EARS33: Appalachian rivers lab

Joanmarie Del Vecchio

April 2022

1 Motivation

Gravel-bedded alluvial rivers appear to exist at a threshold state in which the channel dimensions adjust such that the threshold of motion of the median grain size in the bed (D_{50}) occurs at approximately bankfull flow, which occurs approximately at the 1.5-year flood. Therefore, it follows that the stress required for sediment motion (critical Shields stress τ_c^*) and the bed stress calculated for mean bankfull flows (τ_{bf}^*) should be approximately equal. However, the threshold channel assumption ($\tau_{bf}^* \approx \tau_c^*$) is at odds with the observation that channels in tectonically active settings must adjust to move high sediment loads by generating *excess* shear stress, such that $\tau_{bf}^* > \tau_c^*$.

Pfeiffer et al. (2017) used a compilation of 341 gravel-bedded river reaches with channel geometry and bed surface grain size data to map out τ_{bf}^*/τ_c^*, with an eye toward locations that might have heightened sediment supply as implied by tectonic activity and ^{10}Be-derived erosion rates. They found that τ_{bf}^*/τ_c^* was twice as high on the tectonically active West Coast as on the East Coast, and that high ^{10}Be-derived erosion rates in these locales suggest more coarse sediment is being transported in regions with high sediment supply. The authors assert that association between erosion rate and τ_{bf}^*/τ_c^* suggests that high sediment supply channels are some combination of deeper (greater bankfull depth), steeper (higher slope), and finer (smaller bed surface grain size) than their low sediment supply counterparts. One of the authors' concluding thoughts is that perhaps channels are, on average, adjusted to threshold conditions across much of the continent because most channels are subject to modest sediment supply.

In a follow-up, Pfeiffer and Finnegan (2018) "zoomed in" to three regions that represented a spectrum of sediment delivery regimes and used the Mid-Atlantic Appalachians as a "low sediment supply" area. Using USGS discharge data the authors estimated the frequency with which the riverbed would be partially or fully mobile, and they determined that (1) many Appalachian rivers are rarely mobile, (2) many Appalachian rivers' mobility conditions are well above bankfull flow, and (3) there is a wide range in the consistency of bed mobility in Appalachia. The authors remark on both the consistently low bedload transport rates in Appalachia and a dearth of bedload data from Appalachian rivers.

But there is more to central Appalachian rivers than meets the eye! Many, if not all, of the Pfeiffer sites lie within a zone that, at numerous times throughout the Pleistocene (the period beginning 2.6 million years ago and ending at the end of the last Ice Age), would have been underlain by perennially frozen ground, also known as permafrost. When permafrost thaws, it can heave an entire soil profile (and any cobbles embedded within it) from a slope down to a valley floor in a process known as solifluction (Matsuoka, 2001). Solifluction is evident from bare-earth lidar maps across Appalachia (Merritts et al., 2022), and solifluction can transport large boulders into channels, and if those channels are small enough (e.g. in headwaters), that coarse material will not be transported during the proceeding warmer interglacial, leading to a multi-glacial buildup of coarse debris (Del Vecchio et al., 2018). In the folded sedimentary units of central Appalachia, solifluction is particularly good at transporting coarse sandstone boulders from prominent ridgelines down to shale-bottomed river valleys.

So, my curiosity is this: are central Appalachian rivers "adjusted" to modern discharge regimes, or are their bedloads "too coarse" for their geometries and annual floods, implying lasting impact of permafrost thaw?

2 Dataset

I am presenting you with a dataset from Brush (1961) that was lovingly digitized by Rose Martin, a research student at Penn State. 118 measurements of bankful width, depth, slope, and grain size were made in the area centered around State College, PA. It spans two physiographic provinces of Appalachia - the Valley and Ridge, with older, tigher-folded rocks compared to the Allegheny Plateau, where rocks are younger and more gently folded. I used ArcGIS's Spatial Join to map bedrock geology units and physiographic province information to each station. To my knowledge this dataset has not been leveraged by other work.

3 Equations

3.1 Bankfull vs critical Shields stresses

Pfeiffer et al approximate the bankfull Shields stress τ^*_{bf} describes the stress acting on the bed during bankful flow as

$$\tau^*_{bf} = \rho R_{bf} S/(\rho_s - \rho) D_{50} \tag{1}$$

where ρ is the density of water (1,000 kg/m^3), ρ_s is the density of sediment, R_{bf} is the bankful hydraulic radius, and S is the channel slope.

