Lab 3: Soil-mantled hillslopes

Objectives
In this lab, you will analyze the elevation, slope, and curvature of two soil-mantled landscapes, and build intuition about the connection between topography, soil thickness, and erosion rates.

Figure 1. (mostly) Soil mantled hillslopes in Tennessee Valley, CA

Background
Most upland landscapes are blanketed with a mobile soil layer that varies in thickness from ~10 centimeters to a few meters. The ubiquity of this form is due to a feedback whereby the production of soil from the underlying bedrock depends inversely on the soil thickness. Additionally, because the transport of soil downhill is a function of topographic slope, landscapes tend towards a morphodynamic equilibrium between topography, soil thickness, and erosion rate. While this conceptual framework extends back to the time of G.K. Gilbert in the late 19th century, recent advances in characterizing topography (e.g., LiDAR) and erosion rates (e.g., cosmogenic radionuclides) have enabled researchers to test hypotheses about what governs the rate of soil transport downslope, and what controls the presence or absence of soil on hillslopes. In today’s lab, we will be analyzing data from a series of studies on soil-mantled hillslope process and form in California and Oregon. To aid you with your written report, I have included the following journal articles:


3.0 Summary of provided datasets

You have been provided with two file geodatabases for this week, one for the Tennessee Valley study site in northern California, and one for the Coos Bay study site in the Oregon Coast Range. Each folder contains a 2 m resolution digital elevation model derived from airborne LiDAR surveys, a full-color satellite image, and a profile line I generated for this lab.

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<th>Source</th>
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<td>USGS National Map</td>
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<td>Elevation in meters</td>
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I will walk you through the steps to generate a curvature map and extract elevation profiles for the Tennessee Valley site, and then you will run through the exact same steps for the Coos Bay site so you can directly compare the results in your write-up.

3.1 Generating slope and hillshade maps

To start, right click on the file geodatabase “tennessee_valley_data.gdb” and select Make Default Geodatabase. Load the layers “tenn2_dem”, “tennessee_hilltop_profile”, and “tennessee_orthophoto.tif” into your data frame (note that the orthophoto is in the folder “imagery”). While you are at it, rename your data frame from “Layers” to “Tennessee Valley”, as you will be adding a separate data frame for the Coos Bay site later.

Your first task for the lab is to generate a slope map (in degrees) and hillshade using “tenn2_dem”. Because we will be generating lots of similar files in this lab, make sure to keep organized. I suggest naming the above two rasters “tenn2_slope” and “tenn2_hillshade”. This should be familiar to you by now, and is typically the first step in visualizing any new landscape.

Additionally, for this lab you will be asked to report the mean slope for the 1 km x 1 km extent of each study area. There are a couple ways to do this, but the easiest is to open up the symbology of the slope map, make sure you are in the classified window, and press the classify button. This will bring up a histogram of all of the values in the raster dataset, and some basic statistics. Note the mean slope, and record it here for later (only use one decimal place!)

Mean value for “tenn2_slope” =

3.2 Smoothing elevation data using Focal Statistics

Looking at the hillshade derived from “tenn2_dem”, you will notice that there are lots of little pits and mounds across the landscape surface (as well as some roads and trails). For this lab, we are interested in characterizing how topography varies over longer length scales (10-20 m), so it is necessary to smooth the DEM using a moving average filter.

Navigate to the tool \Spatial Analyst Tools\Neighborhood\Focal Statistics, and double click to bring up the dialog box (Fig. 2).
For the input raster, choose “tenn2_dem”, and name the output raster something useful, like “tenn2_smooth_dem”. For the neighborhood, we will use a circular window with a radius of 5 cells. Because the grid size of “tenn2_dem” is 2 m, this means we are averaging the elevation over a scale of about 20 m for each pixel in the raster.

Once you have generated a smoothed DEM, go ahead and make another slope map and hillshade, this time using the raster data set “tenn2_smooth_dem” as your input. I suggest naming your new datasets something like “tenn2_smooth_slope” and “tenn2_smooth_hillshade”. Flip back and forth between the original hillshade and the smoothed hillshade to get a sense for how much we “blurred” the landscape. Determine the mean of the smoothed slope map, and compare this to the value you wrote down above for the original slope map. Is it higher or lower?

Mean value for “tenn2_smooth_slope” =

Finally, use the \Spatial Analyst\Surface\Contour tool to generate a contour map of elevation for the data set “tenn2_smooth_dem”. Name your output something like “tenn2_smooth_5m_contour”, and use a contour interval of 5 meters.

