Geospatial Problem Solving

Digital Terrain Analysis

Image from NASA:
https://commons.wikimedia.org/wiki/File:Earth_Western_Hemisphere_transparent_background.png#filelinks

In this module we will expand upon the raster analysis techniques discussed in the previous lecture. Specifically, we will focus on digital terrain analysis.

Module Topics

1. Raster grids vs. TINs
2. Elevation data sources
3. Slope and aspect
4. Terrain visualization
5. Land surface parameters
6. Viewshed analysis
7. Cut and fill
8. Profiles

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These are the topics covered in this module.

Digital Terrain Data

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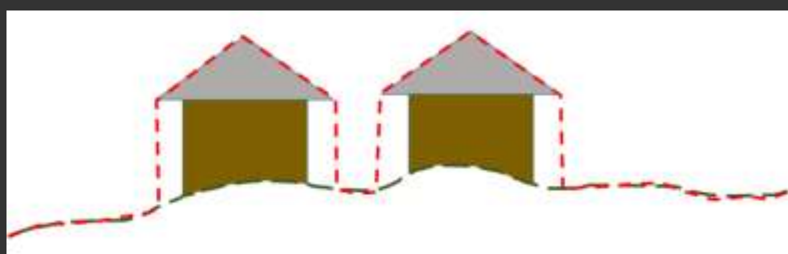
Elevation Data in a GIS

- DTM (Digital Terrain Model) = A representation of a terrain surface calculated by measuring elevation values at a series of locations
- DEM (Digital Elevation Model) = A model of the terrain surface
- DSM (Digital Surface Model) = Ground surface + objects above the ground surface



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Three different terms can be used to describe digital elevation data, and they are commonly confused. So, I will define them here.

A Digital Terrain Model, or DTM, represents just the ground surface. It does not include aboveground features.

Although more ambiguous, a digital elevation model, or DEM, also generally refers to a model representing the ground surface.

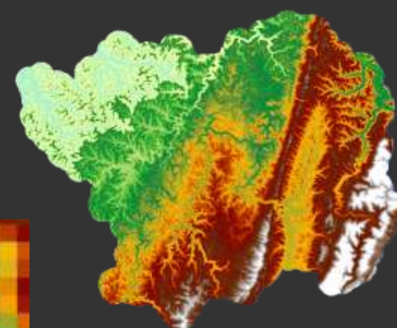
In contrast to DTMs and DEMs, digital surface models, or DSMs, include aboveground features, such as trees and buildings.

In the example image, the green line would represent a DTM or DEM whereas the red line would represent a DSM.

If you would like to calculate the height of features above the ground surface, you can subtract a DTM or DEM from a DSM. This product is known as a normalized digital surface model, or nDSM.

Digital Elevation Models (DEMs)

- A continuous raster-based representation of terrain
- Each pixel holds an elevation measurement in feet or meters



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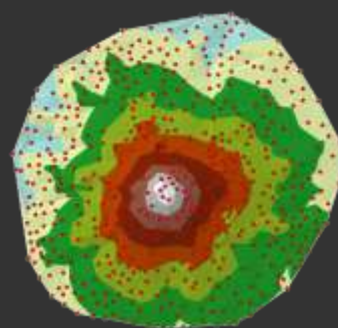
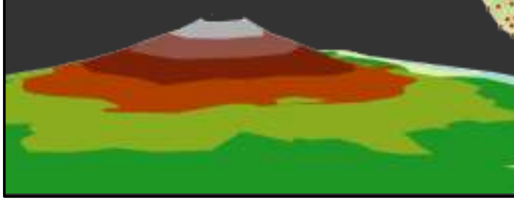
Elevation or terrain data can be represented as a continuous raster grid.

Each cell will hold an elevation measurement in some height units, such as feet or meters.

Vector Data, Not for Discrete Features

- TINs (Triangulated Irregular Network)
- Good for representing terrain data
- A space filling model

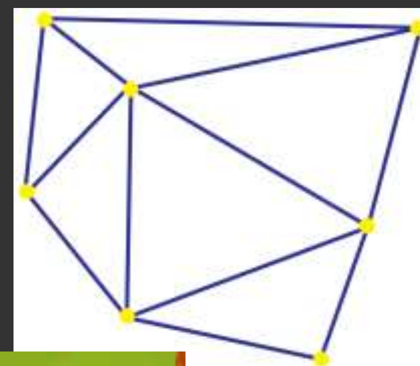




As mentioned in a prior module, it is possible to represent continuous variables using a vector data model as a TIN or Triangulated Irregular Network.

TINs

- Connecting measurement points to form a triangle (face)
- Can also include contours and/or breaklines
- Lines connecting points = edges
- Can be used to represent a terrain (or other continuous surfaces)
- Pros and cons compared to raster data



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TINs are generally produced from mass points or discrete measurements.

Near points are connected to form triangular faces or facets. The lines connecting the points are called edges.

The triangles hold a measure derived from the connected points.

If the phenomenon of interest changes abruptly, breaklines can also be included. Breaklines represent breaks in the surface. For example, road cuts could be modeled as breaklines in a terrain surface.

There are pros and cons when representing a continuous surface as a TIN vs. a raster grid.

TINs are inherently multiresolution. Smaller triangles or more detailed surfaces will be produced in areas with more point measurements whereas larger triangles or less detailed surfaces will be produced in areas with less point measurements. In contrast, a raster-based surface must have the same cell size across the entire extent. TINs can also be smaller files in comparison to raster grids, though this depends on many factors.

Many of the tools available for performing terrain analysis or overlay are designed for raster data. So, it might be necessary to convert the TIN to a raster grid to undertake these analyses.

Data Sources

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What are the sources of terrain data

1. Contour Lines and hypsography data
2. Photogrammetry
3. Radar (Radio Detection and Ranging)
4. LiDAR (Light Detection and Ranging)
5. GPS
6. Structure from Motion

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There are many methods available to create digital terrain data.

Radio Detection and Ranging (RaDAR)

- SRTM (Shuttle Radar Topography Mission)
- February 2000
- 11 day mission
- Mapped 80% of world at 90 m resolution
- 30 meter over US

https://www2.jpl.nasa.gov/srtm/

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RaDAR, or radio detection and ranging, uses radio waves or microwaves to map terrain surfaces.

An active sensor releases radio waves or microwaves. The waves can then strike a target then potentially bounce back to a detector.

The system can then record the two-way travel time and use this information to determine the distance between the sensor and surface.

If the location of the sensor is known, then elevations can be derived.

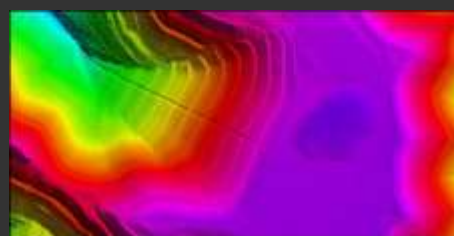
One example of RaDAR data is the Shuttle Radar Topography Mission, or SRTM, data.

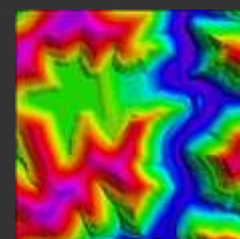
These data were collected in February of 2000 during an 11 day mission in which 80% of the globe was mapped.

90 m resolution data are available globally and 30 m data are available over the United States. Later, the 90 m data were processed to 30 m.

Light Detection and Ranging (LiDAR)

- Use laser pulses
- Often collected from a aircraft
- Provides multiple returns per each laser pulse
- High resolution (sub meters)
- High accuracy (+/- 10 cm)





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Light detection and ranging, or LiDAR, is similar to RaDAR in that the two-way travel time of electromagnetic radiation is used.

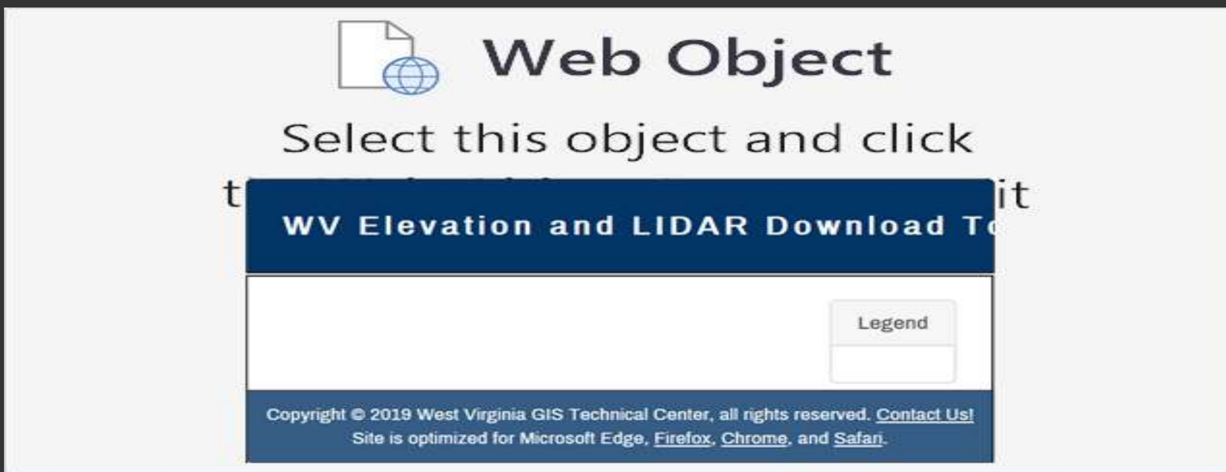
However, shorter wavelengths are used, generally a visible or near infrared wavelength.

