. **Statistics type (optional):** Select 'STD' (standard deviation) from the pull down menu.
    e. Leave the other options as default (as shown above) and click OK to run. The output raster is added to your map as a new layer

4. Open the **Reclassify** tool once more to continue processing the **Aspect** raster layer:


a. **Input raster:** Your Aspect Focal Statistics raster layer from the previous step (aspect_FS)
b. **Reclass field:** This should default to 'Value'
c. **Reclassification:** Click on the 'Classify...' button
    o   Using the classification method pull down, select Equal Interval, and select 1 from the Classes pull down.
    o   Click the 'Exclusion...' button and type '0-40' (without quotes) in the exclusion value field, and then click OK.
    o   Click OK at the bottom right of the Classification window to return to the Reclassify tool dialog.
        •   *Note:* The 'Old values' range listed may not be rounded to 40. It is okay to leave the value as is, or simply click the value and change it to 40, without decimals. The same is true for previous Slope and Flow Accumulation reclassifications.
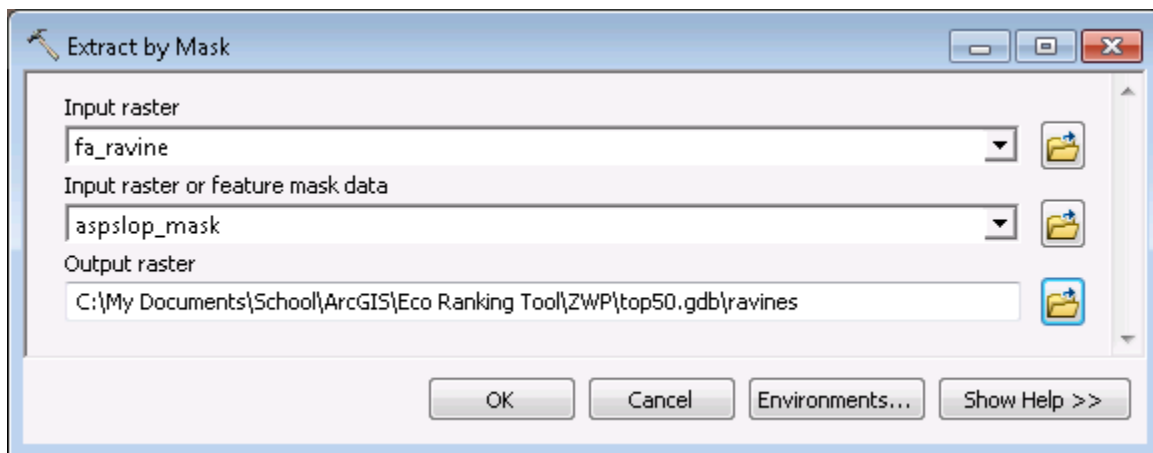

d. **Output raster:** Browse to output workspace and name output layer 'aspect_ravine'
e. Check the box next to **Change missing values to NoData (optional)**
f. Click OK to run. The output raster is added to your map as a new layer

5. Now that all thee raster layers have been reclassified into single-level rasters, the **Extract by Mask** Arctool will be used to extract only the pixels from all three layers that overlay each other.

   a. In ArcMap, open **ArcToolbox > Spatial Analyst Tools > Extraction > Extract by Mask**
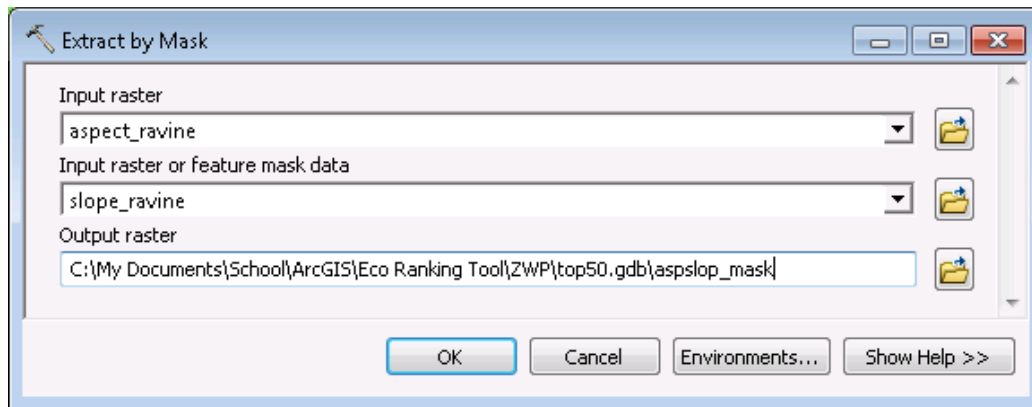
   b. **Input raster:** Your reclassified Aspect layer 'aspect_ravine'
   c. **Input raster or feature mask data:** Your reclassified Slope raster 'slope_ravine'
   d. **Output raster:** Browse to output workspace and name output layer 'aspslop_mask'
   e. Click OK to run. The output raster is added to your map as a new layer

6. The **Extract by Mask** Acrtool will be used one more time to create the final ravine raster.

   a. In ArcMap, open **ArcToolbox > Spatial Analyst Tools > Extraction > Extract by Mask**

   b. **Input raster:** Your reclassified Flow Accumulation layer 'fa_ravine'
   c. **Input raster or feature mask data:** Your Aspect/Slope masked raster from the previous mask iteration 'aspslop_mask'
   d. **Output raster:** Browse to output workspace and name output layer 'ravines'
   e. Click OK to run. The final Ravine output raster is added to your map as a new layer

A.4 Calculating thresholds using R statistical package

It may be preferable to use a dedicated statistical software program to calculate percentile thresholds, as they are capable of handling large data sets. Though most any statistical program can be used for this calculation, R is recommended as it's both free to use and able to process simple to complex functions. The calculation of thresholds using R is straight forward and will require downloading and installing the R stats package along with a small add-on.

1. Acquire and install R
   Download R for your Windows, Mac, or Linux operating system from the following link:
   http://cran.r-project.org/bin/windows/base/old/2.14.2/
   o   *Note:* It is recommended to install R version 2.14.2 for full compatibility with maptools.

2. Launch the R application. RGui will open with an active R Console window. The R console contains a command line that will be used for all R function inputs.
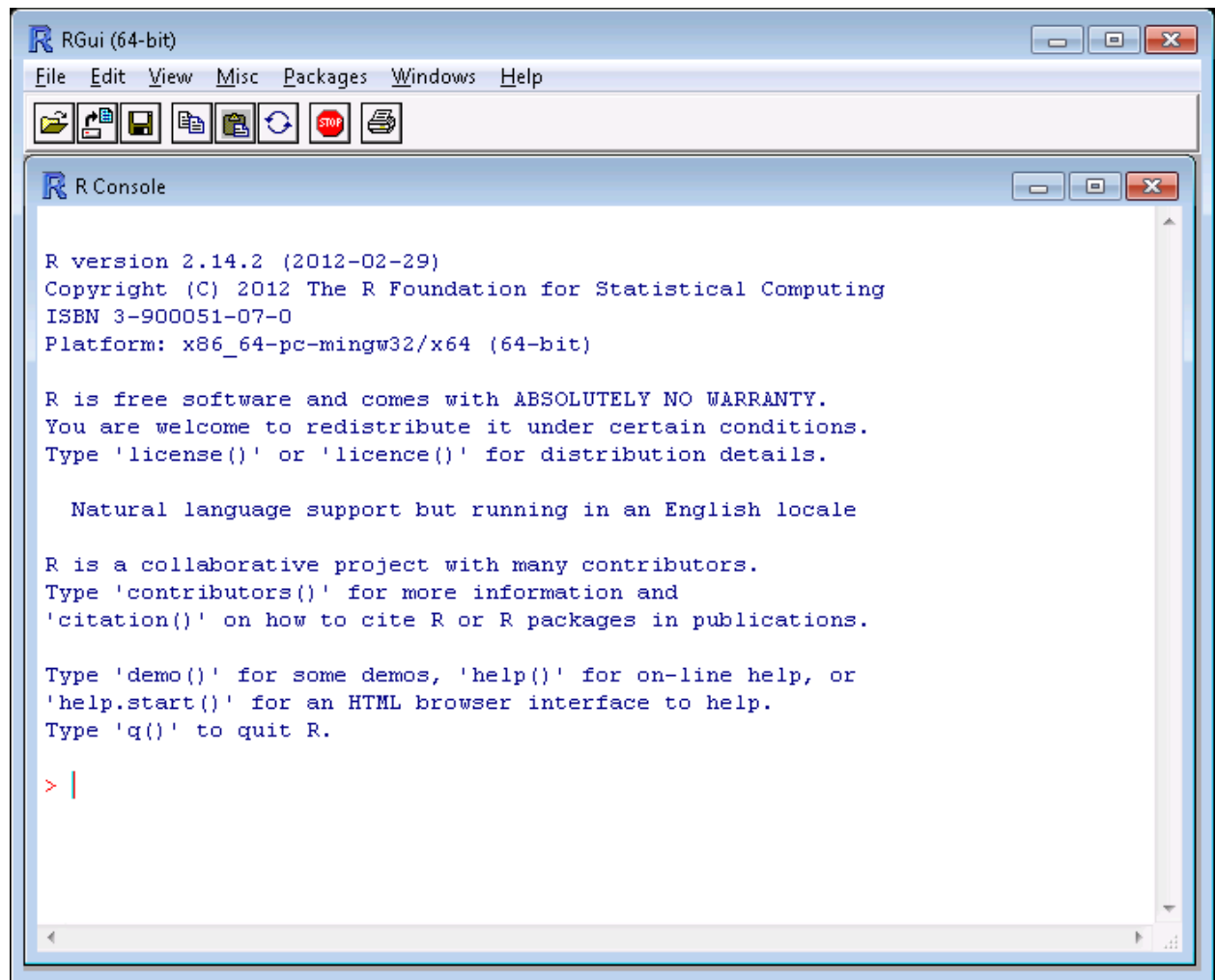
3. Install and load the maptools add-on package. This will allow the user to import dbf files directly into R.
   a. To install maptools, type in command line:

   install.packages("maptools", repos = "http://cran.case.edu")

   If prompted to use personal library, choose Yes.
   *Note:* Make sure computer is connected to internet for this step.

   b. Load maptools package into R by typing in command line:

   library(maptools)

   Note: The maptools package will need to be loaded into R each time the application is run using the above command. It will only need to be installed one time.

4. Prepare data for import into R. When exporting raster layer data for R input, any NoData cells around the area of interest will be exported as well. To circumvent NoData cells in exported data, convert raster cells to point shape data by using the **Raster to Point** Arctool as follows:

   a. Open **ArcToolbox > Conversion Tools > From Raster > Raster to Point**
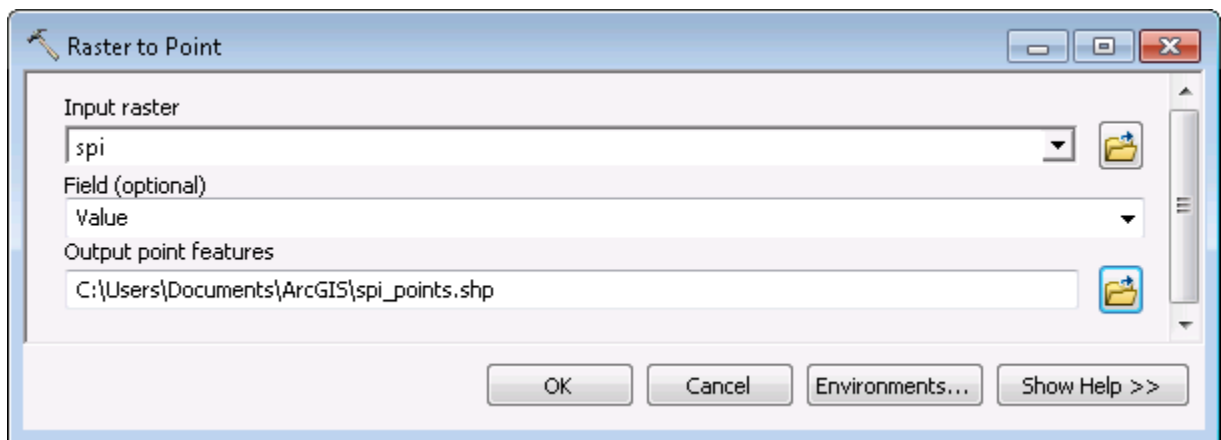
   b. **Input raster:** your SPI or CTI layer.
   c. **Output point features:** Browse to output workspace and name output layer either spi_points or cti_points.
      o *Note:* Avoid storing the output feature in a geodatabase, as the .dbf table will be inaccessible from that location. Instead, store it in a folder as a shapefile.
   d. Click OK to run.
      o *Note:* The output from the **Raster to Point** shapefile contains three types of files, one of which is a .dbf file that contains attribute information. In this case, it contains each 3x3 meter cell value needed to compute a threshold (assuming a 3m DEM was used).

5. Import data into R
    a. We will import the **Raster to Point** shapefile's .dbf table computed previously. Recall the output location of that file. R uses programming language that is case sensitive and requires certain formatting. We will use the following format for the **read** import function:

    identifier <- read.dbf("directory address/file_name.dbf")

    The identifier is a user created name assigned to data and is therefore not case sensitive. It cannot contain spaces. Users should adopt naming conventions using either no space or a period (.) symbol as a separator to make reading, sharing, and verifying code easier. The address location must use forward slash (/) as the directory separator.

    Example of **read** import syntax:

    SPIpoints <- read.dbf("C:/My GIS data folder/spi_points.dbf")

    Press enter once the command has been typed. There should be no messages displayed.

    Note: The program may not be responsive for a few minutes depending on the size of the imported file.
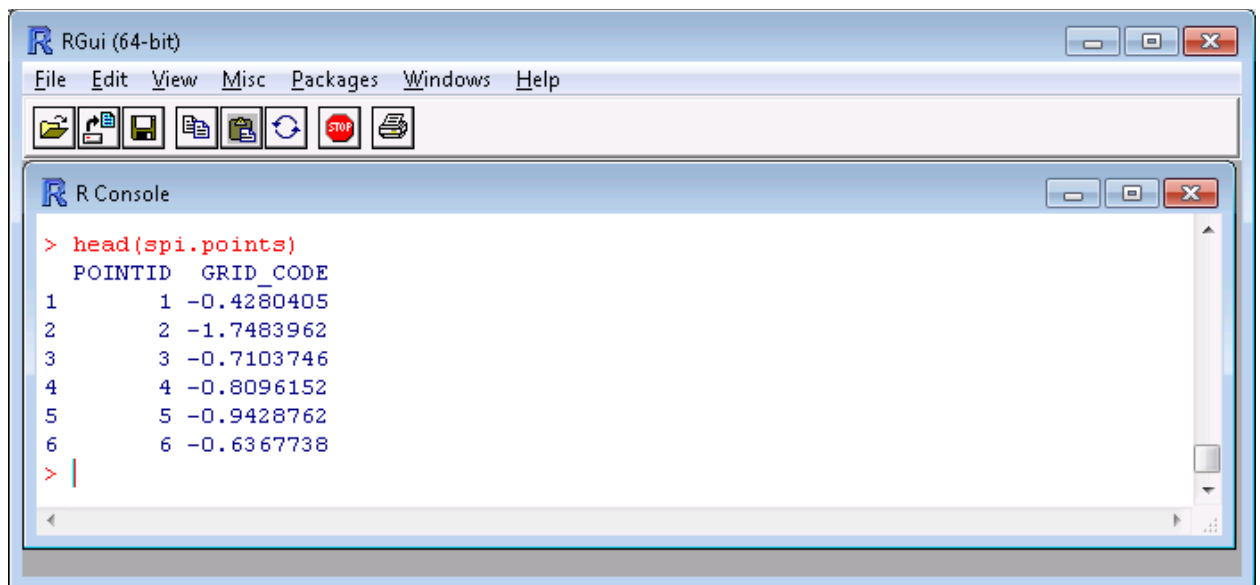
    b. Check your imported data's header and make note of the column names by using the head function in the R console:

    head(your.identifier.name)

    Example:
    head(SPIpoints)

    The exact name of the raster value's column is needed for threshold calculations. Typically, **Raster to Point** dbf files use 'GRID_CODE' for the raster value column name.

```
R RGui (64-bit)
File  Edit  View  Misc  Packages  Windows  Help

R R Console
> head(spi.points)
  POINTID  GRID_CODE
1       1 -0.4280405
2       2 -1.7483962
3       3 -0.7103746
4       4 -0.8096152
5       5 -0.9428762
6       6 -0.6367738
>
```

6. Calculate threshold percentile values

    Percentiles are calculated using the quantile function in R.

    quantile(your.identifier.name$raster_value_column_name, percentile)

