Short Training Initiative on Soil Erosion Risk Modelling and Mapping Using RUSLE and GIS

Practical Guide

13th – 17th May, 2024

Introduction

The aim of this short course is to introduce the trainees to modelling of soil erosion risk using the Revised Universal Soil Loss Equation (RUSLE) and Geographical Information Systems (GIS) tools. The training will cover the fundamentals of RUSLE and working with spatial data in ArcGIS. A practical soil erosion study, implementing RUSLE will be performed to give the trainees a chance to learn using an array of GIS analytical tools in ArcGIS environment. Data, software and desktop computers will be availed at the training venue.

Data

You will calculate the average annual soil loss by sheet and rill erosion in Al Damar in the River Nile State of Sudan using the following raster datasets found in the data folder.

1. Rainfall (mean annual precipitation & average monthly precipitation)
2. Soil texture (sand, silt & clay)
3. Organic carbon
4. Digital Elevation Model (DEM)
5. Land cover
6. Normalized Difference Vegetation Index (NDVI)

Overall approach

1. Your first task will be to source and geo-process (i.e., mosaic, project, resample, subset, etc.) all the spatial datasets needed for the soil erosion modelling exercise. Here, we have provided geo-processed datasets due to time constraints.
2. You will then calculate the five (5) main RUSLE model inputs (factor maps); namely, rainfall erosivity (*R*), erodibility (*K*), length-slope factor (*LS*), cover management factor (*C*), and conservation practice factor (*P*).
3. Finally, you will multiply the five (5) factor maps using raster calculator in a GIS to get the final spatially-distributed water erosion risk map.

A. Calculating slope-length *(LS)* factor

The *LS* factor represents the effects of slope length (*L*) and slope steepness (*S*) on the erosion of a slope. Increase in *L* causes increase in erosion due to a progressive accumulation of runoff in the downslope direction. Similarly, increase in *S* increases erosion due to increased velocity. The combination of the two factors is commonly referred to as the "topographic factor." The *L* factor is the ratio of the actual horizontal slope length to the experimentally measured slope length of 22.1m, while the *S* factor is the ratio of the actual slope to an experimental slope of 9%. The *L* and *S* factors are designed such that they are 1 (one) when the actual horizontal slope length is 22.1 and the actual slope is 9%.

To calculate *LS* factor, you will use the following equation:

$$L = (\mathrm{FA} \times \frac{\text{cell size}}{22.13})^{m};\ \ S = (\frac{\sin(\theta_{deg} \times 0.01745)}{0.0896})^{n}$$

$$LS = (\mathrm{FA} \times \frac{\text{cell size}}{22.13})^m \times (\frac{\sin(\theta_{deg} \times 0.01745)}{0.0896})^n$$

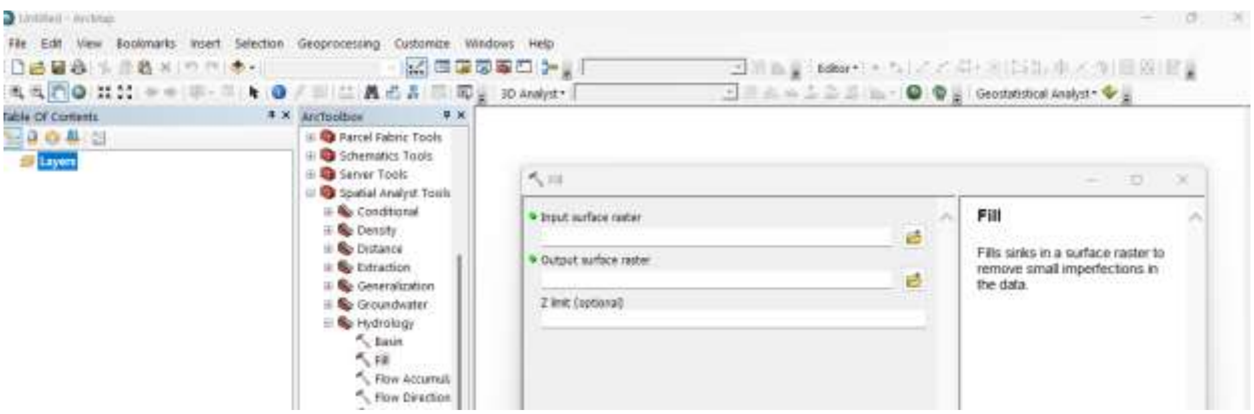
OR

$$LS = (m+1)(\mathrm{FA} \times \frac{\text{cell size}}{22.13})^m \times (\frac{\sin(\theta_{deg} \times 0.01745)}{0.0896})^n$$