LiDAR generally allows for the collection of very accurate and precise elevation data at a high spatial resolution.

It is possible to generate sub-meter elevation data with accuracies in the centimeter range.

These data can be collected from aircrafts, satellites, and drones.

LiDAR in West Virginia



https://data.wvgis.wvu.edu/elevation/

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Public LiDAR data that have been collected across the state of West Virginia can be downloaded using the WV Elevation and LiDAR Download Tool.

Structure from Motion (SfM)

- Terrain data created from overlapping drone imagery

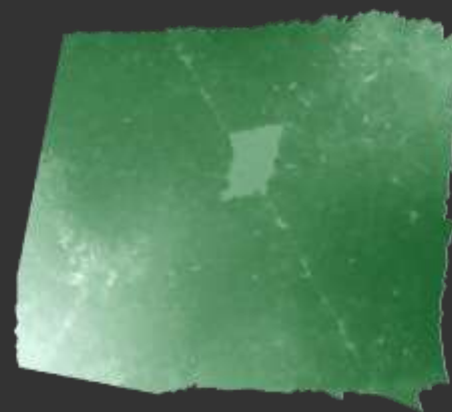

Image provided by NRAC

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Digital surface models can be generated from overlapping drone images using the structure from motion, or SfM, methodology.

Structure from motion is similar to photogrammetric methods as it makes use of overlapping stereo images and stereo parallax.

Currently, it is not easy to generate DTM or DEM models (i.e., remove above ground features from SfM data).

USGS 3DEP Program

- ❖Free elevation data download
- ❖Draws from a variety of data sources
- ❖A replacement for the National Elevation Dataset (NED)
- ❖This is still developing

https://www.usgs.gov/3d-elevation-program

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The 3DEP program in the United States is working toward high spatial resolution, predominantly LiDAR-derived, elevation data for the entire country. Interferometric Synthetic Aperture RaDAR, or IfSAR, data will be collected over Alaska.

This program is ongoing. A nationwide LiDAR coverage is not currently available but should be completed soon.

National Elevation Dataset (NED)

- US data
- 30 m (1 arc-second)
- 10 m (1/3 arc-second)
- 3 m (1/9 arc-second)

http://wvgis.wvu.edu/data/dataset.php?ID=28

https://lta.cr.usgs.gov/NED

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3DEP replaced the older National Elevation Dataset, or NED, program.

This program provides digital elevation data at variable resolutions for the United States.

Depending on your location, 30 meter, 10 meter, or 3 meter data may be available.

These data were generated using primarily stereo imagery and photogrammetric methods.

The older 30, 10, and 3 m products are now being updated using the 3DEP data.

WV Statewide Addressing and Mapping Board (WVSAMB) 3 m Data

- Photogrammetric DEM
- 2003
- 3 m data

http://wvgis.wvu.edu/data/dataset.php?ID=261

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In West Virginia, 3 meter digital elevation data were generated using stereo imagery and photogrammetric methods in 2003.

These data are made available from the West Virginia Statewide Addressing and Mapping Board (WVSAMB) and can be downloaded from the West Virginia GIS Tech Center.

ASTER Global Digital Elevation

- Photogrammetric
- Derived from the Advanced Spaceborne Thermal Emission Reflectance Radiometer (ASTER) onboard Terra
- Global coverage
- 30 m

https://asterweb.jpl.nasa.gov/gdem.asp

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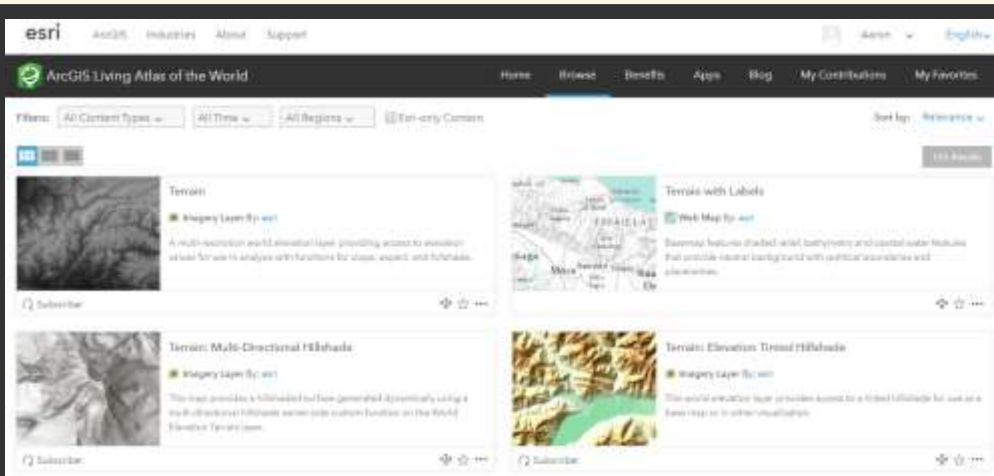
Another example of digital elevation data is the ASTER Global Elevation Map.

These data were generated from the ASTER sensor onboard the Terra satellite.

ASTER stands for Advanced Spaceborne Thermal Emission Reflectance Radiometer.

These data were generated using stereo imagery and photogrammetric methods and offer a global coverage at 30 meter spatial resolution.

DEM data from Living Atlas



https://livingatlas.arcgis.com/en/home/

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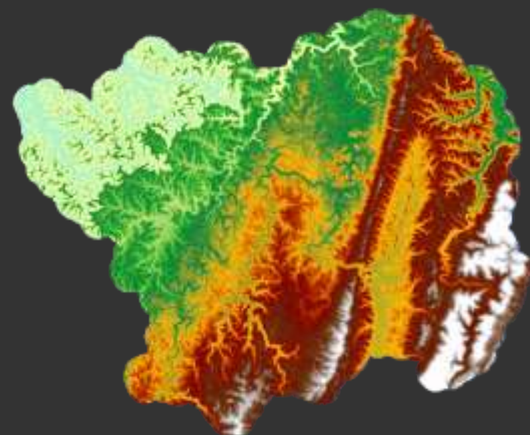
Digital elevation data and derived products are also made available by ESRI via the Living Atlas of the World.

Things to know about your data

1. Source
2. Collection date(s)
3. Feet or meters?
4. Vertical datum
5. Horizontal datum
6. Accuracy/precision



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When using digital elevation data in an analysis, it is important to have an understanding of its characteristics.

For example, it is important to note the data source or how it was generated, collection dates, vertical units, vertical and horizontal datums, and accuracy and precision.

Understanding the data is important. The characteristics of the data will determine if they are adequate for your analysis.

Data Conversion

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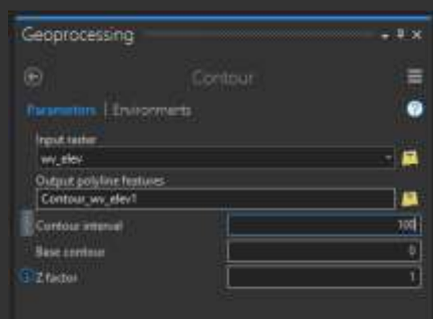
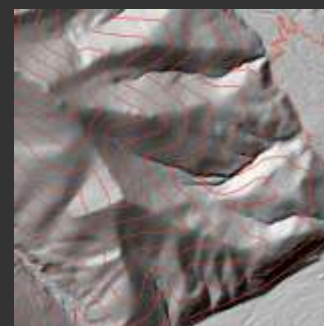
Contours

- Raster → Vector
- Must define an interval
- May require some smoothing





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You can generate contour lines from raster-based digital elevation data.

When generating contours, you must decide on an adequate contour interval so that the contours are not too sparse or crowded.

After generating contours, you might find that you need to smooth or generalize the result to make the lines more cartographically pleasing.

This can be accomplished using the vector generalization methods discussed in a prior module.