    The 'your.identifier.name' is taken from previous step a; 'raster_value_column_name' is taken from previous step b; and percentile is recognized in R as a probability statement – any numerical value between 0 and 1 can be used.
    Note: a list of several percentiles can be used in one command line by using c(percentile1, percentile2,…percentileN)
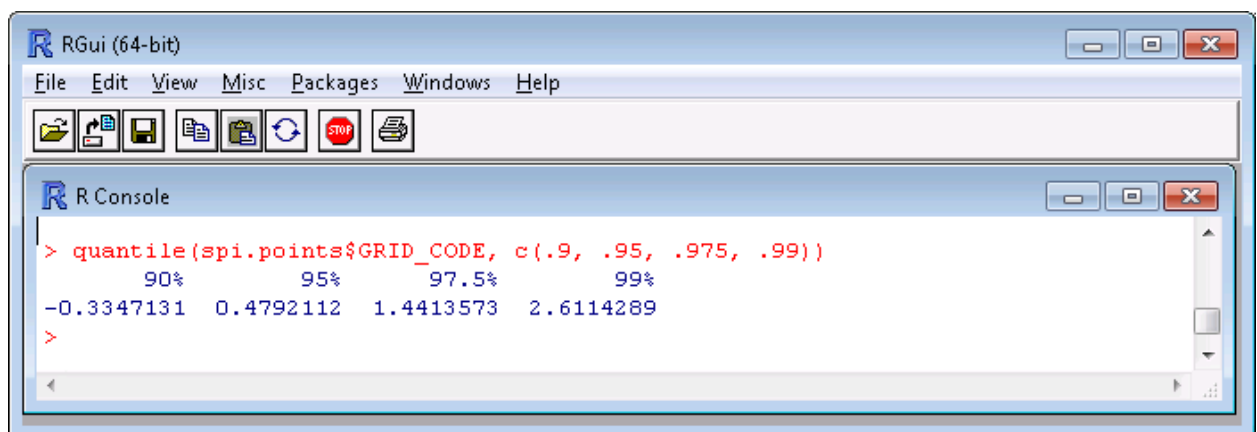
    Examples:

   quantile(spi.points$GRID_CODE, .85)   #one percentile
    quantile(SPIpoints$GRID_CODE, c(.9, .95, .975, .99))   #multiple percentiles

```
R RGui (64-bit)
File  Edit  View  Misc  Packages  Windows  Help

R R Console
> quantile(spi.points$GRID_CODE, c(.9, .95, .975, .99))
       90%        95%       97.5%        99%
 -0.3347131  0.4792112   1.4413573   2.6114289
>
```

A.5 Determine the cell count of your raster layer of interest

1. Double click on the layer in the table of contents window.
2. In the symbology tab, select 'classified' in the left window. If asked to calculate a histogram, say yes.
3. Click on the 'Classify…' icon.
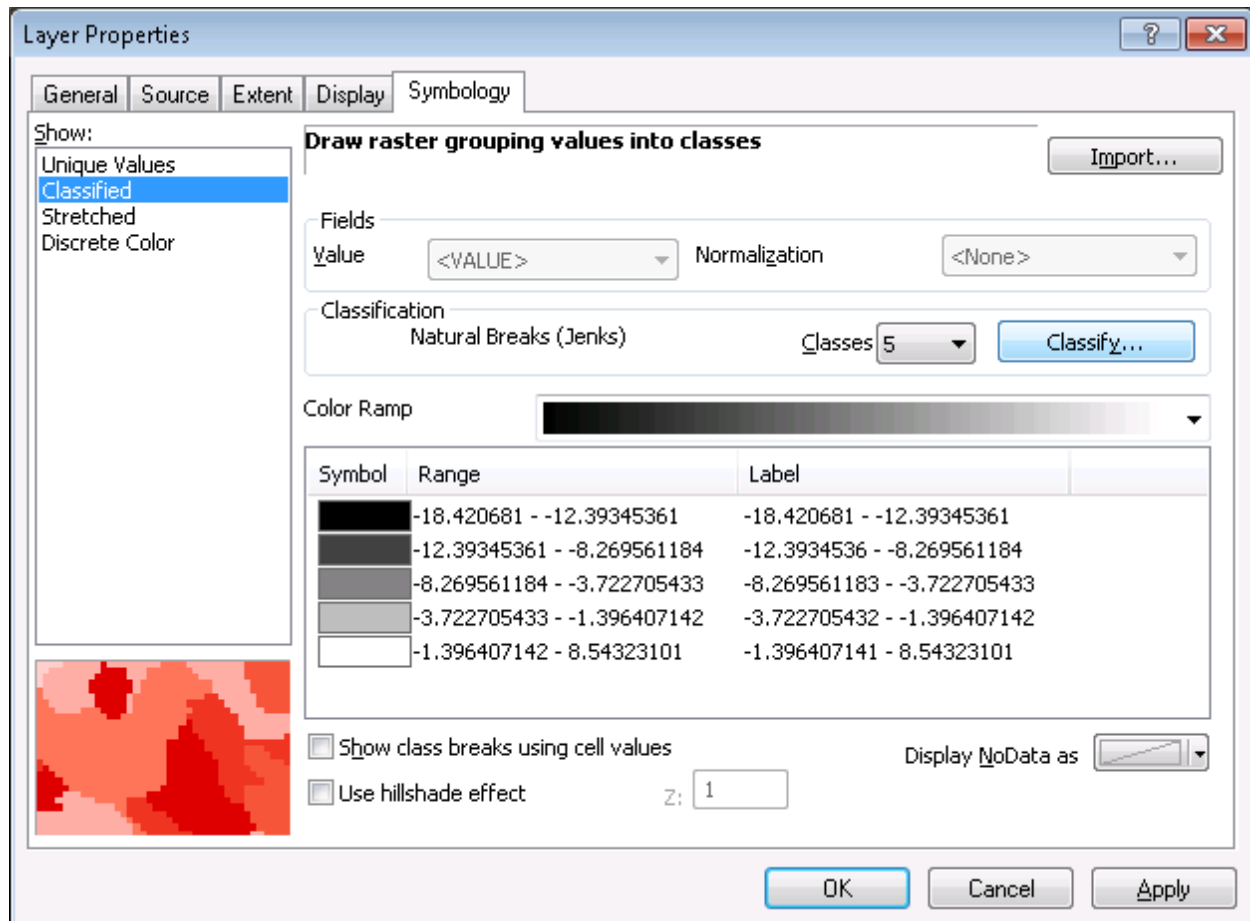
4. The number of records in the raster layer will be displayed in the top right under Classification Statistics as Count. This can also be thought of as the population size of the SPI raster.
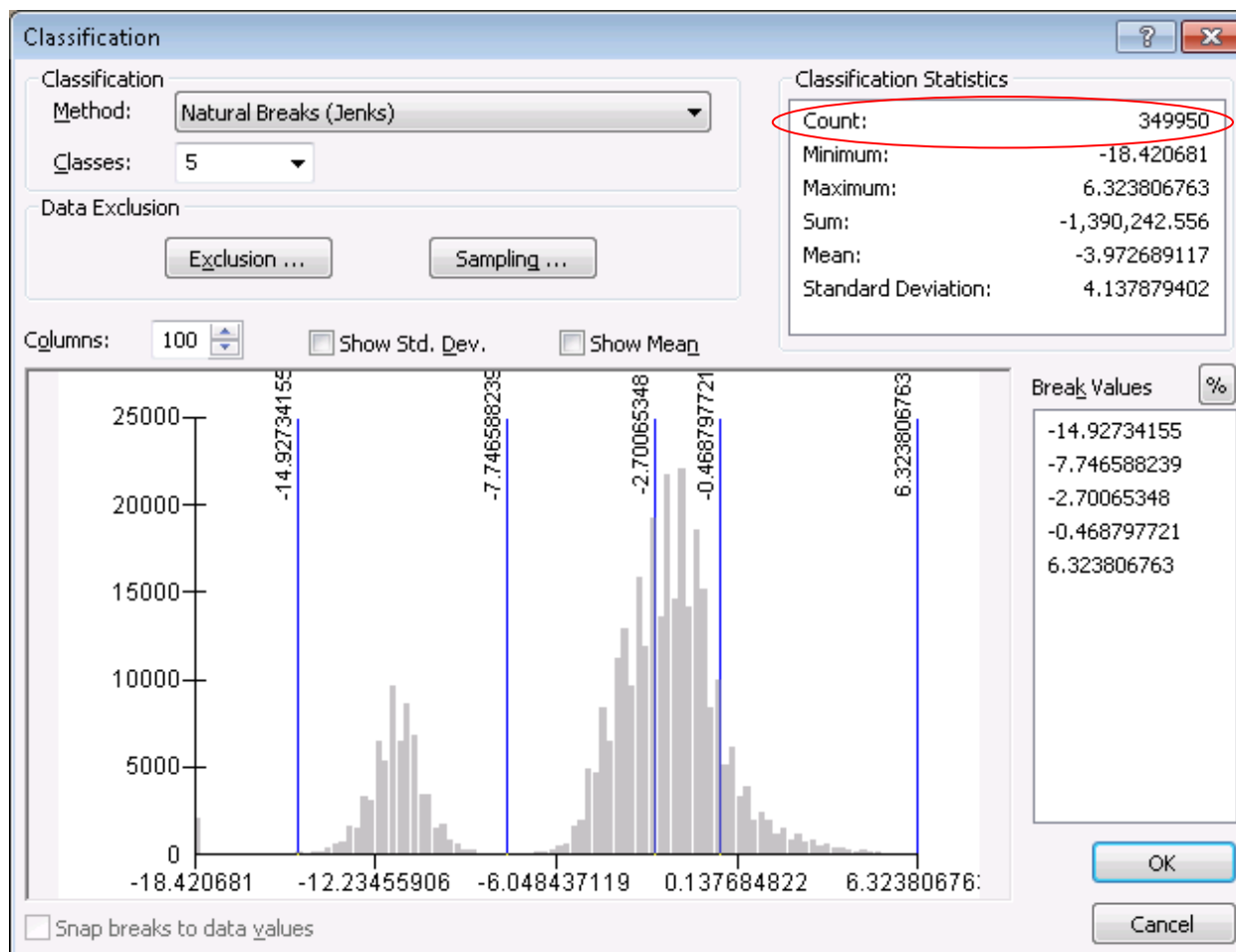