Where: cell size is the resolution of the raster dataset, *FA* is flow accumulation, θ_{deg} is slope gradient in degrees, and *m* and *n* are exponents that can be adjusted based on the steepness of the terrain and soil's susceptibility to erosion. That is, *m* is 0.5, 0.4, 0.3 and 0.2 for slopes of > 9%, 3 - 9%, 1 - 3% and < 1%, respectively. It appears that using *m=0.4* and *n=1.3* is typical of farms and rangelands with low susceptibility to rill erosion. 0.01745 is a constant factor used to convert the slope values from degrees to radians for the *sin* calculation, while 22.13 and 0.0896 are constants for the unit plot length and slope gradient, respectively.

Both *flow accumulation* and *slope* layers can be extracted from a DEM. The DEM must be depressionless, without sinks. So, you will first create a depressionless DEM and then derive *flow accumulation* and *slope* layers from it.

To create a depressionless DEM, fill the sinks in the DEM (if any) using *Fill Tool* from the spatial analyst toolbox. Name the output file *filled_dem*.



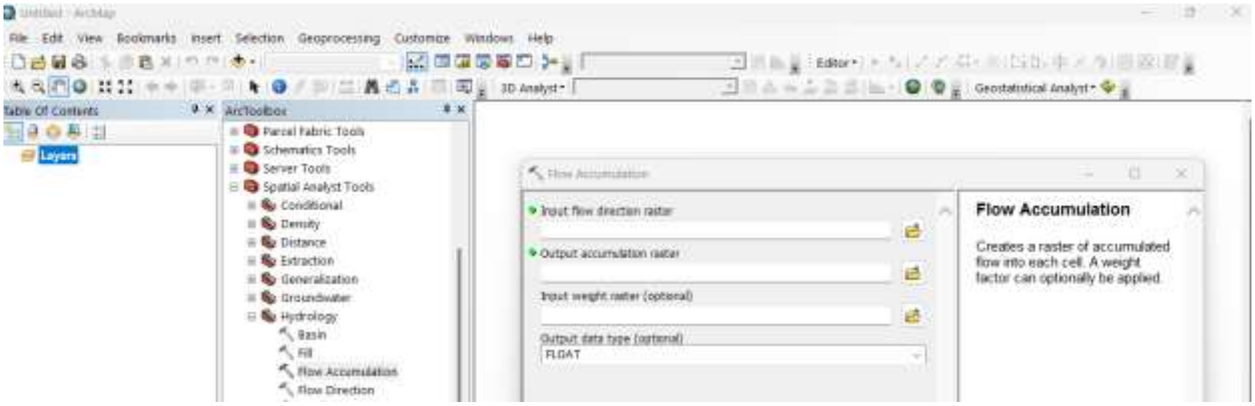
Now you can proceed to calculate the *LS* factor using the filled DEM that you have just created.

Step 1:

Calculate *Flow Direction* from the filled DEM using *Flow Direction Tool* from the spatial analyst toolbox and name the output file *fdr_dem*.

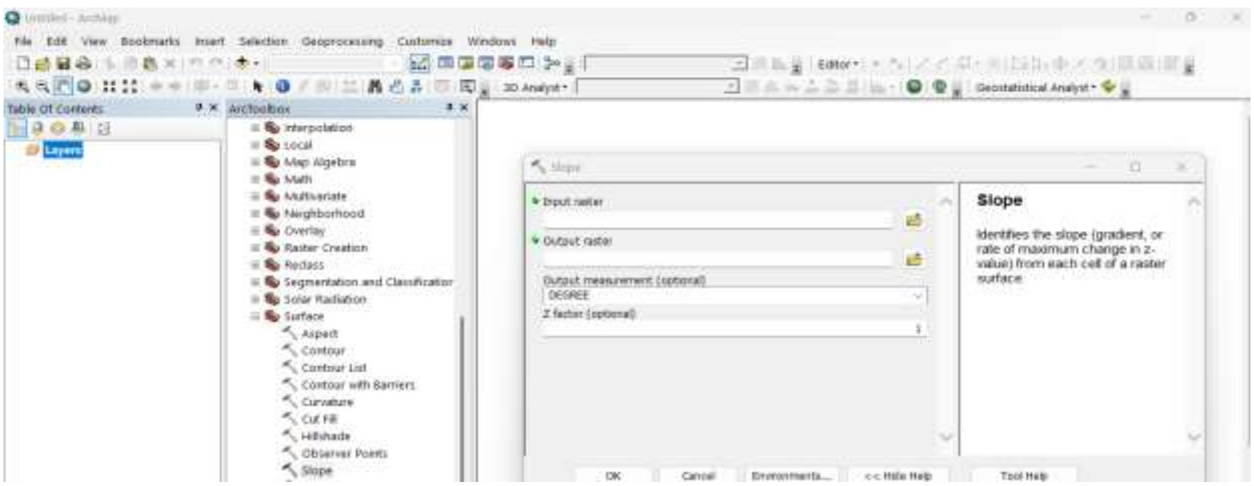
Step 2:

Calculate *Flow Accumulation* using *Flow Accumulation Tool* with the *fdr_dem* your input raster. Name the output file *facc_dem*.



Step 3:

Calculate *slope* in degrees using *Slope Tool* with the filled DEM as your input layer. Make sure that output measurement dropdown menu is set to DEGREES. Name this output file *slope_deg*.



Step 4:

Copy and paste the *LS* factor formula below into the *Raster Calculator*, then run it. Name the output layer *LS_factor.*

*Power("facc_dem.tif" * 90 / 22.1, 0.4) * Power(Sin("Slope_Deg1.tif" * 0.01745) / 0.0896, 1.3)*

Note that: *facc_dem* = Flow accumulation layer from Step 2; *90* = Resolution of the DEM in meters (Look in Properties of layer); and, *slope_deg* = Slope layer in Degrees from Step 3

B. Calculating rainfall erosivity (*R*) factor

Rainfall erosivity (*R*) is the kinetic energy of raindrop impact and rate of the associated overland runoff. It is affected by the volume, intensity and duration of rainfall.

To calculate *R* factor, you will use the following equation. Many such equations have been developed for specific regions of the world and are available in the literature. They should, however, be used with care when transferred to other regions.

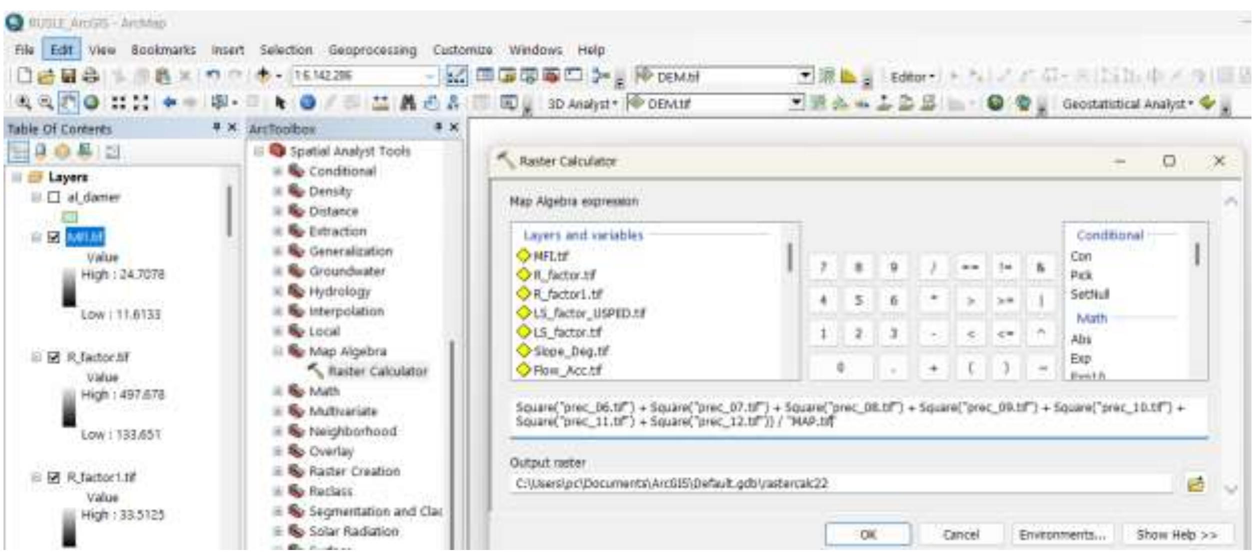
$$R = 27.8\text{MFI} - 189.2$$

$$MFI = \frac{\sum_{i=1}^{12} P_i^{\,2}}{P}$$

Where: R is rainfall erosivity (MJ mm ha^{-1} h^{-1} yr-1), *MFI* is the Modified Fournier Index (mm), P_i is the average monthly precipitation (mm), and *P* is the average annual precipitation (mm).