Contours to DEM

❖Vector → Raster

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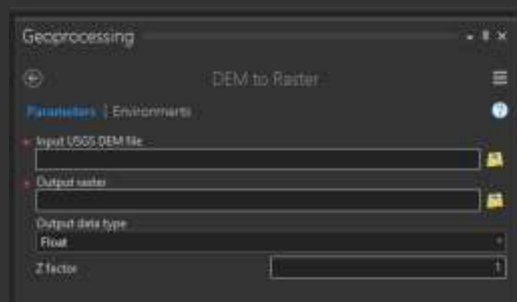
It is also possible to generate raster-based digital terrain surfaces from contour lines.

DEM to Raster

❖Converts a DEM in United States Geologic Survey (USGS) format to a raster dataset



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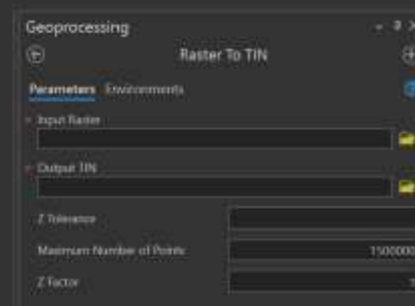
The United States Geologic Survey used to use a format for storing digital elevation data known as USGS DEM files.

If you ever obtain such files, you will need to convert them to raster data for use in analyses.

ArcGIS offers a tool to complete this conversion.

DTM → TIN

- In ArcGIS Pro, a raster grid (DTM) can be converted to a TIN using the Raster to TIN Tool
- Z-Tolerance = maximum allowable difference in (z units) between the height of the input raster and the height of the output TIN; by default, the z tolerance is 1/10 of the z range of the input raster.
- Maximum Number of Points = The maximum number of points that will be added to the TIN before the process is terminated; by default, the process will continue until all the points are added



https://pro.arcgis.com/en/pro-app/3.5/tool-reference/3d-analyst/raster-to-tin.htm

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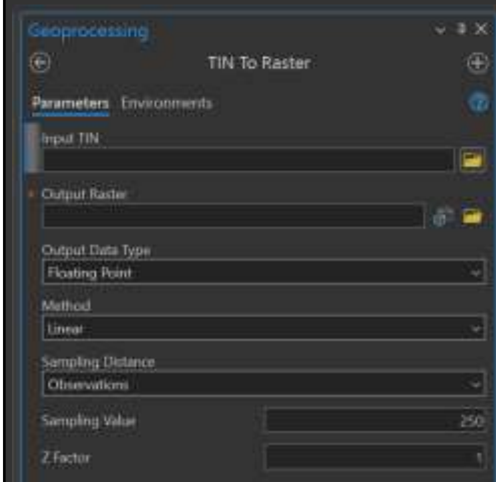
The Raster to TIN tool supports the conversion of a raster-based DTM to a TIN.

TIN → DTM



- In ArcGIS Pro, a TIN can be converted to a raster (DTM) using the TIN to Raster Tool
- Method
  - Linear = uses linear interpolation
  - Natural Neighbor = uses natural neighbor interpolation
- Sampling Distance = Observation or Cell Size

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The TIN to Raster Tool uses an interpolation method (linear or natural neighbor) to convert a TIN to a raster grid with a defined cell size.

Slope and Aspect

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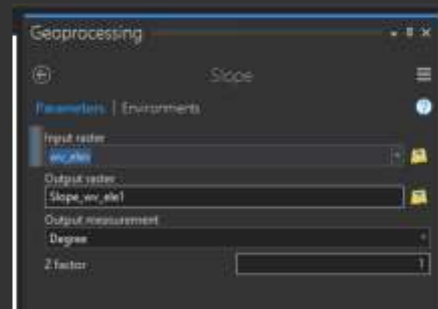
Z-Factor

- If vertical and horizontal units are different, you can correct for this with a Z factor
- You can also use a Z factor to exaggerate the vertical relative to the horizontal



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Many terrain analysis tools provide a Z-factor option.

This setting can be used to change the vertical units to match the horizontal units.

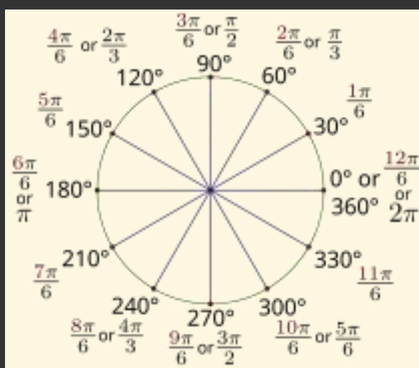
For example, if your data are referenced to a UTM zone for the horizontal datum and the units are in meters, you would likely want the vertical units to also be in meters.

So, if the vertical units are in feet, you could use the feet-to-meters conversion factor to convert the units so that there is a one-to-one relationship between the horizontal and vertical scales.

In situations where you would like to exaggerate or de-exaggerate the vertical scale relative to the horizontal scale, a Z-factor can be used to accomplish this.

Degrees vs. Radians

- Degree = divides a full circle into 360 equal parts (1-degree)
- Radians = angle created when the arc length along the circle is equal to the radius



$$180° = \pi \times \text{radians}$$

https://commons.wikimedia.org/wiki/File:30_degree_rotations_expressed_in_radian_measure.svg

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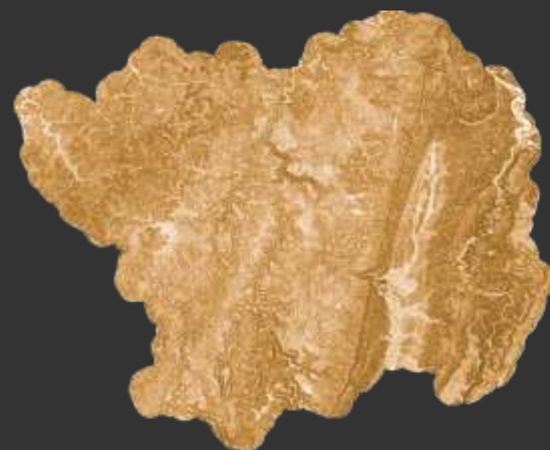
This slide provides a review of the difference between degrees and radians measurements, which are two different units of measurement used to measure angles. These concepts/measures are used on some of the following slides.

Topographic Slope

- Rate of elevation change
- Calculated using a 3 x 3 window

Percent Slope = $\frac{Rise}{Run}$ X 100

Degrees Slope = $\frac{Rise}{Run} = \tan(\theta)$



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One common terrain derivative from digital elevation data is topographic slope.

Topographic slope represents the rate of change of elevation or how steep the landscape is.

Using raster data and GIS software, this calculation is made using a 3-by-3 moving window.

Slope can be calculated as percent slope, which is simply rise over run times 100. Think of this as grade for a road.

It can also be calculated in degrees relative to the horizon.

How is slope calculated in a GIS?

$$\begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} \qquad \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix}$$

$$\text{Slope (Degrees)} = \tan^{-1}\left(\sqrt{\frac{\partial z^{2}}{\partial x} + \frac{\partial z^{2}}{\partial y}}\right) \times \frac{180}{\pi}$$

http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-slope-works.htm

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This slide provides an example of how slope is calculated.

Here are a few notes.

The slope in the x direction and y direction are calculated separately.

The cell values from the three cells on each side are compared. The center cell is double weighted compared to the other two cells.

Once the slope is calculated in the x and y directions, these measures are combined to obtain an overall slope estimate.

Units can then be converted.

How is slope calculated in a GIS?

a	b	c
d	e	f
g	h	i

$[dz/dy] = ((g + 2h + i)*4/wght3 - (a + 2b + c)*4/wght4) / (8 * y\_cellsize)$

$[dz/dx] = ((c + 2f + i)*4/wght1 - (a + 2d + g)*4/wght2) / (8 * x\_cellsize)$

c, *f*, and *i* all have valid values, $wght1 = (1+2*1+1) = 4$.
i is NoData, $wght1 = (1+2*1+0) = 3$.
f is NoData, $wght1 = (1+2*0+1) = 2$.

$slope\_radians = \text{ATAN} (\sqrt{[dz/dx]^2 + [dz/dy]^2})$

$slope\_degrees = \text{ATAN} (\sqrt{[dz/dx]^2 + [dz/dy]^2}) * 57.29578$

$slope\_degrees = \text{ATAN} (rise\_run) * 57.29578$

http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-slope-works.htm

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Slope calculations make use of a 3-by-3 moving window.

To accomplish this task, the drop or change in elevation is calculated in the x direction and y direction by comparing the cell values on one side of the window to the cell values on the other side of the moving window.

This slide provides further elaboration relative to the prior slide. Note how the 3-by-3 window is used to estimate [dz/dx] and [dz/dy].

Note that 8 * the cell size is used in the denominator to take into account the combined cell weights and the distance in the x or y directions.

How is slope calculated in a GIS?