3.3 Making a curvature map

The curvature tool in ArcMap provides a measure of the convexity or concavity a topographic surface. In the same way that gradient (the tangent of the slope angle) represents the first derivative of elevation with distance, topographic curvature is the second derivative of elevation with distance. Often times you will see topographic gradient written as $\nabla z$, and topographic curvature written as $\nabla^2 z$.

Navigate to and open up the tool \Spatial Analyst\Surface\Curvature (Fig. 3). For the input raster, use the smoothed elevation data set “tenn2_smooth_dem”. Give your output raster a
useful name like “tenn2_smooth_curvature”. Finally, because ArcMap outputs the curvature in “percent” units, we need to change the Z factor to 0.01. This way, the output will be in units of m-1, so we can compare more easily with published data sets. Press OK. Note that you can also split curvature up into profile curvature, which is calculated in 1-D in the direction of steepest descent and planform curvature, which is calculated in 1-D orthogonal to this direction. In this lab, we are only interested in the total (2-D) curvature.

To more easily visualize the curvature data, we will need to change to a classified symbology (Fig. 4). To make things easier, I included a layer file containing the appropriate symbology. Select the import button (file folder icon), and navigate to and select the layer file “curvature_symbology.lyr”.

Figure 3. Layer properties dialog showing symbology for slopeshade map.

Figure 4. Adjusting symbology for the curvature layer (the dark blue symbol level for < -0.08 is out of view)
Now, make the **curvature** map partially (~50%) transparent over the original **hillshade** “tenn2_shd”, and spend some time exploring around. It is also helpful to overlay the contour map of elevation very faintly (~70% transparency) over the **curvature** and **hillshade** as well. Note that ArcMAP uses the convention that positive curvature corresponds to a convex-upwards surface (Fig. 5). Which parts of the landscape are convex up? Concave up? How is this expressed by the elevation contours (think about what ridges and valleys look like on topographic maps)? Do you think you could map curvature with just a contour map?

**Figure 5. Curvature sign convention in ArcMap**

**You can try running the curvature tool on the original DEM, but the result will be very noisy and hard to interpret. Remember that the curvature corresponds to the second spatial derivative of elevation. That is, we are looking at the “changes in the changes in elevation“ with distance, which means any small topographic roughness elements will be greatly amplified! For a discussion about the influence of grid size on curvature, see pages 157-158 of Heimsath et al. (1999).**

### 3.4 Analyzing hilltop elevation profiles

While maps of elevation contours, slope, and curvature enable us to assess how these variables change across the whole landscape, it can be helpful to analyze hilltop elevation profiles in one dimension to build intuition about landscape form.

Load the **line feature class** “tennessee_hilltop_profile” into your map. This is a 3D shapefile that was generated using the **interpolate line** tool. Normally, when you use the **interpolate line** tool, the resulting profiles are saved as graphics elements. However, you can make these profile lines permanent feature classes by going to the **drawing toolbar** menu and selecting “convert graphics to features”.

Now, use the **select features** tool on the toolbar to highlight the hilltop profile line (you can de-select the highlighted line by clicking the **clear selected features** tool), and then click the **profile graph** button on the **3D Analyst** toolbar to generate a profile graph. Instead of working with this plot in ArcMap, as we have done for the last two labs, we are going to export the data and analyze it in Microsoft Excel. To do this, right click on the graph, and select **Export…** (Fig. 6). Go to the **Data** tab, and de-select the boxes **Point Labels** and **Header**. You can preview the distance-elevation data by checking the **Preview** box (though this may not work on public computers). Click the **Copy** button, and then **paste** the data into Excel.
Once in Excel, label your data columns with “Distance (m)”, “Elevation (m)”, “Tangent of slope (m/m)” and “Slope (degrees)”. You should have Distance and Elevation from the profile you extracted in ArcMap. To calculate the tangent of the slope, write a formula to take the change in elevation divided by the change in distance over three points (Fig. 7). Drag the bottom right corner of this cell down to apply the equation to all rows. BUT, leave the first and last rows empty, as you cannot accurately estimate slope at the endpoints.