First, copy and paste the *MFI* factor formula below into the *Raster Calculator* after loading the 12 Average Monthly Precipitation layers, as well as the Mean Annual Precipitation (MAP) layer provided in the data folder. Run and name the output layer *MFI*.

(Square("prec_01.tif") + Square("prec_02.tif") + Square("prec_03.tif") + Square("prec_04.tif") + Square("prec_05.tif") + Square("prec_06.tif") + Square("prec_07.tif") + Square("prec_08.tif") + Square("prec_09.tif") + Square("prec_10.tif") + Square("prec_11.tif") + Square("prec_12.tif")) / "MAP.tif"



After that, copy and paste the *R* factor formula below into the *Raster Calculator*, run and name the output layer *R_factor.*

*27.8 * "MFI.tif" - 189.2*

C. Calculating soil erodibility (*K*) factor

Soil erodibility is the inherent resistance of soil particles to detachment and transportation by rain water (ease with which a soil can be eroded). It is more sensitive to the physical and chemical properties of soil especially soil texture and organic matter content, which determine soil permeability, infiltration rate and structural stability (strength).

To calculate *K* factor, you will use the following equation.

$$K = F_{sand} \times F_{clay} \times F_{soc} \times F_{silt} \times 0.1317$$

Where:

$$F_{sand} = \left\{0.2 + 0.3 \times exp\left[-0.0256 \times \mathrm{SAN} \times (1 - \frac{\mathrm{SIL}}{100})\right]\right\}$$

$$F_{clay} = (\frac{\mathrm{SIL}}{\mathrm{CLA+SIL}})^{0.3}$$

$$F_{soc} = \left(1 - \frac{0.25\mathrm{C}}{\mathrm{C}+exp[3.72-2.95\mathrm{C}]}\right)$$

$$F_{silt} = 1 - (\frac{0.7(1 - \frac{\mathrm{SAN}}{100})}{(1 - \frac{\mathrm{SAN}}{100})+exp[-5.51+22.9\left(1 - \frac{\mathrm{SAN}}{100}\right)]})$$

Note that: *SAN* is % sand, *SIL* % silt, *CLA* is % clay, and *C* % organic carbon.

Step 1:

Copy and paste the F_{clay} formula below into the *Raster Calculator*, then run it. Name the output layer *F_Clay*.

Power("SIL.tif" / ("CLA.tif" + "SIL.tif"),0.3)

Step 2:

Copy and paste the F_{SOC} formula below into the *Raster Calculator*, then run it. Name the output layer *F_SOC*.

*1 - ((0.25 * "SOC.tif") / ("SOC.tif" + Exp(3.72 - (2.95 * "SOC.tif"))))*

Step 3:

Copy and paste the F_{Sand} formula below into the *Raster Calculator*, then run it. Name the output layer *F_Sand*.

*0.2 + 0.3 * Exp(- 0.0256 * "SAN.tif" * (1 - ("SIL.tif" / 100)))*

Step 4:

Copy and paste the F_{Silt} formula below into the *Raster Calculator*, then run it. Name the output layer *F_silt*.

*1 - (0.7 * (1 - ("SAN.tif" / 100)) / ((1 - ("SAN.tif" / 100)) + Exp(- 5.51 + 22.9 * (1 - ("SAN.tif" / 100)))))*

Step 5:

Copy and paste the *K* formula below into the *Raster Calculator*, then run it. Name the output layer *K_factor.*

D. Calculating cover management (*C*) factor

The cover management or *C*-factor is related to land cover types. It relates soil erosion from a specific land cover type and management (e.g., tillage & fertilization) to erosion under a continuous bare fallow land. Here, you will infer *C* factor from the standard and readily-available remote sensing-based vegetation index (i.e., NDVI) using the following equation.

$$C = exp\left(-2\ \frac{NDVI}{1 - NDVI}\right)$$

C values range from 0 to 1, depending on vegetation cover (0 for complete vegetation cover and 1 for bare lands). Alternatively, a land cover map can be used, with *C* values being assigned to each land cover class based on literature.