5. Click cancel on both windows to revert back to your original symbology.

A.6 Delineate catchments using NRCS GIS Engineering Tools

The contributing area upland of CSAs can be used to estimate the amount of potential sediment and nutrient delivery at those pour points. The Natural Resource Conservation Service (NRCS) offers a free tool called 'NRCS GIS Engineering Tools v1.17' which allows creation of contributing area catchments from a user defined point.
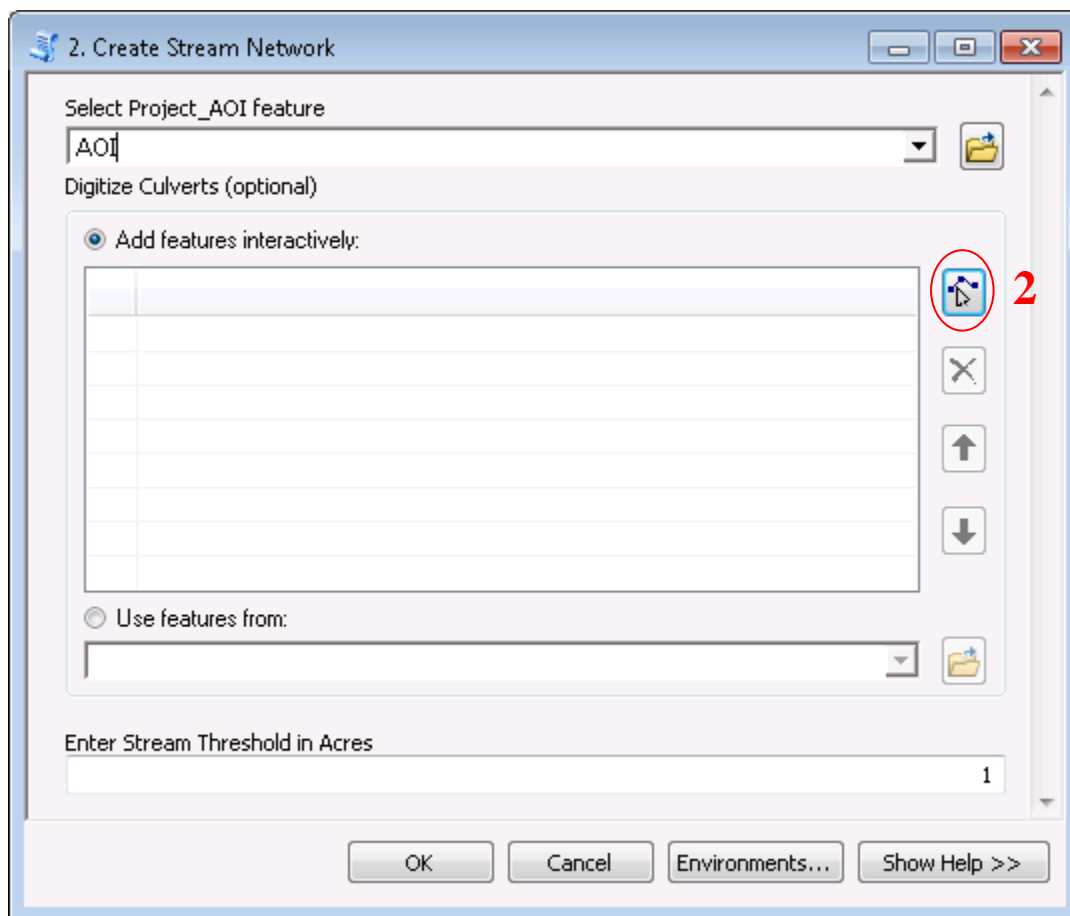
1. Define Area of Interest
   a. In the **NRCS Engineering Tools** toolbox, expand **Watershed Tools** followed by **Watershed Delineation** and double click the **Define Area of Interest** tool script
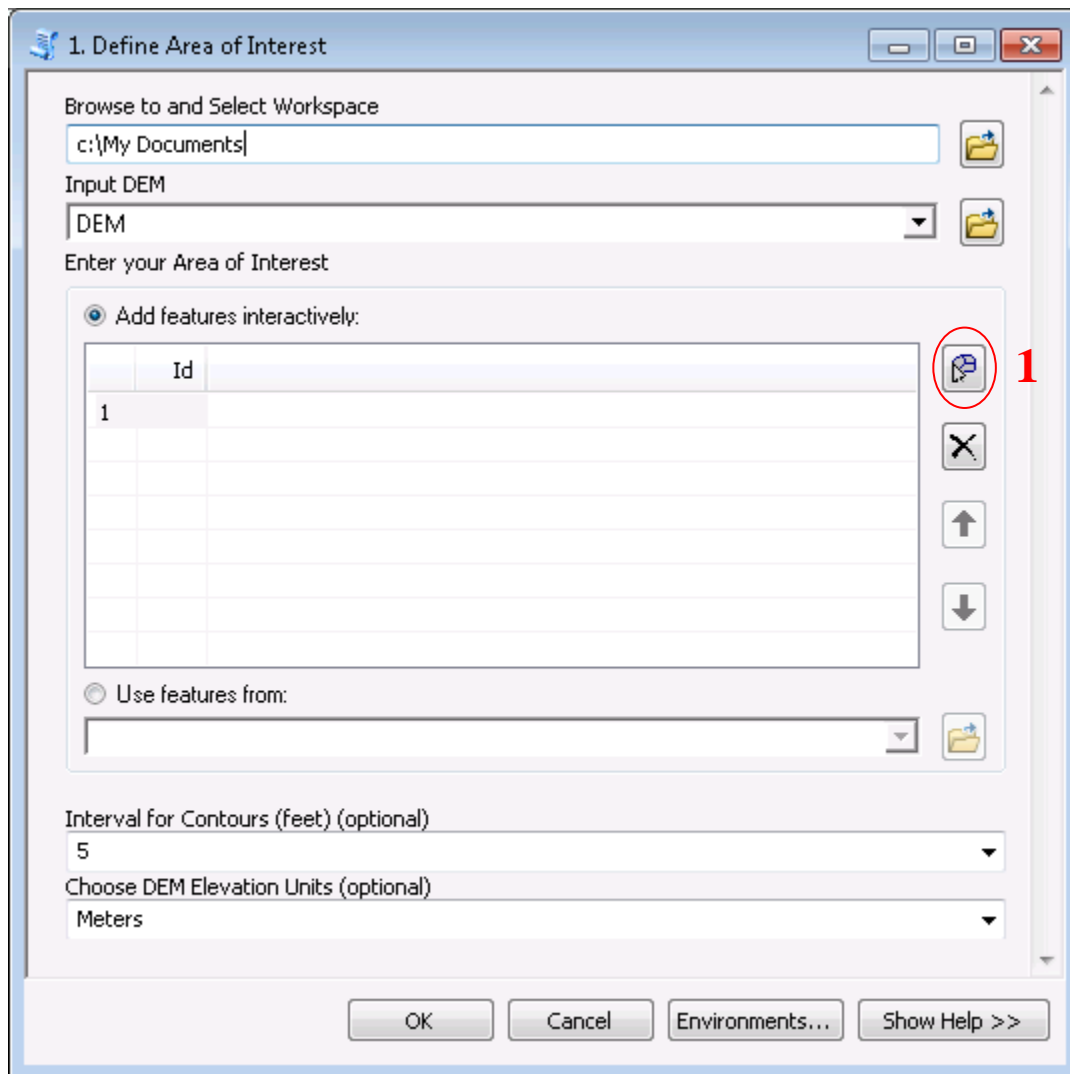
b. **Browse to and Select Workspace:** Choose your workspace folder where outputs will be stored
c. **Input DEM:** Your DEM, preferably a 3m LiDAR elevation dataset.
d. **Enter your Area of Interest:** Click the **Add feature** icon (**1** circled red in above image), then minimize the **Define Area of interest** window. The add feature tool works as a polygon editor, with each click creating a new vertex. The sketch is finished by double clicking to connect the first and last sketch vertices.
e. **Interval for Contours (feet) (optional):** Select desired contour foot contours. If left blank, no contours will be created
f. **Choose DEM Elevation Units (optional):** User preference
g. Click OK to run tool script. Several new layers will be added to your map