Although τ^*_c is often taken as a constant between 0.03 and 0.08, Pfeiffer et al. normalize τ^*_c by a slope dependence as formulated by Lamb et al. (2008):

$$\tau^*_c = 0.15 S^{0.25} \tag{2}$$

3.2 Bankfull vs critical discharge

Bankfull discharge can be approximated via mass conservation by

$$Q_{bf} = A * U \tag{3}$$

where A is the cross-sectional area and U is the mean flow velocity.

We can estimate mean flow velocity using the Law of the Wall:

$$U = \frac{\sqrt{gRS}}{\kappa}(ln3.14\frac{h}{D_{84}}) \tag{4}$$

where R is the hydraulic radius ($R = hw/(2h + w)$; w is channel width and h is channel depth), κ is von Karman's constant (0.4), D_{84} is the grain size for which 84 percent of the bed is finer, S is local bed slope, and g is gravitational acceleration.

Since we only have D_{50}, we will follow Pfeiffer et al 2017 who estimated

$$D_{84} = 2.1D_{50} \tag{5}$$

after Rickenmann and Recking, 2011.

Critical discharge can be estimated using the following steps:

First, solve the Shields equation for τ_c:

$$\tau_c^* = \frac{\tau_c}{(\rho_s - \rho)gD_{50}} \tag{6}$$

where τ_c is the critical boundary shear stress, ρ_s is sediment density (2.65 g/cm^3), ρ is water density, and τ_c^* is dimensionless critical shear stress (the Shields number).

Then, calculate the critical flow depth for movement:

$$h_c = \frac{\tau_c}{(\rho)gS} \tag{7}$$

Then, calculate A_c, the cross-sectional area for h_c, using the existing channel width.

Finally, calculate the critical velocity U_c using Law of the Wall and continuity to calculate critical discharge ($Q_c = A_c$*U).

3.3 Recurrence intervals

First, acquire peak discharge data from the USGS:

1. Go to https://nwis.waterdata.usgs.gov/usa/nwis/peak
2. Check the box next to "Site Number" under "Site Identifier" and press submit

3. The site numbers for this activity are found in `app_gage.csv` under "Station ID". Type the site number into the box, including the leading "0" (e.g. 01547700) and select **Tab-separated file** as the output and **display in browser** from the drop-down menu on that line.

4. The data that we need is after all of the metadata at the top of the file; highlight all of the columns and rows starting with the `agency_cd` header and copy.

5. Open Excel. Under the paste tab, pull down 'Paste special' and paste as text. of the data should now be in columns within Excel. The data that we need are in the columns labeled `peak_dt` (the date of peak streamflow) and `peak_va` (the annual peak streamflow in cubic feet per second, cfs); you can delete the other data if you wish to keep things simpler.

The first flood frequency analysis technique that we will use is the traditional Gumbel method, where the recurrence interval (RI) is calculated using:

$$RI = (n + 1)/m \tag{8}$$

where n is the number of years of record and m is the rank of the flood.

For Gumbel FFA, you will first need to rank your data. Rank the discharge data from largest flow to smallest flow using the 'sort' function in Excel (sort is located under the data tab). In the column to the right of the sorted discharge data, assign a rank. The highest discharge has a rank of 1, the second highest a rank of 2, and so on. Now, calculate the RI using the formula above.

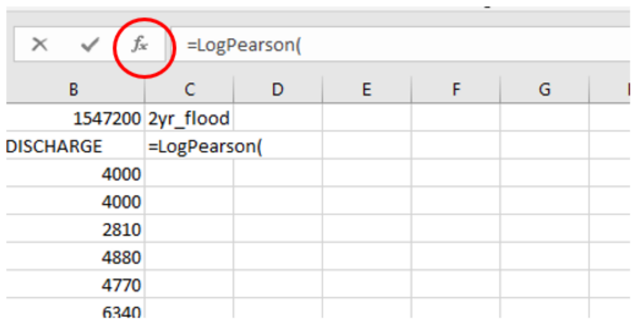
(Isn't it much easier with dataretrieval and Pandas? Unfortunately we can't use Pandas for the next bit, unless someone wanted to code it!!)