![Figure 7. Calculating local slope in Microsoft Excel from distance-elevation data.](image)

To see the slope in degrees, enter the equation to calculate the arctangent in units of degrees (Fig. 8).
Next, generate plots of elevation vs. distance and slope vs. distance. It is helpful to combine these into a single plot by plotting elevation on the primary y-axis (left hand side) and slope on the secondary y-axis (right hand side). Make sure to include a legend and label your axes appropriately (see Fig. 9 for an example). If you have not used Excel much, take some time to learn how to change the look of the series, add a secondary axis, add a legend and title, and insert text box annotations. It will be a big help for the remainder of this class and beyond.

Figure 9. Example hilltop elevation and slope profile plotted in Excel. Note: your cross sections will be different from this one, which was picked from a lower nose in Tennessee Valley.

Take some time to investigate the patterns of elevation and slope shown in your plots. How does slope vary with distance? How about curvature? Remember, curvature can be thought of as the “slope of the slope” in one dimension.

3.5 Comparison between two soil-mantled landscapes

Now that you have generated a series of map calculations and analyzed a hillslope profile for the Tennessee Valley site, do the same for the Coos Bay data. It will make things easier for you to insert a new data frame rather than start a whole new map. To do so, go the Insert drop down menu and select Data Frame. To switch back and forth between the two maps, either select the appropriate map in Layout View or right click on the Data Frame in the Table of Contents window and select Activate.
To view your maps side by side in Layout View at the same scale, adjust the map scale in the Standard Toolbar (Fig. 10). For this lab, a scale of 1:8,000 is best. This means that one centimeter on the map corresponds to 8,000 cm, or 80 m, in the real world.

When you have finished generating both datasets, make a table to include with your report that includes the calculations shown below. I have filled in a few of the boxes for you to get started.

<table>
<thead>
<tr>
<th></th>
<th>Tennessee Valley, CA</th>
<th>Coos Bay, OR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total relief in scene (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean slope angle (degrees)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average hilltop curvature (m$^{-1}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width of hilltop convexity (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average soil thickness (cm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum soil production rate (m/Myr)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drainage density</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landscape-averaged erosion rate (m/Myr)</td>
<td>80 m/Myr</td>
<td>117 m/Myr</td>
</tr>
</tbody>
</table>

- Remember, total relief is the max elevation minus the min elevation in a given area.
- For mean slope angle, use the value for the unsmoothed slope map.
- For average hilltop curvature, use the info button to click around on different ridgelines within the scene, and give a range of values (you can also estimate this from the symbology of the curvature layer).
- For the width of the hilltop convexity, use your 1-D profiles to estimate how much of the hilltop is convex-up. For example, in the profile shown in Fig. 9, the hilltop is convex between ~150 m and 250 m, so the width of the hilltop convexity would be 100 m.
- To estimate average soil thickness, look at Figure 6 in Heimsath et al. (1999) and Figure 6 in Heimsath et al. (2001). Assume that these soil pit measurements are representative of the whole landscape.
- To find the maximum soil production rate, look at Figure 7 in Heimsath et al. (1999) and Figure 5 in Heimsath et al. (2001).
- Drainage density is defined as the length of the stream network divided by the area of interest, and is a measure of how “dissected” the landscape is. For this lab, simply note which landscape has a higher drainage density (e.g., “high” or “low” for each box).
- The erosion rate for each landscape corresponds to the catchment-averaged erosion rate determined from $^{10}$Be concentrations in stream sands.
3.6 3D Visualization of data in ArcScene (OPTIONAL)

Often times, it is helpful to view a 3D rendering of the landscape, as when you use Google Earth. The program ArcScene enables you to directly load custom image and elevation datasets that you have generated in ArcMap in a much more flexible manner than Google Earth. This part of the lab is entirely optional, but I encourage you to experiment a bit with it.

First, open up the program ArcScene using the shortcut on the 3D Analyst toolbar: . The layout looks quite similar to ArcMap, and you have access to the same tools and catalog. Open the catalog window, navigate to the raster dataset “tenn2_dem”, and load it into your map window. Right now it is a flat plane that you can rotate and move around using various mouse buttons.

To make this layer 3D, we need to assign base heights. Double click on the layer and go to the Base Heights tab (Fig. 11).

![Figure 11. Assigning base heights in ArcScene.](image)

We want to assign the elevation values from “tenn2_dem”, so select **Floating on a custom surface** and then navigate to the raster “tenn2_dem”. We can also control the resolution of the base height assignment. Since our data set has a Cell size of 2 m, set the values to 2 in order to show the highest level of detail. If your elevation dataset is too large, you can increase this number to enable faster 3D rendering. You can also adjust vertical exaggeration and offset in this window. Try setting the conversion factor to 2.0 and see what happens.