Copy and paste the *C* factor formula below into the *Raster Calculator* after loading the NDVI layer that has been provided in the data folder. Run it and name the output layer *C_factor.* The NDVI layer used here is the mean of a time series of NDVI maps derived for the years 2013-2023 from MODIS data set.

*Exp(- 2 * ("NDVI.tif" /(1 - "NDVI.tif")))*

E. Calculating support practice (*P*) factor

The support practice factor or *P* factor reflects the effect of soil conservation practices (e.g., terracing) on soil erosion. It relates erosion resulting from the described conservation practice to that which would occur with up-and-down slope cultivation.

You will calculate *P* factor from a *slope* layer based on the following table. Note that *slope* measurement in this case is in PERCENT. So, to start with, calculate *slope* in percent using *Slope Tool* with the filled DEM as your input layer. Name the output file *slope_percent.*

Slope (%)	***P* factor**		
	Contouring	**Stripping**	**Terracing**
0.0 – 7.0	0.55	0.27	0.10
7.0 – 11.3	0.60	0.30	0.12
11.3 – 17.6	0.80	0.40	0.16
17.6 – 26.8	0.90	0.45	0.18
26.8 >	1.00	0.50	0.20

Step 1:

Reclassify the *slope_percent* layer using *Reclassify Tool* from the spatial analyst tools and name the output file *slope_reclass*.

Step 2:

Convert the reclassified *slope* layer to a polygon using *Raster to Polygon Tool* from the conversion tools. Name the output polygon file *slope_reclass_poly*

Step 3:

Get the unique values for each slope class in the output polygon file (*Selection menu* > *Select By Attributes* > *Get Unique Values*) and merge them. To merge the selected records of the same slope class go to the *Editor Toolbar* > *Start Editing* > *Merge*.

Step 4:

Add a new field, give it an appropriate field name, assign the associated *P* factor value to each slope class, and the stop editing (*Editor Toolbar* > *Stop Editing*).

Step 5:

Finally, rasterize the polygon using *Polygon to Raster Tool* from the conversion tools. Name the output raster file *P_factor.*

Alternatively, you can calculate *P* factor from the *slope* layer and *land cover* layer based on the following table and steps.

Land use type	**Slope (%)**	***P* factor**
Agricultural land	0 – 5	0.10
	5 – 10	0.12
	10 – 20	0.14
	20 – 30	0.19
	30 – 50	0.25
	50 - 100	0.33
Other land cover types	All	1.00

P values range from 0.1 to 1, depending on the land use and slope classes

Step 1:

Reclassify the *slope* layer using *Reclassify Tool* from the spatial analyst tools and name the output file *slope_reclass*.

Step 2:

Convert the reclassified *slope* layer and the *land cover* layers to polygons using *Raster to Polygon Tool* from the conversion tools. Name the output polygon files *slope_reclass_poly* and *landcov_poly*.

Step 3:

Intersect the slope (*slope_reclass_poly*) and land cover (*landcov_poly*) layers. *Geoprocessing menu* > *Intersect*. Add a new field with the name *P_value* and save the output file as *slope_landcov_int.*

Step 4:

Get the unique values for each land cover class in the output polygon file (*Selection menu* > *Select By Attributes* > *Get Unique Values*) and assign the appropriate *P* values. For the agricultural/ crop land, assign *P* values based on the unique combination of land cover and slope classes. To activate the *P* value field in order to enter the *P* values, got to the *Editor Toolbar* > *Start Editing*.

Step 5:

Finally, exit the editing mode (*Editor Toolbar* > *Stop Editing*) and then rasterize the polygon using *Polygon to Raster Tool* from the conversion tools. Name the output raster file *P_factor.*

F. Generate the water erosion risk map

Once you have created the five (5) RUSLE factor maps, multiply them using the *Raster calculator* to generate a spatially-distributed water erosion risk map for Al Damar. Name the output file *Soil_loss.* Be sure that all the factor maps have the same cell size (resolution) and projection before you multiply them.

*"C_factor.tif" * "K_factor.tif" * "P_factor.tif" * "R_factor.tif" * "LS_factor.tif"*

Finally, reclassify the output file into four (4) classes using the *Reclassify tool* and then create a neat map (with all cartographic elements), showing the annual soil loss (erosion rates) in Al Damar, Sudan.