The second flood frequency analysis technique that we will use is the log Pearson type III analysis. This analysis is more complicated than the Gumbel analysis, but it attempts to capture the effects of outliers in a given flood distribution. For this technique, we will be using an excel add-in developed by Professor Renshaw in the EARS department (see the toolbox here), which has already been installed on the lab computers. Follow these steps and see the following figures:

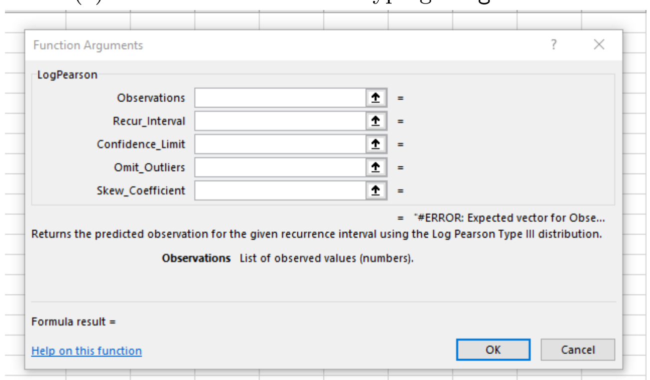
1. Go to an empty cell in your spreadsheet and type in '=' sign and go to the list function. Select `logPearson`.

2. A function argument box will open; put the cells for discharge in the range for the `observations` variable.

3. Type '2' (for the 2-year discharge) in the `recur_interv` cell and hit 'OK'. The number in the cell is the discharge for the 2-year flood.



(a) Press this button after typing `=LogPearson`



(b) The dialog box will appear

Figure 1: Hydrotools operation

4 Tasks

1. Calculate the bankfull to critical shear stress ratio using Equations 1 and 2 for each of the 118 survey stations (`brush_stations.csv`). Use these ratios to determine if geology or physiographic province is related to the amount of excess shear stress for a survey location.

2. Four USGS stations are either close to one station or between two Brush survey stations (`app_gages.csv`). Using equations 3-8, calculate discharge and corresponding Gumbel and logPearson recurrence intervals for estimated bankfull and critical discharge. If in Excel, your best bet is plotting recurrence interval versus discharge and, for the given Q, eyeballing the approximate RI (you could perform a linear interpolation between observed discharges if working in Python). Do this for at least one of the four gage stations; for three extra credit points calculate the Q and RI for all four (this is where our Data Tutorial code could come in handy!). If "Brush Station 1" is only listed, use that site's geometry; if two sites are listed, take the average bankfull and critical discharges between the two

sites.

3. When you have finished your calculations, import the data from `brush_stations.csv` by lat/long into ArcMap to examine spatial relationships of your data (see attached instructions).

5 Deliverables

Please submit a report, 2-4 pages long (excluding figures), that presents the following (40 pts):

1. An introduction to the study; what's motivating the work?

2. A description of the methods, with any additional information supplied by accompanying literature

3. The results of your bankfull vs critical shear stress calculations presented as both a summary in words, at least one scatterplot that demonstrates grouping of data by lithology, physiographic province, etc., and one map inspired by Fig. 1A in Pfeiffer et al. (2017).

4. The results of your discharge and recurrence interval calculations for at least one station associated with a stream survey.

5. A discussion on the significance of your findings with regard to the motivation and Pfeiffer conclusions. Are the Appalachian channels we studied at threshold geometry? How frequently might transport occur? Are these new data in line with the range of the previous calculations, especially those in the study area? (see `central_app_pfeiffer.csv`) Also list the major assumptions that went into this work and describe how they might be overcome (check out Pfeiffer papers for some inspiration).