50	45	50
30	30	30
8	10	10

[dz/dx] = $((c + 2f + i)*4/wght1 - (a + 2d + g)*4/wght2) / (8 * x\_cellsize)$ = ((50 + 60 + 10)*4/(1+2+1) - (50 + 60 + 8)*4/(1+2+1)) / (8 * 5) = (120 - 118) / 40 = 0.05

[dz/dy] = $((g + 2h + i)*4/wght3 - (a + 2b + c)*4/wght4) / (8 * y\_cellsize)$ = ((8 + 20 + 10)*4/(1+2+1) - (50 + 90 + 50)*4/(1+2+1)) / (8 * 5) = (38 - 190) / 40 = -3.8

$rise\_run = \sqrt{([dz/dx]^2 + [dz/dy]^2)} = \sqrt{((0.05)^2 + (-3.8)^2)} = \sqrt{(0.0025 + 14.44)} = 3.80032$

$slope\_degrees$ = ATAN ($rise\_run$) * 57.29578 = ATAN (3.80032) * 57.29578 = 1.31349 * 57.29578 = 75.25762

http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-slope-works.htm

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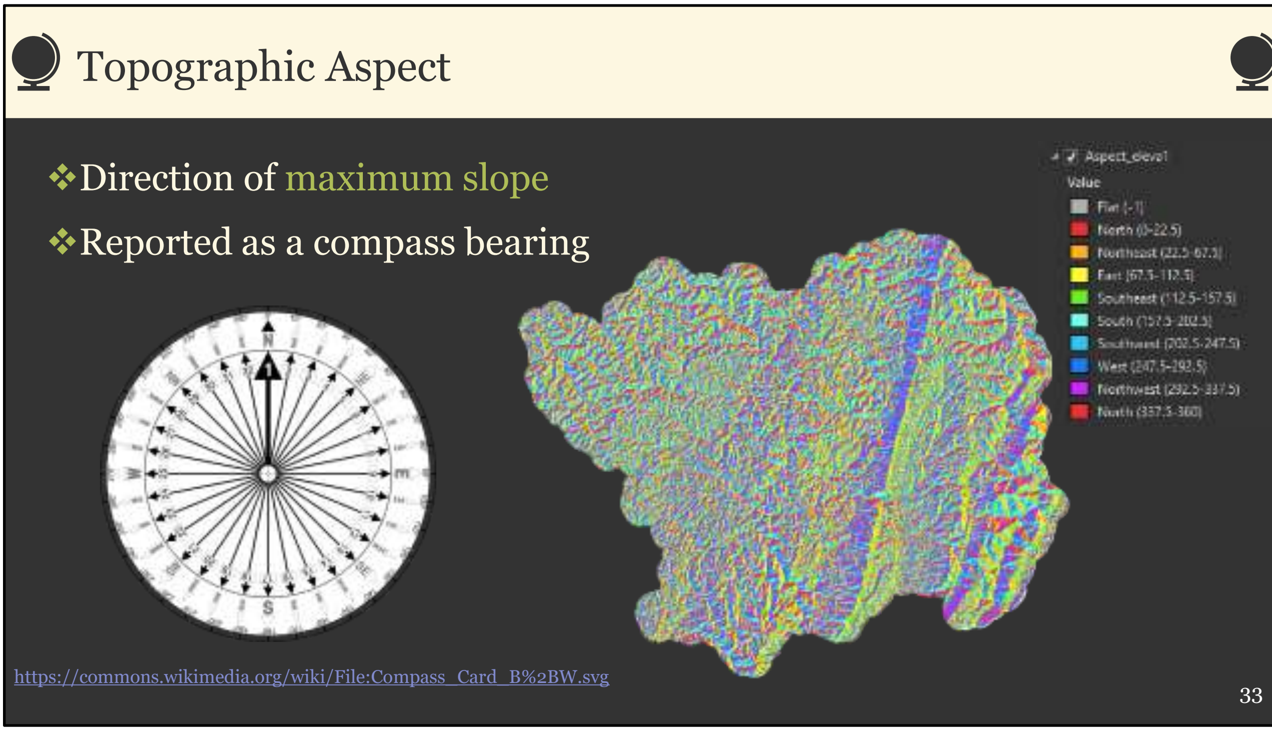
This slide provides an example using real numbers within the 3-by-3 window to calculate slope at the center cell location.



Topographic aspect represents the compass direction or bearing of maximum slope.

In other words, it represents the direction that the slope faces.

North facing slopes would be coded as 0 or 360, east facing slopes as 90, south facing slopes as 180, and west facing slopes as 270.

Aspect cannot be calculated for flat areas because there is no direction of maximum slope. These locations are coded as -1.

How is topographic aspect calculated in a GIS?

$$\text{Aspect (radians)} = \frac{\pi}{2.0} - atan2\left(\frac{\partial z}{\partial y}, -\frac{\partial z}{\partial x}\right)$$

http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-aspect-works.htm

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This slide provides an example of how aspect is calculated using a two-argument arctangent function.

How is topographic aspect calculated in a GIS?

a	b	c
d	e	f
g	h	i

$$[dz/dx] = ((c + 2f + i)*4/wght1 - (a + 2d + g)*4/wght2) / 8$$

$$[dz/dy] = ((g + 2h + i)*4/wght3 - (a + 2b + c)*4/wght4) / 8$$

$$aspect = 57.29578 * \text{atan2}([dz/dy], -[dz/dx])$$

http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-aspect-works.htm

This slide provides an example of how aspect is calculated.

Again, a 3-by-3 moving window is used.

How is topographic aspect calculated in a GIS?

101	92	85
101	92	85
101	91	84

[dz/dx] = $((c + 2f + i)*4/wght1 - (a + 2d + g)*4/wght2)$ / 8 = ((85 + 170 + 84)*4/(1+2+1) - (101 + 202 + 101)*4/(1+2+1)) / 8 = -8.125

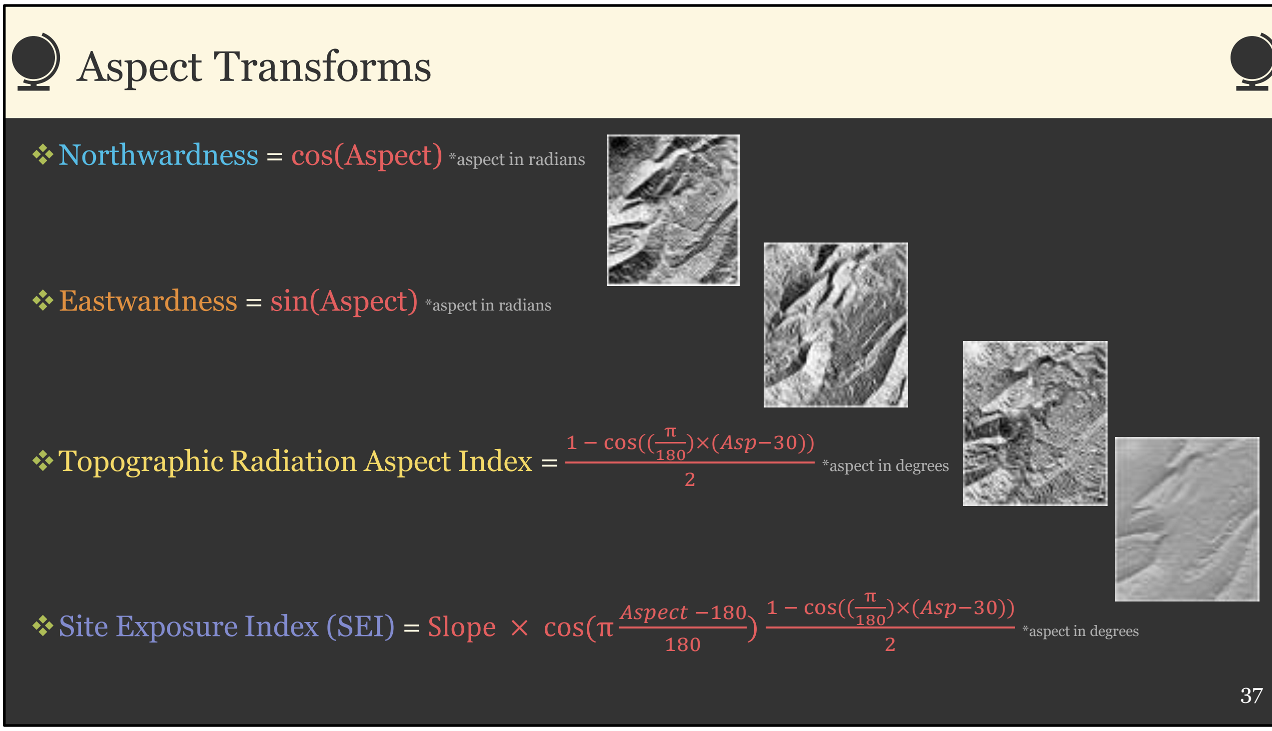
[dz/dy] = $((g + 2h + i)*4/wght3 - (a + 2b + c)*4/wght4)$ / 8 = ((101 + 182 + 84)*4/(1+2+1) - (101 + 184 + 85)*4/(1+2+1)) / 8 = -0.375

aspect = 57.29578 * atan2 ([dz/dy], -[dz/dx]) = 57.29578 * atan2 (-0.375, 8.125) = -2.64

cell = 90.0 - *aspect* = 90 - (-2.64) = 90 + 2.64 = 92.64

http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-aspect-works.htm

This slide provides an example using real numbers within the 3-by-3 window to calculate aspect at the center cell location.