2. Create Stream Network
   a. In the **NRCS Engineering Tools** toolbox, expand **Watershed Tools** followed by **Watershed Delineation**, and double click the **Create Stream Network** tool script

b. **Select Project_AOI feature:** Select the AOI that was created by the previous **Define Area of Interest** tool

c. **Digitize Culverts (optional):** Click the Add feature icon **2** circled in red above then minimize the current window. The add feature function works as a line sketch tool. Use the function to make a line that represents a culvert at any obvious or known locations where a culvert exists. The DephthGrid layer created by the previous tool can aid in showing where water backs up at impoundments such as road crossings. Culverts are likely to exist at these locations. Create as many digitized culverts as necessary to ensure an accurate stream network representation.
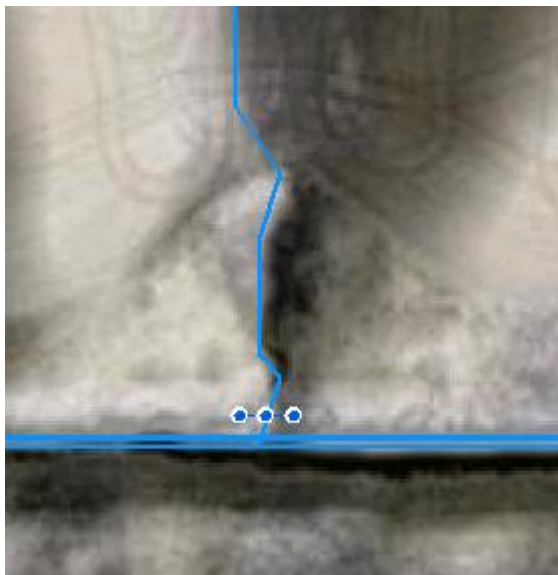

d. **Enter Stream Threshold in Acres:** This value is the minimum contributing area required to form a stream. The default value of 1 is adequate in most situations and will form stream headwaters near catchment boundaries.

e. Click OK to run tool script

3. Create Watersheds
   a. In the **NRCS Engineering Tools** toolbox, expand **Watershed Tools** followed by **Watershed Delineation**, and double click the **Create Watershed** tool script
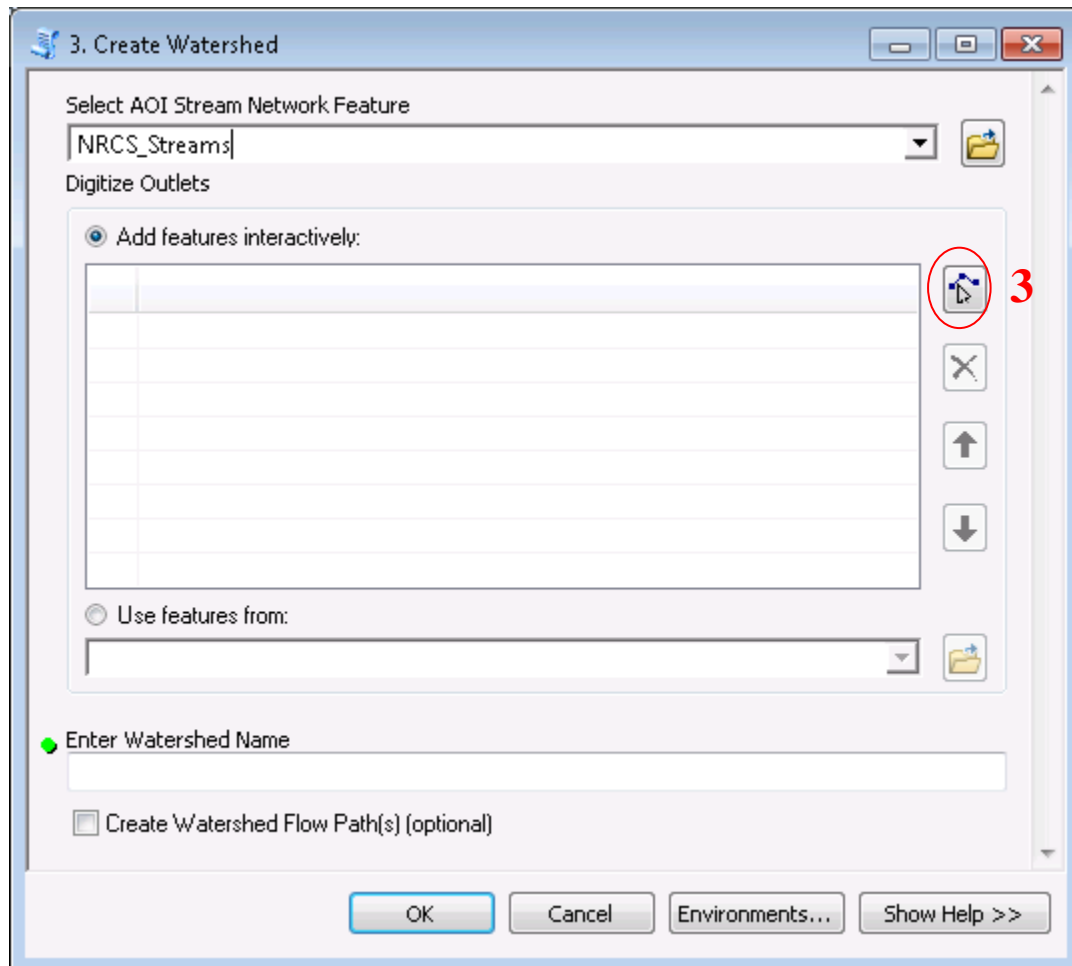
   b. **Select AOI Stream Network Feature:** Select the stream network feature that was created by the previous **Create Stream Network** tool
   c. **Digitize Outlets:** Click the Add feature icon **3** circled in red above then minimize the current window. The add feature function works as a line sketch tool. Each click adds a vertex and double clicking ends the sketch. Use the function to make a small line perpendicular to any stream outlets where a watershed is to be created. A catchment will be created upstream of the digitized outlet line(s).
   d. Click OK to run tool script. The watersheds will be added to your map as a new layer

The blue stream line oriented north-south in the image on left is flowing south and empties into the east-west oriented stream. To create a catchment of the north-south stream, a digitized outlet (shown with blue dots) is made perpendicular on that stream near its outlet. The catchment will terminate at that perpendicular line.

e. **Enter Stream Threshold in Acres:** This value is the minimum contributing area required to form a stream. The default value of 1 is adequate in most situations and will form stream headwaters near catchment boundaries.

A.7 Identification and prioritization of potential bank erosion locations

Previous estimates of streambank erosion rates from the Zumbro River Watershed TMDL study, as well as MNDNR's recent work on Cascade Creek, have been based on Rosgen's Bank Assessment for Non-point Consequences of Sediment (BANCS) methodology. The BANCS determinations produce risk ratings associated with the potential for bank and channel changes, which results in an erosion (recession) rate that is applied to the respective bank height and length of erosion to estimate the average annual amount of erosion. For this study, we compared the available BANCS determinations, streambank erosion inventory and field verification observations from the Zumbro watershed to the LiDAR-derived slopes for the respective banks. Our analysis indicated that there was a strong correlation between stream bank slopes greater than 25% and the respective areas that were deemed most susceptible to erosion according to the BANCS determinations and field verification observations.