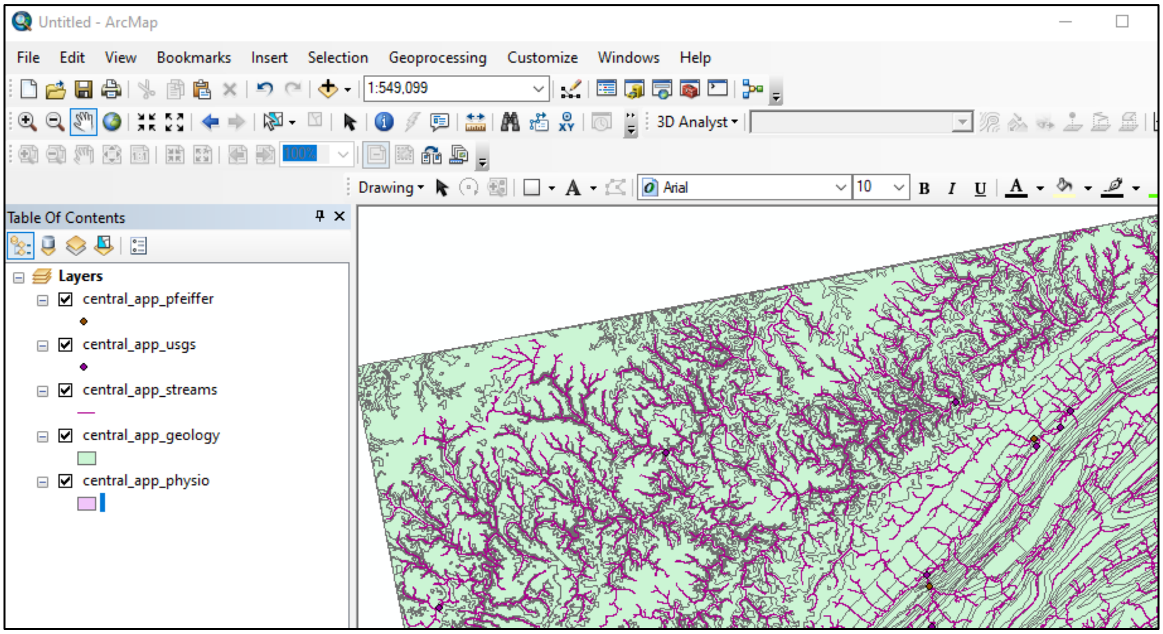
Please include the following figures at a minimum:

1. A map demonstrating the Brush survey stations, the USGS gages in the study area, and the Pfeiffer data locations, overlain on a geologic map colored by major rock type. Color the Brush data by τ^*_{bf}/τ^*_c. Include a scale bar and north arrow, and the map explanation should be clear to a casual viewer.

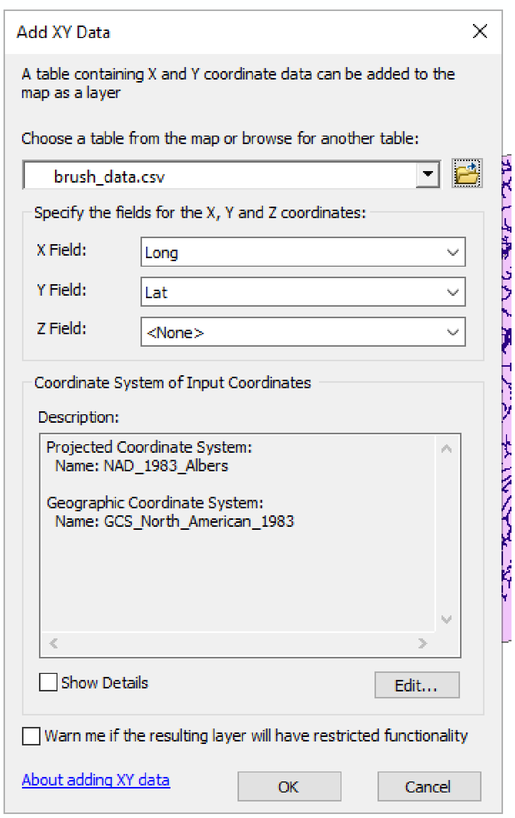
2. A scatterplot of τ^*_{bf} vs τ^*_c in which data are grouped (colored) by some property (rock type, physiographic province, etc.) and a 1:1 line ($\tau^*_{bf} = \tau^*_c$.) is added to the plot. Feel free to do this in Excel or Python.

How to do some things in Arc for this lab:

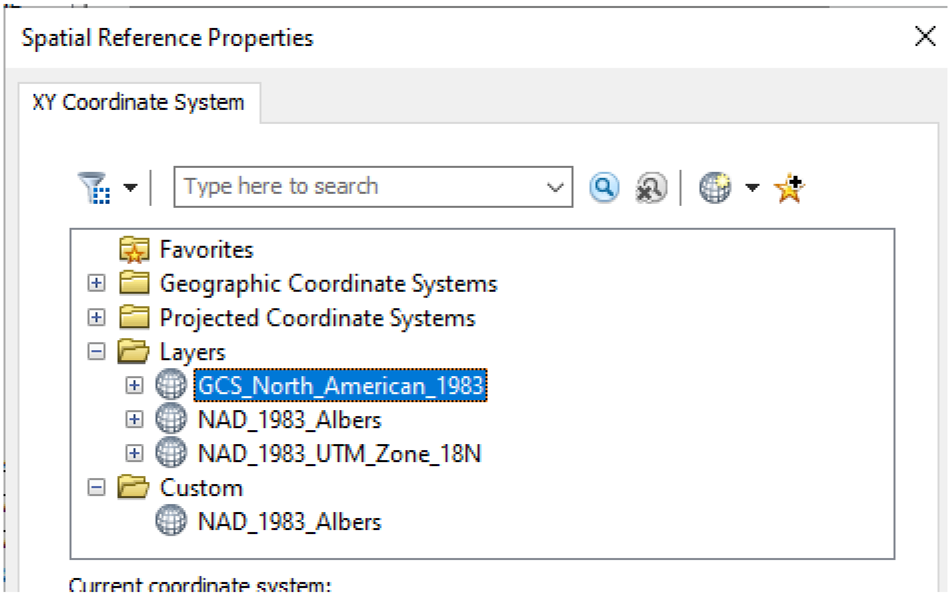
1. Load in all the polygon and line elements. You'll get something like this:



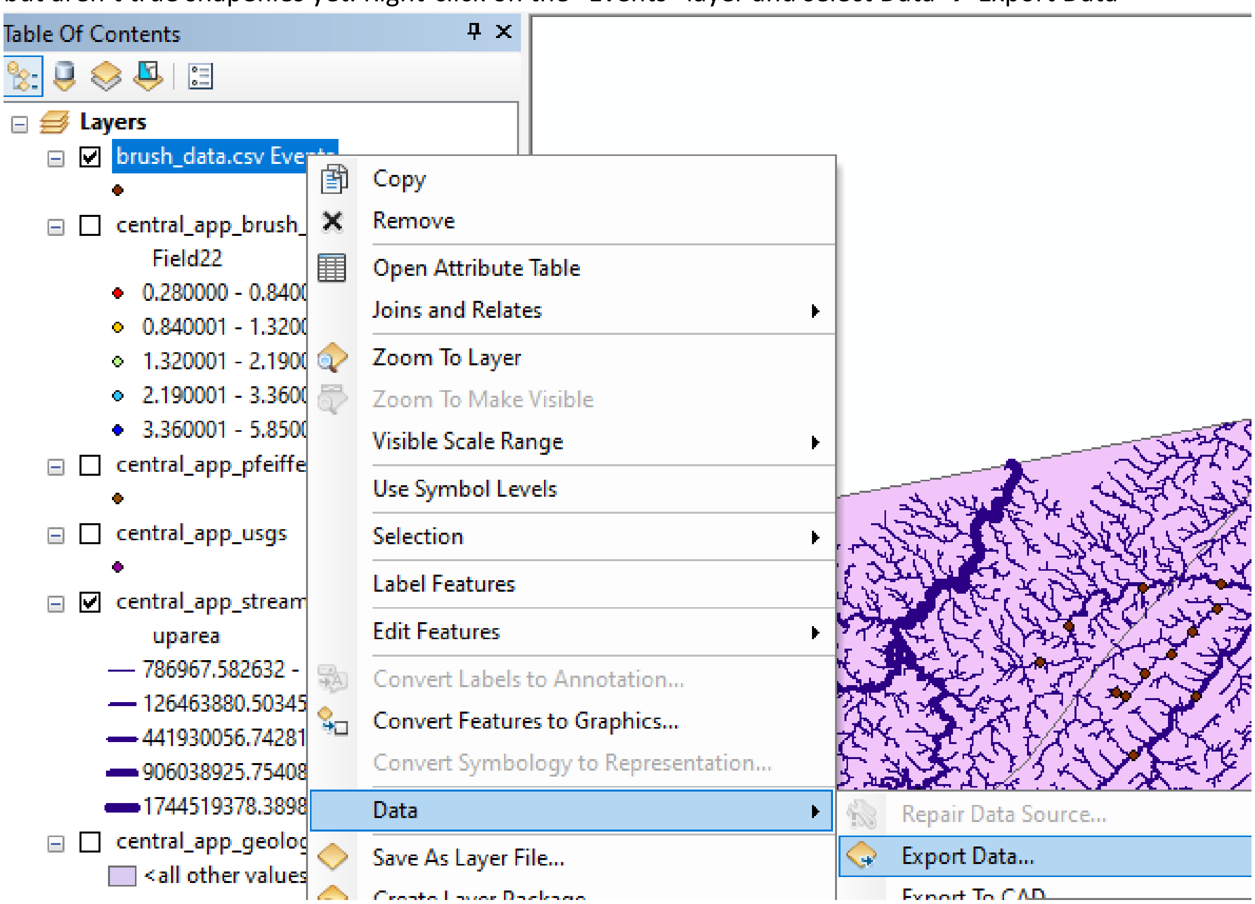
2. Next, navigate to File → Add Data → Add XY Data….
3. Click the open folder icon **Browse** and choose brush_data.csv. It should load in with Long and Lat properly assigned as X and Y coordinates, respectively:



4. You need to adjust the coordinate system. Click **Edit**… and on the resulting menu click on **Layers** to expand to show what CRS are already on your map. Select GCS_North_American_1983.