Aspect can be transformed to provide other measures of slope orientation. The cosine of aspect in radians yields a value of 1 for a north orientation, a value of -1 for a south orientation, and a value of 0 for an east or west orientation. This is termed northwardness.

In contrast, the sine of aspect in radians yields a value of 1 for an east orientation, a value of -1 for a west orientation, and a value of 0 for a north or south orientation. This is termed eastwardness.

Another option is the topographic radiation aspect index (TRASP). This produces values from 0 to 1. The transformation rotates aspect so that north-northeast-facing slopes are assigned low values and south-southwest-facing slopes are assigned high values. This is intended to represent a cool/moist to warm/dry gradient.

The site exposure index (SEI) rescales aspect onto a north–south exposure axis and weights that exposure by slope steepness.

It is common to use transformations of aspect in models as opposed to aspect due to the circular nature of the variable (e.g., 355° is closer to 0° than 15° is to 0°).

Terrain Visualizations

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Hillshade

- A visual representation of a terrain using shadows
- Shadows are cast over the landscape to created a shaded relief surface
- Azimuth = compass bearing of Sun
- Altitude = height of Sun above horizon (as an angle)
- Color ramps must run light to dark

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Hillshades offer a means to visualize digital terrain data. In a hillshade, a sun or illuminating source is placed in the sky to model illumination. The result is a shaded relief surface. Bright areas represent areas of light exposure whereas dark areas have less light exposure.

The position of the illuminating source is defined using a compass bearing or direction, this setting is known as azimuth, and the angle of the source above the horizon, or altitude. Using azimuth and altitude, you can position the illuminating source anywhere in the local sky.

Imagine a dome over your head. If you would like to locate an object on this dome, you would need to specify the compass direction or bearing in which to look, or azimuth, and how high up to look as an angle, or altitude.

How is a hillshade calculated in a GIS?

$$255 \times [\cos(\theta_{zenith}) \times \cos(slp_{rad}) + \sin(\theta_{zenith}) \times \sin(slp_{rad}) \times \cos(\theta_{azimuth} - asp_{rad})]$$

θ_{zenith} = Solar zenith in radians (90° - Sun Altitude, converted to radians)
slp_{rad} = Slope angle in radians
$\theta_{azimuth}$ = Solar azimuth in radians
asp_{rad} = Terrain aspect in radians

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This slide provides the equation for calculating a hillshade value at a cell location from slope and aspect. The equation assumes that the units are in radians as opposed to degrees.

The solar zenith angle is the angle from the zenith to the illuminating source and is equal to 90 minus the sun altitude in degrees followed by conversion to radians.

Sun position matters

Azimuth = 315, Altitude = 45

Azimuth = 135, Altitude = 45

41

The location of the illuminating source impacts the effectiveness and look of the hillshade. In ArcGIS Pro, the default settings are an azimuth of 315 and an altitude of 45. So, the illuminating source would be in a northwest position and halfway between the horizon and zenith, or top of the sky.

Since we generally see features illuminated from above or by the Sun, we expect shadows to be cast downward. This is mimicked with a Sun position in the northwest azimuth. If we move the Sun to a southeast azimuth, then features will be illuminated from below. This will result in a strange optical illusion where the topography looks inverted: ridges will be interpreted as valleys and valleys as ridges.

So, we tend to avoid using southeast azimuth positions.

Sun position matters

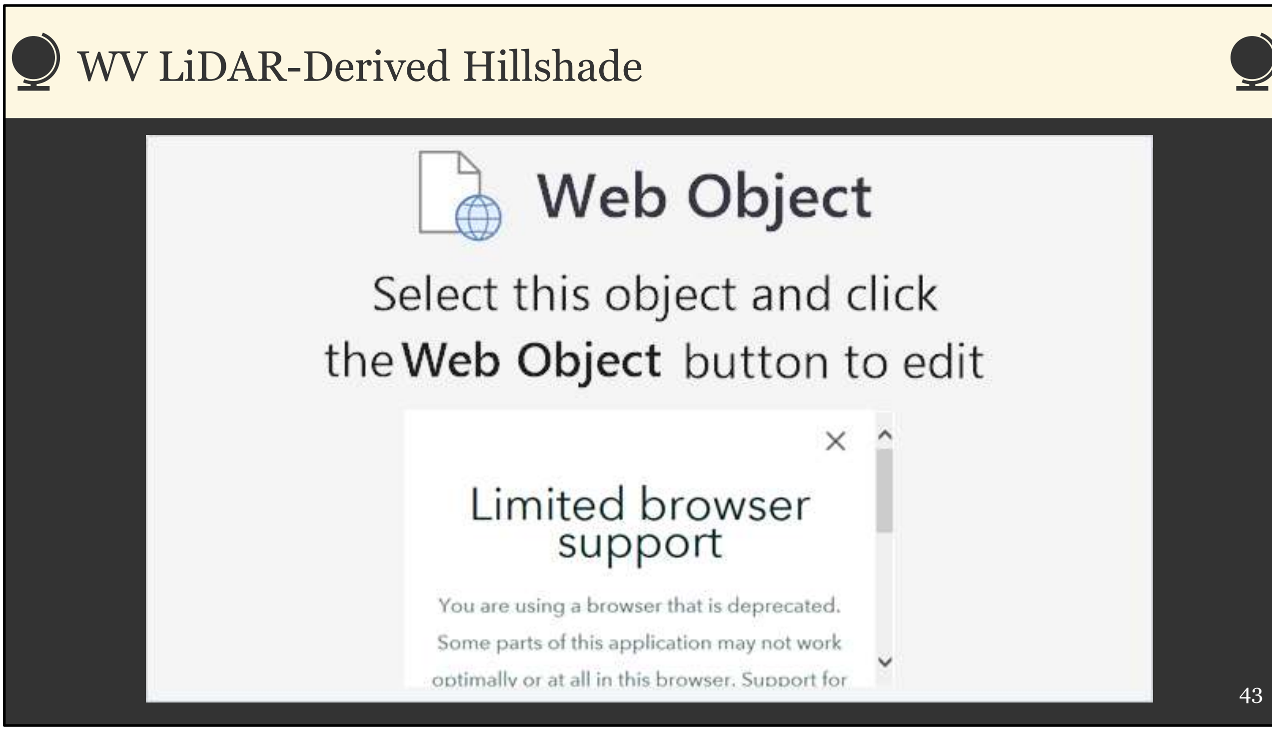
Azimuth = 315, Altitude = 45

Azimuth = 315, Altitude = 10

42

We also tend to avoid using low altitudes as this can create very contrasted hillshade images with very dark and bright slopes. Placing the illumination source very close to the zenith can make hillshade images look very "washed out" or low contrast.

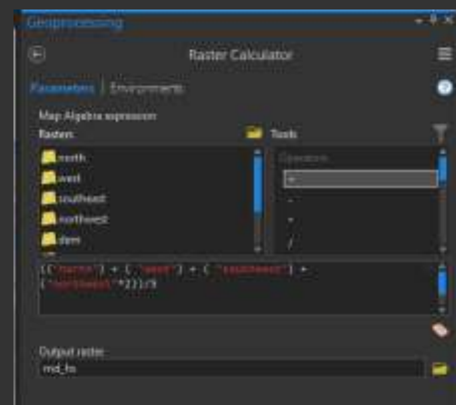
I have generally found the default settings to work well. However, you may want to experiment with different settings. Different settings may be optimal in different terrains.



The web map linked on this slide shows a hillshade generated at a 1 m spatial resolution from LiDAR data. This dataset covers the entire state of West Virginia. Take some time to explore the data and the level of detail provided.