This section describes the methods used to utilize and filter data previously developed from the digital terrain analysis to identify and further prioritize the watershed locations with the greatest potential for bank erosion. Beginning with the earlier procedures outlined in this document, the process of identifying the potential bank erosion locations begins with a Digital Elevation Model (DEM). The first layer needed will be a Slope raster calculated directly from the DEM as shown in the 'Calculate Primary Attributes' section. It is recommended that the input raster for this process not be pre-processed in any way. Remember to use 'PERCENT_RISE' in the arctool output measurement.

The only other layer needed will be a streams layer which is also described in the Pre-process DEM section. For best results, users should plan to first do hydrologic conditioning of the DEM and then do a Fill All in order to ensure accurate flowline delineation. Due to the time investment required to do hydrologic conditioning, this step can be skipped but the accuracy of the resulting flowlines will suffer in some areas. A stream threshold of 10-20 acres is recommended in an effort to limit the flowlines to actual channelized flow.

In the following walkthrough, assume that if a certain tool parameter is not described it involves the use of the default value.

Slope Data Processing

Create an Analysis Extent using the Buffer tool

1. Open **ArcToolbox > Analysis > Proximity > Buffer**
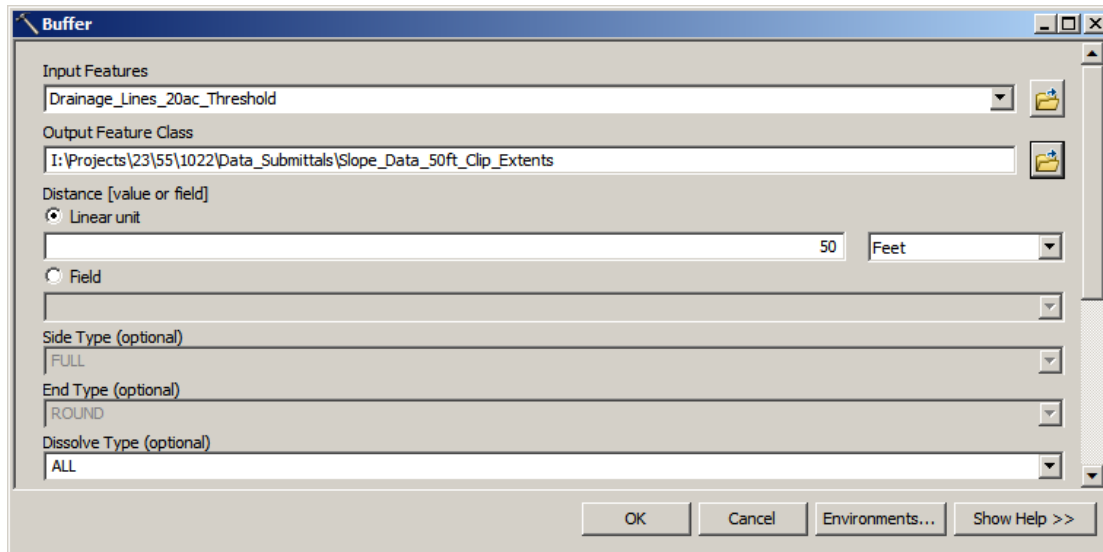
2. **Input Features:** Your streams layer with a suitably large threshold generated using the NRCS Engineering tools. In the case of the Zumbro River Watershed, the streams layer is named "Drainage_Lines_20ac_Threshold".
3. **Output Feature Class:** A name for the temporary buffer which will be used to limit the extents of the percent slope DEM. "Slope_Data_50ft_Clip_Extents"
4. **Linear Unit:** Choose a distance which is sufficient to reach the tops of the banks adjacent to the input streams layer. In the Zumbro River Watershed a buffer distance of 50 feet was suitable to reach the tops of the banks adjacent to the streams layer.
5. **Dissolve:** Choose the 'ALL' option.

Convert Buffered Area to Raster

Due to the size of some watersheds, e.g. the Zumbro River Watershed, it is easier to mask a raster dataset with another raster data rather than clip the data using a polygon.

1. Open **ArcToolbox > Conversion Tools > To Raster > Feature to Raster**
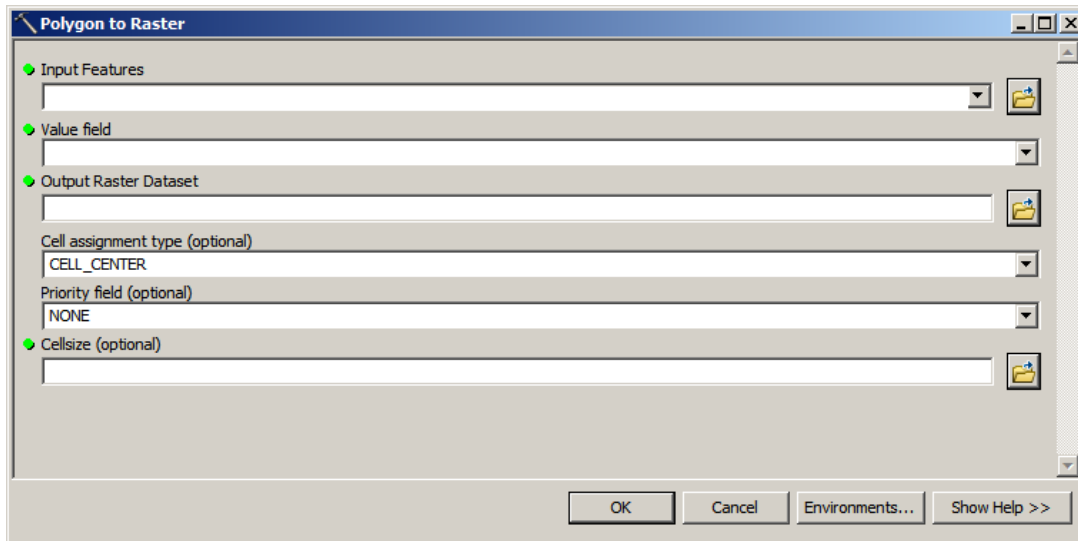
2. **Input Features:** The previously created buffered features to be used to limit analysis extents on the slope raster. "Slope_Data_50ft_Clip_Extents"
3. **Value Field:** The buffered features must have an integer field where there is the same value entered for all features. This may need to be done manually in the attribute table if some records of the input streams layer were not contiguous.
4. **Output Raster Dataset:** The name of the raster dataset that will serve as an analysis extents mask. "Slope_Clip"
5. **Cellsize:** Set the value to be the same as your previously created slope raster, for example 3 meters was used for the Zumbro River Watershed analysis.
6. **Environments…** button**:** Under the **Environment Setting > Processing Extent**, set the Snap Raster to be the same as the slope raster. "LiDAR_03m_Meters_PercSlope"

Limit your slope raster to the analysis mask

1. Open **ArcToolbox > Spatial Analyst Tools > Extraction > Extract by Mask**
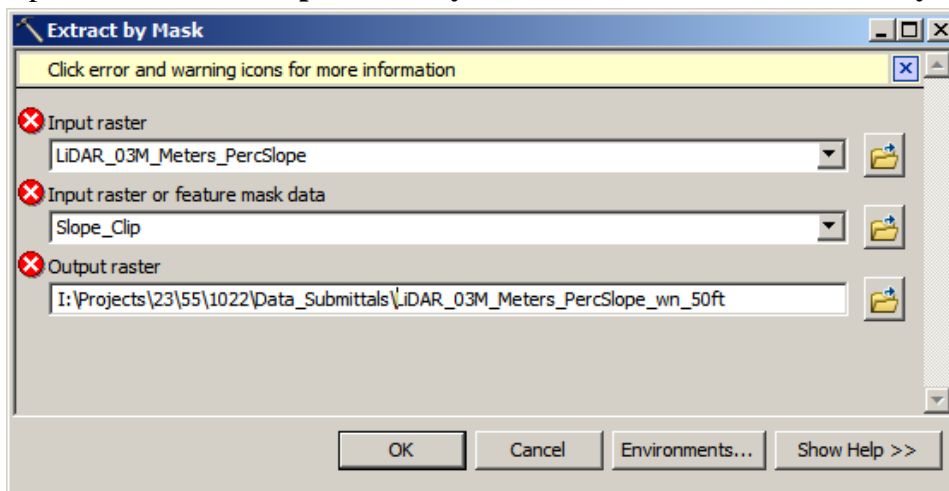
2. **Input raster:** Enter your full slope raster. "LiDAR_03m_Meters_PercSlope"
3. **Input raster or feature mask data:** The analysis mask raster created in the previous steps. "Slope_Clip"
4. **Output raster:** The name of the slope raster which will be limited to the buffer distance of your streams layer. "LiDAR_03M_Meters_PercSlope_wn_50ft"

Finalize Outputs – Classified Method

As previously discussed, our analysis of streambank data indicated that mean stream bank slopes greater than 25% may be most susceptible to erosion. The next two 'Classified Method' processes are optional but will help simplify the slope information into simple, user-defined classes which can be converted into polygon areas representing only areas with mean slopes greater than 25%. The resulting dataset will have many polygon areas, but it may provide some insight into how the high slope areas are distributed across the watershed and how they relate to other landscape features (such as roadways and upland sources of drainage).