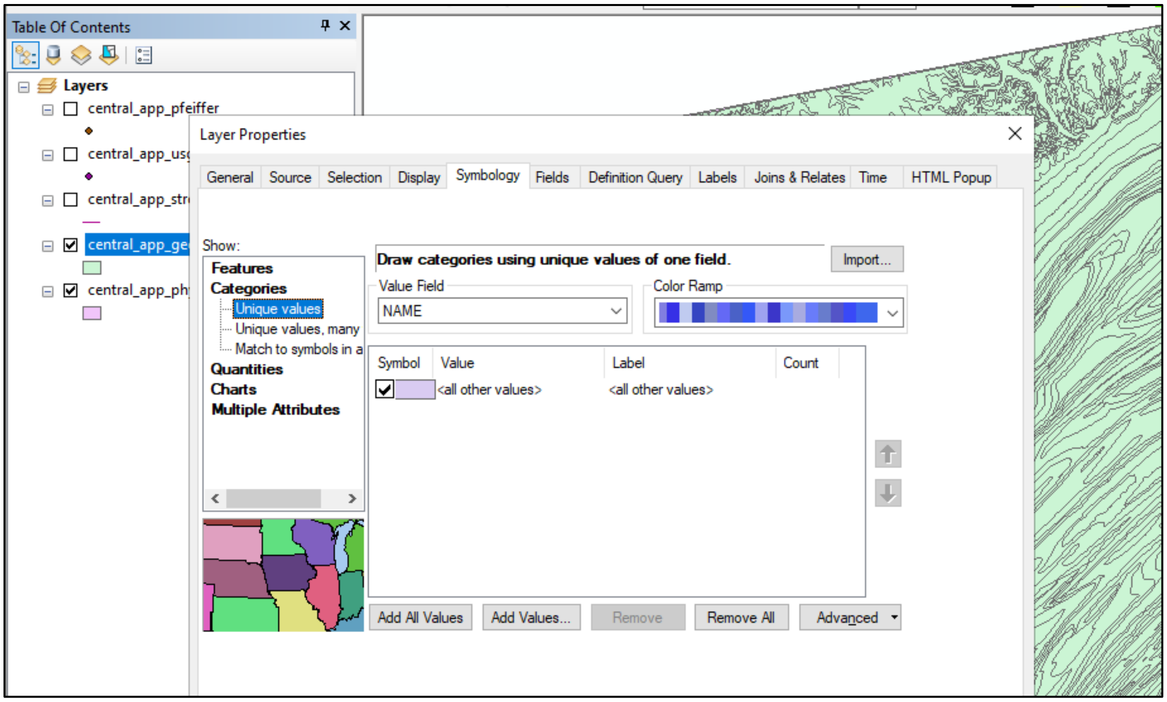
5. You will see your data added as "Events," which means they are temporarily cast as XY points but aren't true shapefiles yet. Right-click on the "Events" layer and select Data → Export Data



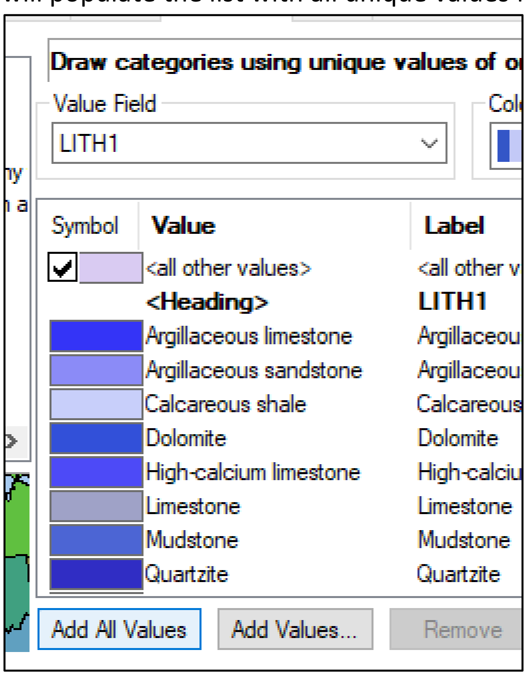
6. Change the Output feature class location to your working folder and name the feature something like “brush_stations.shp.” Make sure you’re saving as a **Shapefile** type. Hit Save, and when it asks you to add it to the map, click Yes.