Multidirectional Hillshades

- ❖Combine multiple Sun positions
- ❖North + Northwest + West + Southeast
- ❖Extra weight for northwest
- ❖Subtle detail on slopes that face different directions
- ❖Useful in subtle terrain



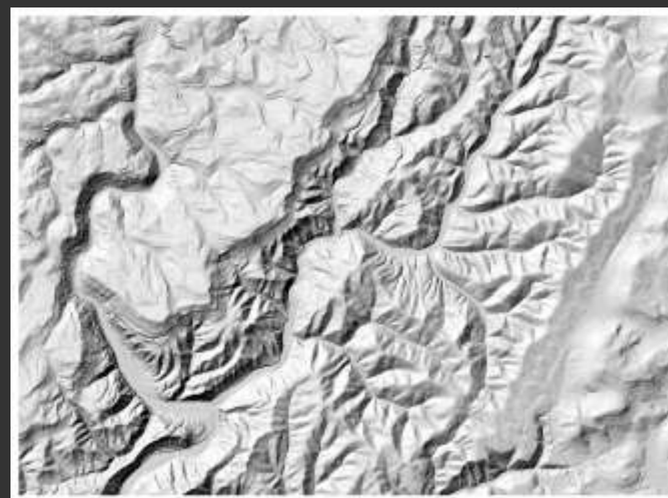
44

Another option is to calculate multiple hillshades using different illuminating positions and then combine them to create a multidirectional hillshade. In the example, I have created hillshades using north, west, southeast, and northwest positions. I then use Raster Calculator to average them. I double-weight the northwestern result so that it has the largest impact on the output.

Using multiple directions generally allows for a reduction in deep shadows or extremely bright cells in complex topography. If a hillshade using the default illuminating position or a single position is not adequate for your visualization, it is worth experimenting with multidirectional hillshades as an alternative.

Multidirectional Hillshades

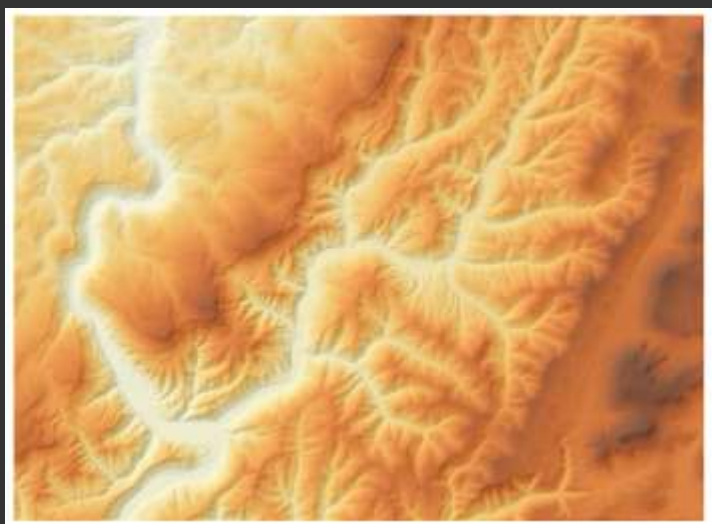
- Combine multiple Sun positions
- North + Northwest + West + Southeast
- Extra weight for northwest
- Subtle detail on slopes that face different directions
- Useful in subtle terrain



45

This slide shows the result of the multidirectional hillshade calculation.

Combining DEMs and Hillshades

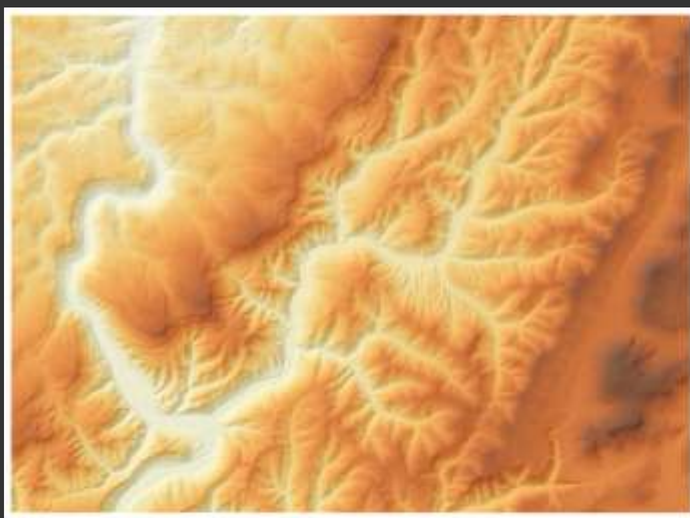


- Hillshade with 70% transparency
- DEM with 0% transparency

46

It is common to combine DEMs and hillshades to generate a textured and colorized terrain surface. These are often referred to as hypsometrically-tinted hillshades. Since both datasets are raster grids, this requires the use of transparency. In this example, the hillshade uses a black-to-white color ramp and has a 70% transparency applied. It is displayed above the DEM, which has an orange/red color ramp applied and no transparency. Determining the optimal amount of transparency will require some experimentation.

Combining DEMs and Hillshades



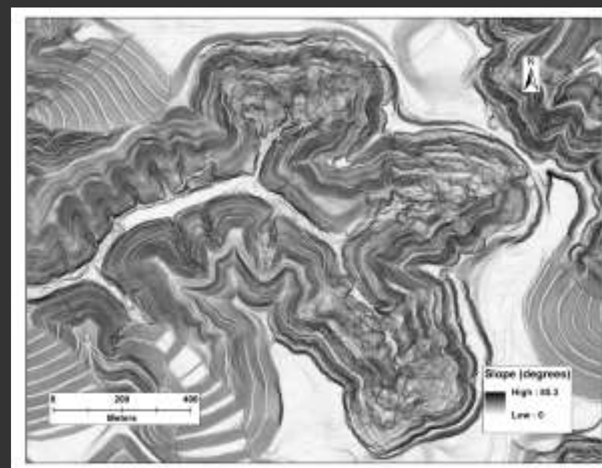
- DEM with 30% transparency
- Hillshade with 0% transparency

47

In this example, I have used the same color ramps but reversed the drawing order and applied a 30% transparency to the DEM data.

Slopeshade

- Display slope using a white-black stretch
- White = shallow slopes
- Black = steep slopes



Map by Miles Reed

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An alternative to the hillshade is the slopeshade. This is simply a topographic slope raster with a white-to-black color ramp applied. White shades indicate low slopes or flat areas while black indicates steep slopes. When quality, high spatial resolution DEM data are used, slopeshades can offer a very detailed terrain representation for interpretation. However, these visualizations are not commonly used in map layouts unless appropriate for the intended audience, such as geomorphologists.

Land Surface Parameters

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We will now discuss other measures that can be derived from digital terrain models. These surfaces are generally called terrain derivatives or land surface parameters (LSPs).

Franklin (2020)


Taylor & Francis

REVIEW ARTICLE

Interpretation and use of geomorphometry in remote sensing: a guide and review of integrated applications

Steven E. Franklin

ABSTRACT

An understanding of topographic surfaces and a system of geomorphometric variables underlies the effective use of Digital Elevation Models (DEMs) in remote sensing. This paper is focused on the basic concepts and structure of geomorphometric variable types relevant to geophysical and biophysical remote sensing applications. In general, remote sensing analysts must be satisfied that there is a reasonable expectation that geomorphometric processing will benefit the remote sensing project at hand based on physical or mathematical relationships. Careful selection of local, textural, and contextual geomorphometric variables is required. The characteristics of these data can help optimize the analysis approach, which increasingly involves machine learning algorithms and Object-based DEM Analysis (OBDA) methods. Examples from the literature and a DEM of the Peterborough Drumlin Field are used to illustrate the discussion.

ARTICLE HISTORY

1. Introduction

Geomorphometry is the science of quantitative terrain analysis using Digital Elevation Models (DEMs) (Evans 1972). Increased use of geomorphometry has been reported in certain, well-defined remote sensing applications, notably wetlands (Merchant et al. 2019), forest biomass (Shen et al. 2018), mass wasting (Maxwell et al. 2020), soils (Guevara, Vargas, and Poulter 2019), drainage mapping (Azizian and Brocca 2020) and structural analyses (Foomans et al. 2019). These and other remote sensing applications expect *a priori* to benefit from the use of geomorphometric variables developed to quantify topographic surfaces. Successful use of geomorphometry requires that remote sensing analysts understand the concept and interpretation of topographic surfaces and be versant with a system of geomorphometric variables. The essential logic is as follows:

Franklin, S.E., 2020. Interpretation and use of geomorphometry in remote sensing: a guide and review of integrated applications. *International Journal of Remote Sensing*, *41*(19), pp.7700-7733.

50

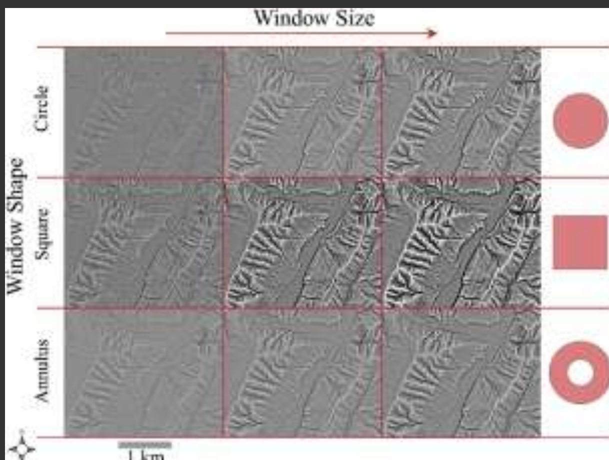
This paper offers a nice reference for using terrain derivatives and geomorphometry in remote sensing.