Classified Method - Reclassify your masked slope raster

1. Open **ArcToolbox > Spatial Analyst Tools > Reclass > Reclassify**
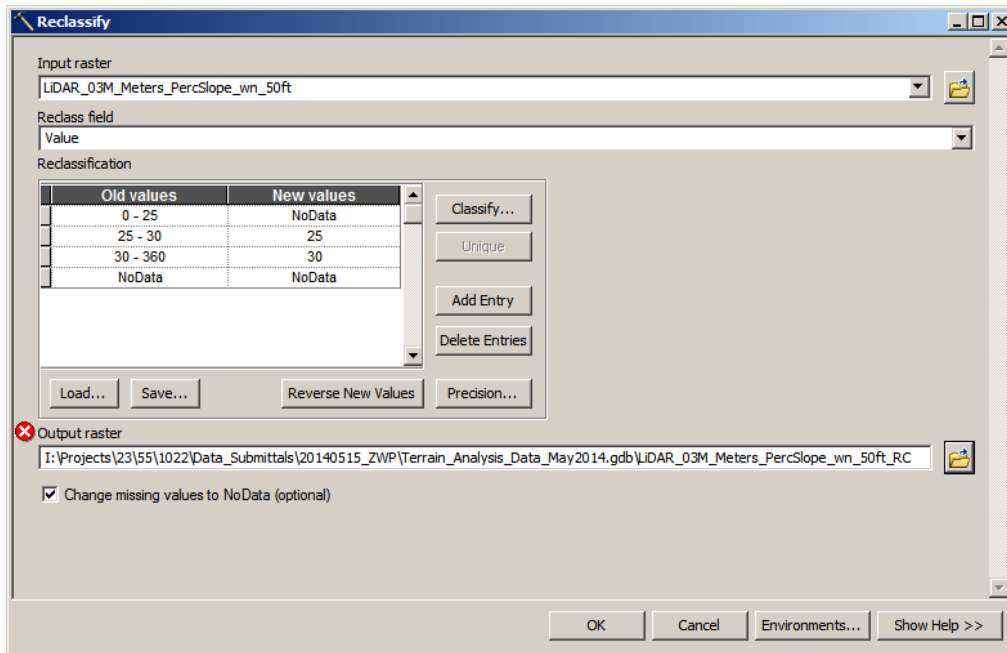
2. **Input Raster:** Input the masked slope raster
3. **Reclass field:** Ensure that 'Value' is entered in this box
4. **Reclassification:** Set values in the 'Old values' tab to the slope values ranges you wish to group and simplify. In the example above all slopes less than 25% will be removed, slopes from 25-30% will be given a value of 25 and slopes greater than 30% will be simplified and given a value of 30.
5. **Output raster:** The name of the reclassified slope raster.
   "LiDAR_03M_Meters_PercSlope_wn_50ft_RC"

Classified Method - Convert the reclassified slope raster to polygon features

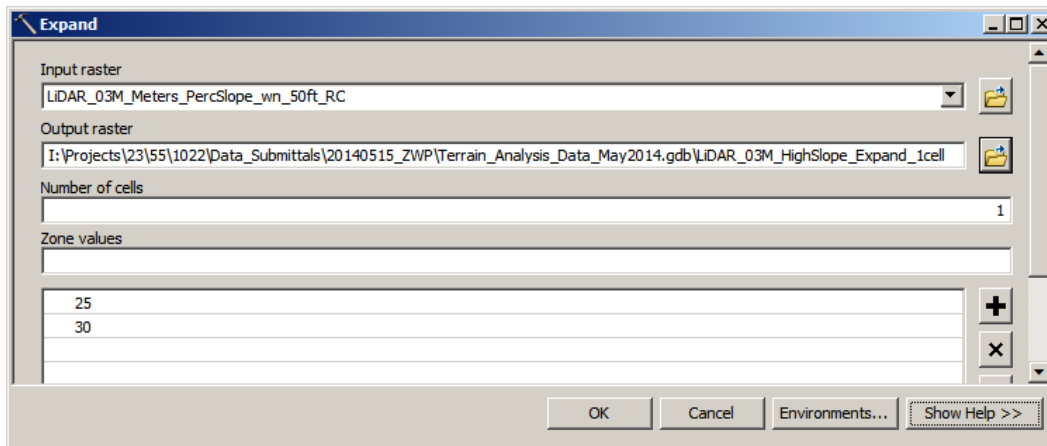1. Open **ArcToolbox > Conversion Tools > From Raster > Raster to Polygon**
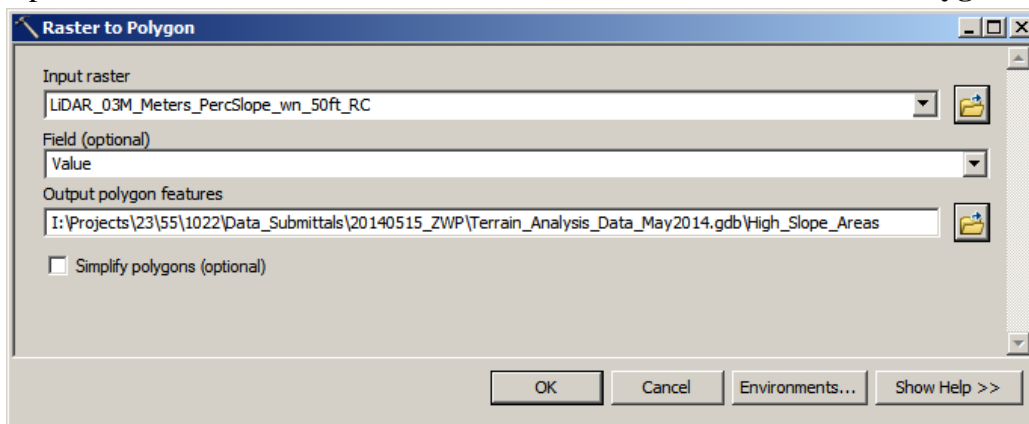
2. **Input raster:** Input the name of your masked and reclassified slope raster. "LiDAR_03M_Meters_PercSlope_wn_50ft_RC"
3. **Output polygon features:** The name of the polygon feature areas. "High_Slope_Areas_Classified"
   a. The polygons will initially have a field with the values of 25 or 30, representing areas of 25-30% slope or greater than 30% slope respectively. A new field should be added and populated to better describe this classification.

Finalize Outputs – Aggregate Method

While the classified polygons may be more useful for viewing and quantifying your slope information they still will not be ideally suited for representativeness. The following steps outline the 'Aggregate Method' which will first slightly expand the original high slope areas and result in larger, aggregated areas which should be more representative of the ground surface. These aggregated areas allow more meaningful statistics to be generated which allows the locations to be prioritized for potential erosion risk.

Aggregate Method - Expand original high slope areas

1. Open **ArcToolbox > Spatial Analyst Tools > Generalization > Expand**

2. **Input raster:** Input the name of your masked and reclassified slope raster. "LiDAR_03M_Meters_PercSlope_wn_50ft_RC"
3. **Output raster:** The name of your expanded masked and reclassified slope raster
4. **Number of cells:** Enter 1 representing 1 cell. In the case of the Zumbro River Watershed study this translates to a horizontal distance of 3 meters.
5. **Zone values:** Enter the names of all the zones created during the previous reclassify steps. *Note:* The zone values or order will actually have no effect on subsequent steps since we are creating aggregated areas encompassing slopes greater than 25%.