After you adjust the base heights, reset the scene extent by clicking the large globe button on the right hand side of the navigation toolbar (Fig. 12).

![Figure 12. Navigation toolbar in ArcScene.](image)
We can add illumination to scene by going to the **Rendering** tab in the **Layer Properties** dialog and selecting **Shade areal features relative to the scene's light position** (Fig. 13). While you are here, crank up the slider bar on **Quality enhancement for raster images**. Similar to choosing the base height resolution, this adjusts the image resolution of your raster datasets. If your computer is getting bogged down, you can slide this back to the left.

![Layer Properties dialog](image1)

Figure 13. Rendering properties for layer in ArcScene.

Often times, it is more useful to visualize a separate dataset, such as curvature or satellite imagery in today’s lab. Navigate to and load up your **curvature** raster for Tennessee Valley, and adjust the symbology by loading it from the layer file “curvature_symbology.lyr” (see Fig. 4). Repeat the steps shown above to assign base heights using the DEM, shade the features using the scene’s light position, and crank up the quality enhancement for the raster image (Fig. 14). Now you should have a nicely-rendered curvature map to explore!

![Curvature map](image2)

Figure 14. Perspective view of curvature map for Tennessee Valley.
Let’s do the same thing for the imagery data, except now we do not need to shade the scene because there are already shadows in photo. We do however need to change the symbology for this layer (Fig. 15). The satellite image is composed of 3 bands, and ArcScene tries to stretch each band individually, which can result in some interesting coloring! For now, change the **Stretch** type to “None” and uncheck **Apply Gamma Stretch**.

![Image of Layer Properties dialog](image)

**Figure 15. Adjusting symbology for multi-band raster image.**

We can also change the offset of each layer to make a nice stacked image. To do this, go to the **Base Heights** tab (Fig. 11) and adjust the layer offset to something like 20 m. You should end up with something that looks like Fig. 16. To save this image, take a screenshot or go to File/Export Scene/2D. You can make a high-resolution output by increasing the **View size** and **resolution**.

![Image of ArcScene scene with satellite imagery offset by 20 m](image)

**Figure 16. Satellite imagery offset by 20 m above curvature raster in ArcScene.**
Lab 3 deliverables, due Friday February 6 before lecture (40 pts total)

Please submit as single PDF file to the Lab 3 drop box on Angel

(5 pts) A curvature map for Tennessee Valley, CA, draped over a hillshade, at a scale of 1:8,000
- Please use the symbology provided in the “curvature_symbology.lyr” layer file, and include a legend, scale bar, and north arrow.
- Include an overlay (~70% transparent) of elevation contours with an interval of 5 m (note that you only need to indicate the contour interval in your legend).
- Include the cross section line for the hilltop elevation profile given in the feature class “tennessee_hilltop_profile”

(5 pts) A curvature map for Coos Bay, OR, draped over a hillshade, at a scale of 1:8,000
- This map should be analogous to the one above, and fit on the same page

(5 pts) A table summarizing your measurements of landscape morphology
- Fill in the table I have provided in section 3.5 using the maps and profiles you have created. To estimate soil thickness, you will need to look up the data from the included journal articles.
- To make things easier, I included a template document “Lab_03_table_1.docx” for you to fill out.

(5 pts) Two hilltop profile plots showing both elevation and slope (1 for each study site)
- Be sure to include appropriate title, legend, and axes labels (see Fig. 8)
- Both plots should be included on the same page. The easiest way to do this is to arrange both charts in a new sheet in Excel and save as a PDF.

(20 pts) A written report no more than 3 pages long (12 pt font, 1.5 line spacing, 1” margins), which should include the following
- A brief introduction (no more than 1 paragraph)
- A description of hillslope morphology at the Tennessee Valley study area – be as quantitative as you can (1 paragraph focused on observations and measurements)
- A description of hillslope morphology at the Coos Bay study area – again, be as quantitative as you can (1 paragraph focused on observations and measurements).
- A discussion focused on addressing, in general, what the pattern of curvature in the landscape tells you about 1) soil depth 2) erosion rate 3) geomorphic process 4) whether or not each landscape is in steady state? (~1-2 paragraphs)
- A discussion comparing the hillslopes of Tennessee Valley to those of Coos Bay. How do the morphology, soil depth, and erosion rates differ between the two landscapes? Is this consistent with what we have been discussing in lecture? Which aspects don’t fit your preconceptions? (~1-2 paragraphs)