Color by category:

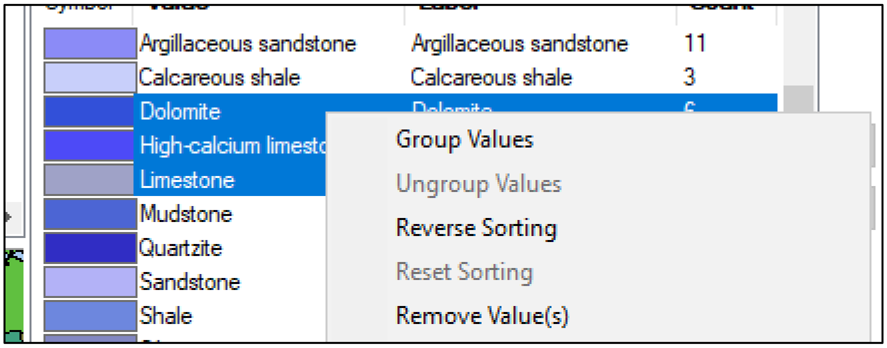
1. Right click “central_app_geology” and click **Properties**. Under the **Symbology** tab, click on **Categories** on the left.



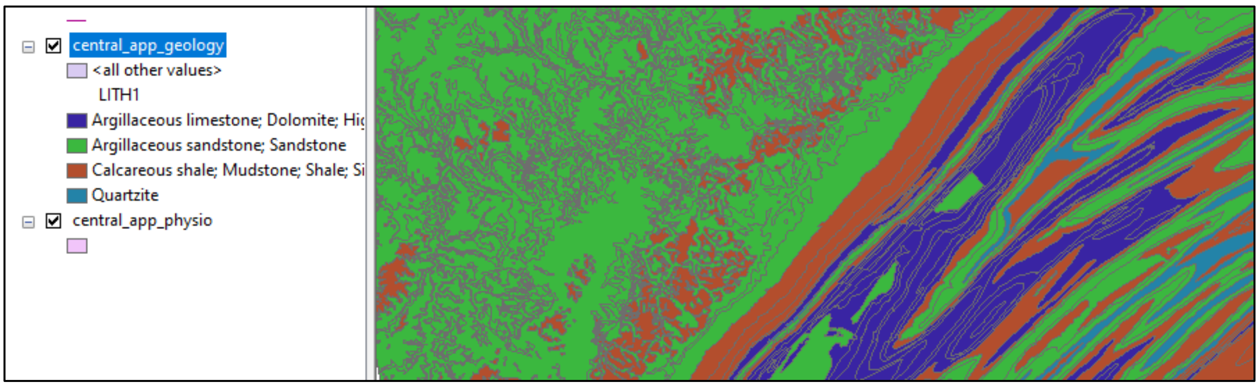
2. In the **Value Field** drop-down menu, open the list and select “LITH1.” Click Add All Values, which will populate the list with all unique values for LITH1 contained in the shapefile.