Maxwell and Shobe (2022)

Maxwell, A.E. and Shobe, C.M., 2022. Land-surface parameters for spatial predictive mapping and modeling. *Earth-Science Reviews*, p.103944.

This paper is another reference for using terrain derivatives and geomorphometry in remote sensing, GIS, and spatial predictive modeling.

Window Shape and Size



- Circle = defined by a radius
- Square = defined by a height/width
- Annulus = defined by an inner and outer radius
- Larger windows yield more generalized patterns
- Smaller windows yield more local patterns
- Can be difficult to determine an optimal window shape/size

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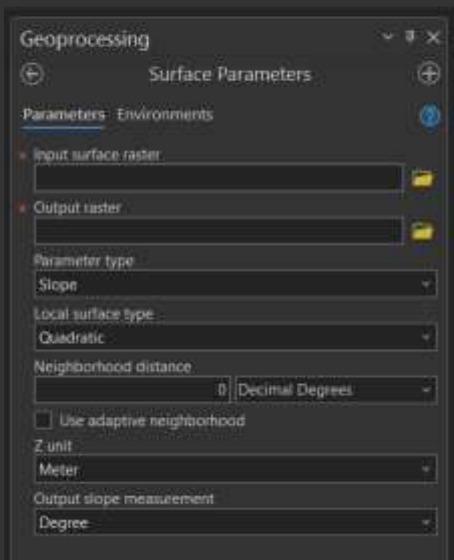
Calculation of LSPs generally rely on local moving windows, and the results will depend on the size and shape of the window. It is common to use circular or rectangular windows. Another option is an annulus. An annulus is a donut shape with an inner and outer radius. This allows for cells that are not immediate neighbors of the center cell to not be included in the calculation.

Larger windows generally results in more generalized terrain patterns while smaller windows yield more localized patterns. It can be difficult to determine an optimal window shape/size for a specific analysis or to capture the terrain characteristics of interest.

Surface Parameters



- Slope, Aspect, multiple measures of Curvature
- Can change the size of the moving window

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ESRI has recently introduced the Surface Parameters Tool into ArcGIS Pro. This tool can be used to calculate slope, aspect, and several measures of curvature. Unlike the original Slope, Aspect, and Curvature tools, it allows for changing the size of the moving window used to perform the calculations. You can even apply an adaptive window size that changes based on the local variability in the surface. This tool is also available as a Raster Function.

Surface Curvature

Negative = Concave
Positive = Convex
Near Zero = Flat

- Concavity/convexity of a surface
- Profile Curvature = curvature in direction of slope
- Planar Curvature = curvature perpendicular to direction of slope

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Surface curvature makes use of a moving window analysis and represents the convexity or concavity of the landscape.

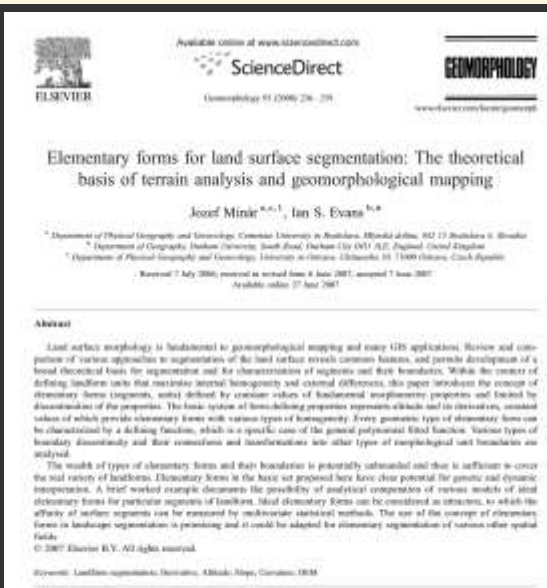
Negative values indicate concavity, positive values indicate convexity, and values near zero indicate near flat or no curvature.

It is also possible to calculate curvature in the direction of maximum slope, or profile curvature, and curvature perpendicular to slope, or planar curvature.

One value of curvature is the ability to detect areas of potential erosion and deposition.

Areas of convex profile curvature are likely to be areas of erosion whereas areas of concave curvature are likely to be areas of deposition.

Curvatures



ELSEVIER

ScienceDirect

GEOMORPHOLOGY

Elementary forms for land surface segmentation: The theoretical basis of terrain analysis and geomorphological mapping

Jozef Minár, Ian S. Evans

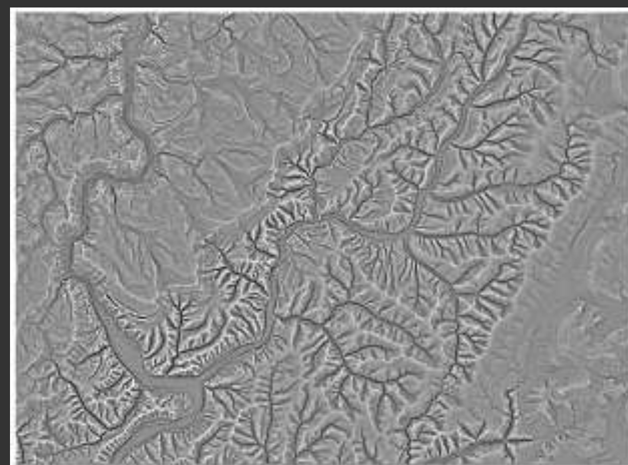
Abstract

Minár, J. and Evans, I.S., 2008. Elementary forms for land surface segmentation: The theoretical basis of terrain analysis and geomorphological mapping. *Geomorphology*, *95*(3-4), pp.236-259.

The concept of terrain curvature is complex, as there are many types of curvature that can be calculated. This paper provides a good review of curvature types and curvature calculation methods.

Slope Position

- ❖Elevation at cell compared to elevation of surrounding cells
- ❖Must calculate mean using neighborhood analysis
- ❖“DEM” – “Mean”
- ❖Ridge vs. Valley



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Slope position provides a measure of slope position or ridge vs. valley by comparing the elevation of a center cell to the mean elevation of its neighbors.

This is just another example of a tool that makes use of a moving window.

Increasing the window size will result in a more generalized pattern whereas smaller window sizes will highlight more local patterns.

There is not necessarily a correct window size, as this depends on the scale and question of interest.

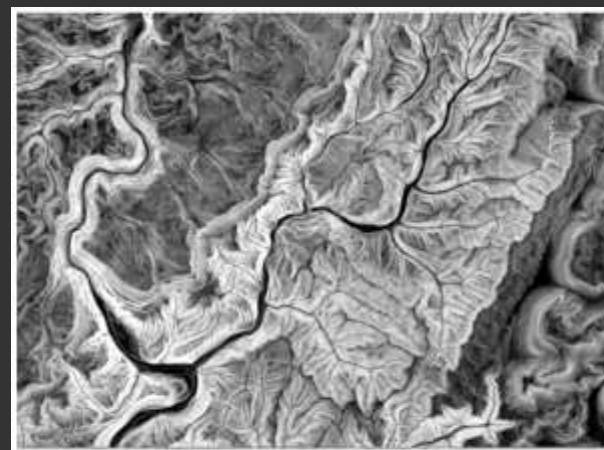
It is possible to make this calculation using multiple window sizes for comparison or even average the results.

In the example provided, bright areas represent ridges or areas where the center cell is higher than its neighbors.

Dark areas represent valleys or areas where the center cell is lower than its neighbors.

Topographic Roughness

- Measure of topographic variability
- Square root of standard deviation of elevation measurements within a neighborhood



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Topographic roughness is a measure of how variable or rough a terrain is within a local neighborhood.

So, it also makes use of moving window analysis. Larger windows will produce more generalized patterns whereas smaller windows will highlight more local patterns.

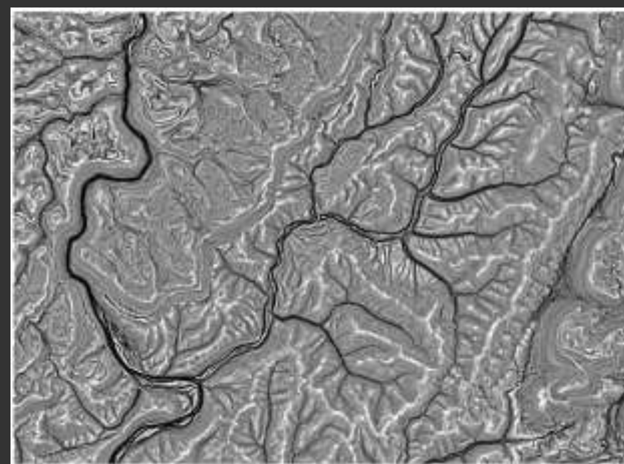
This measure is calculated as the square root of the standard deviations of the elevation measurements within a neighborhood.