Aggregate Method - Reclassify your expanded raster

1. Open **ArcToolbox > Spatial Analyst Tools > Reclass > Reclassify**
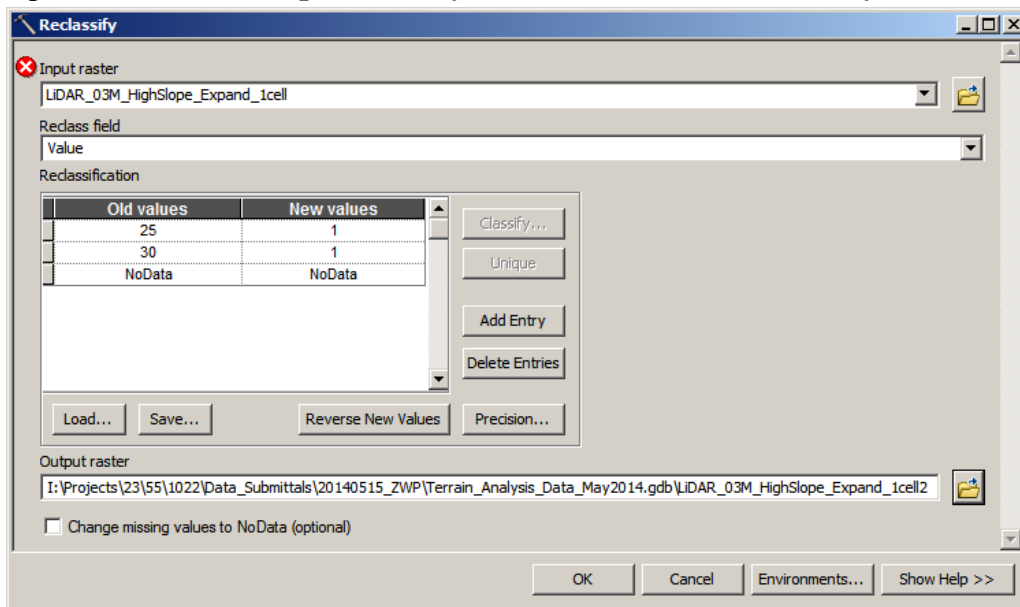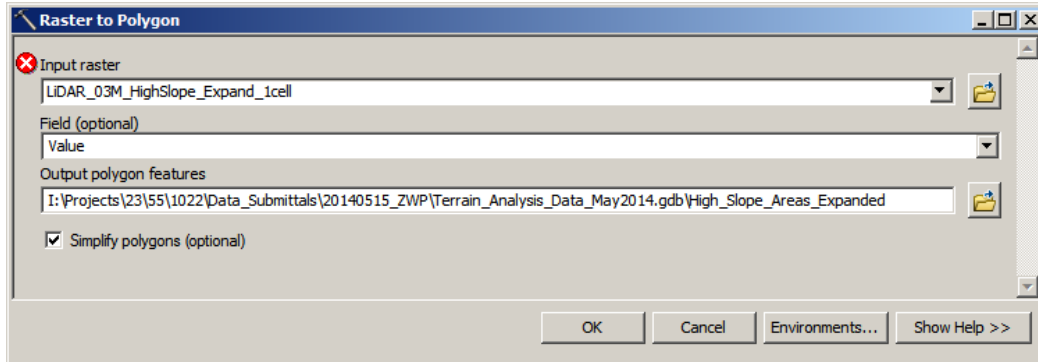

2. **Input Raster:** Input the expanded, classified raster
3. **Reclass field:** Ensure that 'Value' is entered in this box

4. **Reclassification:** The intent for the output raster is to just contain a single value across all cells. The 'Old values' column should contain the previous classification values and each should match with the same value, in this case 1, in the 'New values' column.

Aggregate Method - Convert the reclassified expanded raster to polygon features

1. Open **ArcToolbox > Conversion Tools > From Raster > Raster to Polygon**

2. **Input raster:** Input the name of your reclassified and expanded high slope areas raster
3. **Output polygon features:** The name of the high slope areas.
   "High_Slope_Areas_Expanded"
4. **Simplify polygons (optional):** Check this box to produce more organic, display friendly areas.

Aggregate Method - Give a unique ID to each expanded high slope area polygon

1. Open the attribute table for "High_Slope_Areas_Expanded".
2. Add a new long integer field which will contain a unique ID for the high slope area.
3. Open the field calculator by right clicking the new 'ID' field name. Enter the feature's ObjectID (or FID + 1) into the formula box and click enter.

Aggregate Method – Calculate statistics for each high slope area

1. Open **ArcToolbox > Spatial Analyst Tools > Zonal > Zonal Statistics as Table**
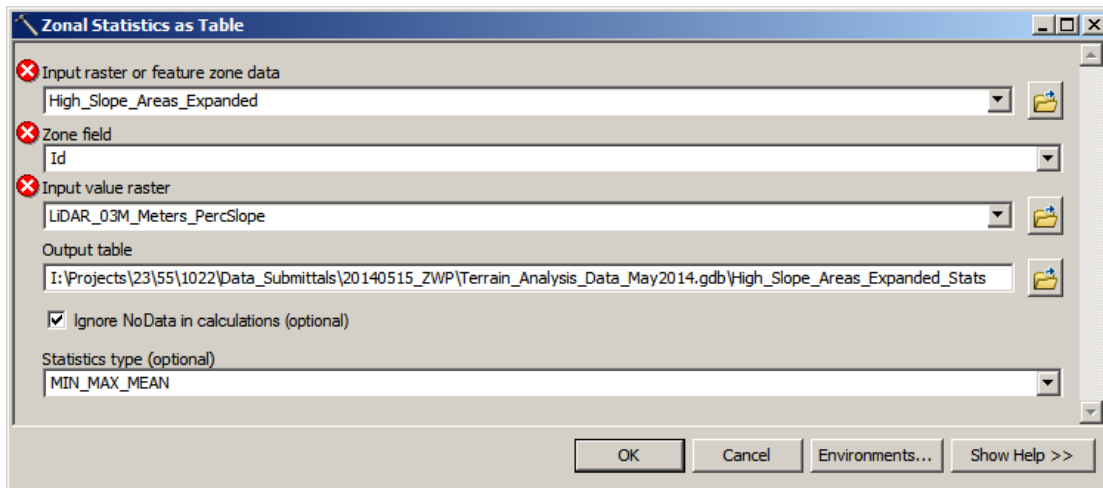
2. **Input raster or feature zone data:** Enter the feature represented the expanded areas around the high slope areas. "High_Slope_Areas_Expanded"
3. **Zone field:** Enter the name of the field containing the unique ID for the high slope areas polygons.
4. **Input value raster:** Enter the original slope grid. "LiDAR_03M_Meters_PercSlope"
5. **Output table:** Enter the name of the table which will hold the slope statistics for each high slope area.
6. **Statistics type:** For prioritization purposes 'MIN_MAX_MEAN' should be sufficient.

Aggregate Method – Join Statistics Table to High Slope Areas

1. Right-click on "High_Slope_Areas_Expanded" in the map document's table of contents and select **Joins and Relates > Join…**
2. Choose the unique ID field created in "High_Slope_Areas_Expanded", the Zonal Statistics Table, and the unique ID field in the statistics table.
3. Open the attribute table for "High_Slope_Areas_Expanded" and ensure that each record has been successfully joined and has MIN, MAX, and MEAN fields populated on the right.
4. Create 'double' fields for: Min_PctSlope, Max_PctSlope, Mean_PctSlope, and Area_Ac.
5. Use the field calculator to populate each of the fields
6. Remove the joined table.

The "High_Slope_Areas_Expanded" feature now contains several fields which can be used to screen the sites down to a manageable number, if necessary. For the Zumbro River Watershed analysis, the following parameters were applied to screen the records to a manageable number, remove likely false positives, take into consideration existing best management practices, and rebalance the results away from an over-represented portion of the watershed (i.e., the Blufflands agroecoregion). It is recommended to create a backup of the full High_Slope_Areas_Expanded featureclass before screening out any locations.

Screen the results – Zumbro River Watershed approach

1. Using the **Select by Location** function, remove all areas within 50 feet of a road. This will help eliminate false positives caused by roadside ditches or culvert/bridge embankments.
2. Remove areas that are less than or equal to 1.0 acres in the Area_Ac field.
3. Remove areas less than or equal to 70% in the Max_PctSlope field.

   Note: The previous steps left us with a higher concentration of results in the Wabasha County or Blufflands agroecoregion area. The screening steps below only apply to areas downstream of the confluence of the North Fork and Main Stem of the Zumbro River.

4. Remove areas more than 1 mile away from the Minnesota DNR's Public Waters Inventory that are flagged as perennial.
5. Remove areas that are within 500 feet of an existing BMP's drainage area. For example, Wabasha County has installed grade stabilization structures and other control practices upgradient from many of the source areas.