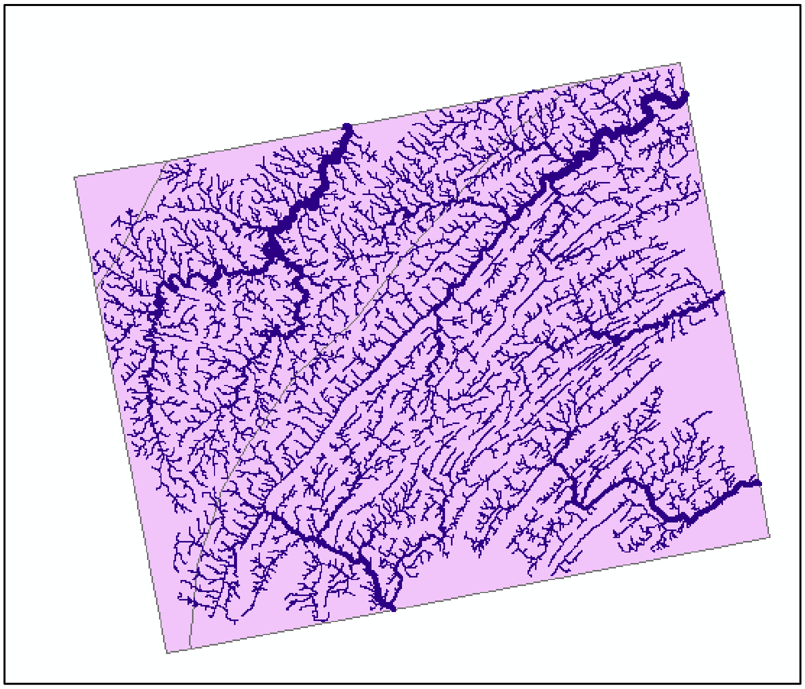
3. Ah, a classic geology case of lumpers versus splitters. We are going to be lumpers here. Holding down **Ctrl**, *left-click* on Argillaceous limestone, Dolomite, High-calcium Limestone, and Limestone. All 3 should be highlighted. Now *right-click* in the selection and click "Group Values"



4. Work until you have four groups: (1) Quartzite, (2) shales, mudstones and siltstones, (3) sandstones and (4) limestones. The result will look something like this:

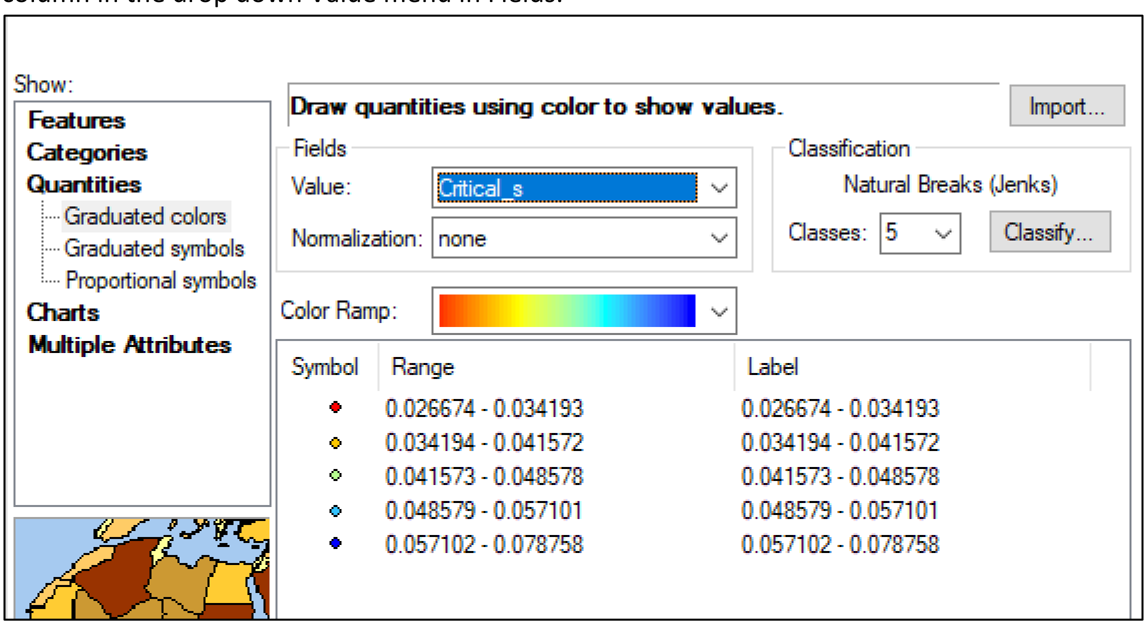


Symbol size by value:
A fun way to visualize a channel network is to make the channel lines wider with increased drainage area. In "central_app_streams," go to Properties → Symbology → Quantities → Graduated symbols. Select "uparea" from the drop down Value menu in Fields. This is upstream drainage area in square meters. Smaller streams will be drawn as thinner lines, and larger streams will be drawn as thicker lines, simulating the change in channel width with increasing drainage area:



Color by value:

Once you load in your Brush data, you can set color by the range of values in a column in the Attribute Table. Go to Properties → Symbology → Quantities → Graduated colors. Select a column in the drop down Value menu in Fields.



You can adjust the classification by clicking **Classify**…, and in that menu you can click on and type your own **Break Values**. For plotting the ratio of bankfull to critical stresses, I'd recommend clearly showing values below and above 1.0.