Larger values indicate more rough or variable terrain and lower values indicate smoother or less variable terrain.

Topographic Dissection

- Measure of incision

$$\frac{Elevation - Minimum\ Elevation}{Maximum\ Elevation - Minimum\ Elevation}$$



58

Topographic dissection is a measure of incision.

It is calculated by subtracting the lowest elevation value in a moving window from the center cell value then dividing by the range of values in the window.

So, like many of the other terrain analysis tools, this calculation makes use of a moving window.

Low values indicate more incision whereas high values indicate less incision.

Heat Load Index

- A southwest facing slope should have warmer temperatures than a southeast facing slope, even though the amount of solar radiation they receive is equivalent
- The McCune and Keon (2002) method accounts for this by "folding" the aspect so that the highest values are southwest and the lowest values are northeast
- Additionally, this method accounts for steepness of slope, which is not addressed in most other aspect rescaling equations

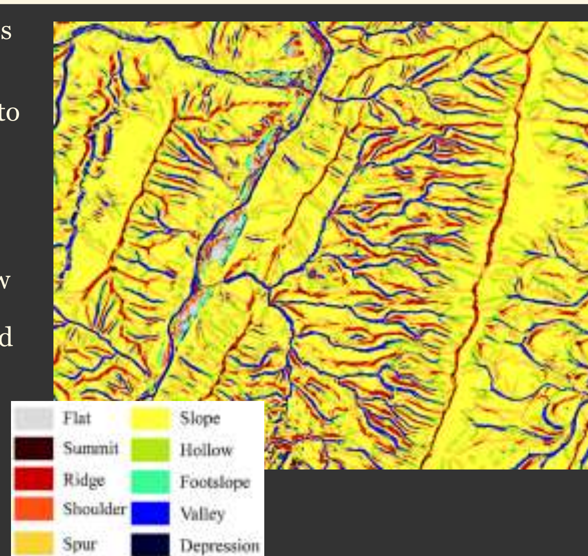
McCune, B. and Keon, D., 2002. Equations for potential annual direct incident radiation and heat load. *Journal of vegetation science*, *13*(4), pp.603-606.

59

This slide describes another useful terrain derivative: the heat load index. This measure relates to incident solar radiation at a location.

Geomorphons

- A categorization of terrain features or landform types that are size-, orientation-, and local relief-invariant
- Cell is compared to its neighbors in eight directions to characterize the patterns on the landscape and determine in which directions elevation is higher, lower, or at the same altitude as the reference cell location
- So as not to limit the analysis to a 3-by-3 cell window and to allow for mapping similar landforms with variable sizes or scales, a line-of-sight method is used as opposed to the direct cell neighbors.



Stepinski, T.F. and Jasiewicz, J., 2011. Geomorphons-a new approach to classification of landforms. *Proceedings of geomorphometry, 2011*, pp.109-112.

Jasiewicz, J. and Stepinski, T.F., 2013. Geomorphons—a pattern recognition approach to classification and mapping of landforms. *Geomorphology*, *182*, pp.147-156.

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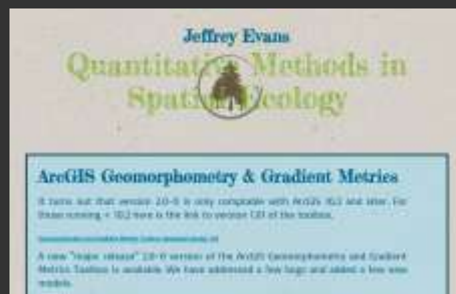
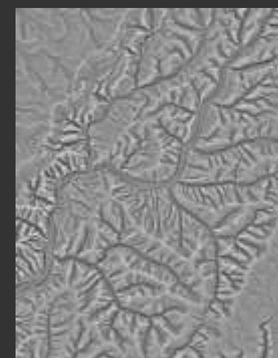
The surfaces discussed above are all continuous measures of landscape characteristics. Geomorphons offer a means to categorize the landscape into landforms, a nominal variable, using the process described on the slide.

Geomorphometry & Gradients Metrics Toolbox

- Slope position
- Dissection
- Topographic roughness
- Compound topographic moisture index (CTMI)
- Heat load index
- Ecological land units (ELUs)
- Etc.



http://evansmurphy.wixsite.com/evansspatial/arcgis-gradient-metrics-toolbox



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If you are interested in performing terrain analysis in ArcGIS, I would suggest the Geomorphometry & Gradients Metrics Toolbox made available by Jeff Evans.

QGIS, including GRASS and SAGA, also provides many terrain analysis tools.

SAGA

- System for Automated Geoscientific Analysis
- Wide variety of terrain analysis tools included
- Integrated with QGIS
- Available in R and Python

http://www.saga-gis.org/en/index.html

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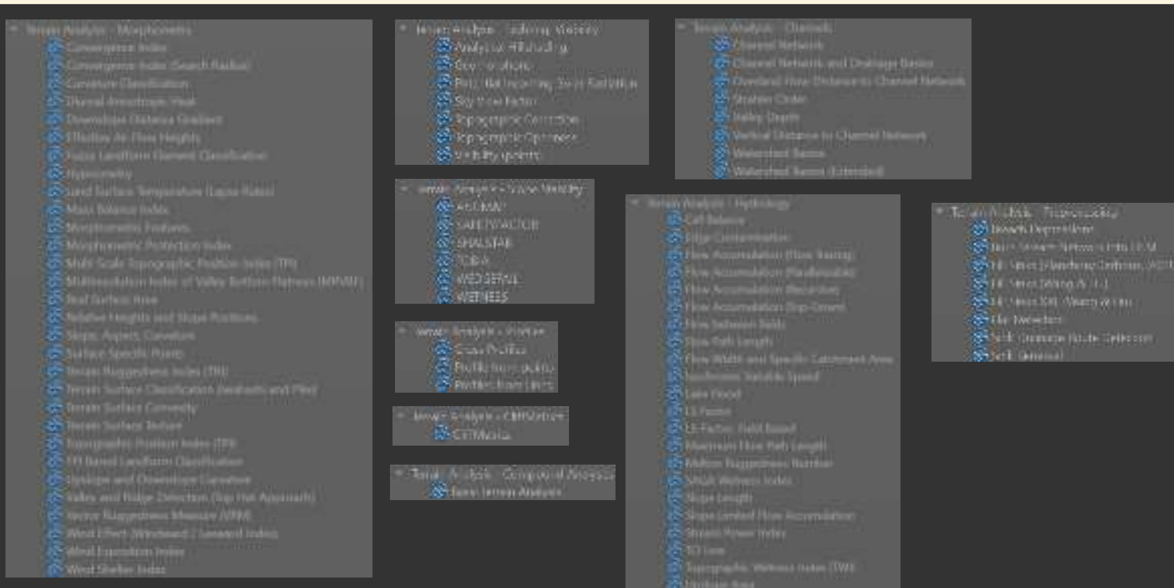
The System for Automated Geoscientific Analysis (SAGA) tool provides access to a wide variety of digital terrain analysis tools. This software is currently free and open-source and can be accessed via QGIS, R, and Python.

Example Terrain Analysis Tools (SAGA)



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A variety of digital terrain analysis tools are provided by SAGA.

Digital Terrain Analysis

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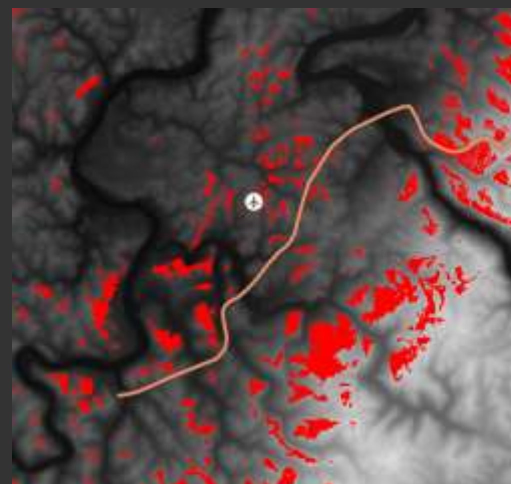
Viewshed Analysis

- Given terrain conditions, what can you see from a vantage point?
- Requires: DEM and location of vantage point
- Just takes into account topography
- Above Ground Level Output = raster output of height that must be added to the cell in order for it to be visible from the vantage point



65

Viewshed analysis is used to determine what areas are visible from a vantage point or location based on the terrain characteristics.

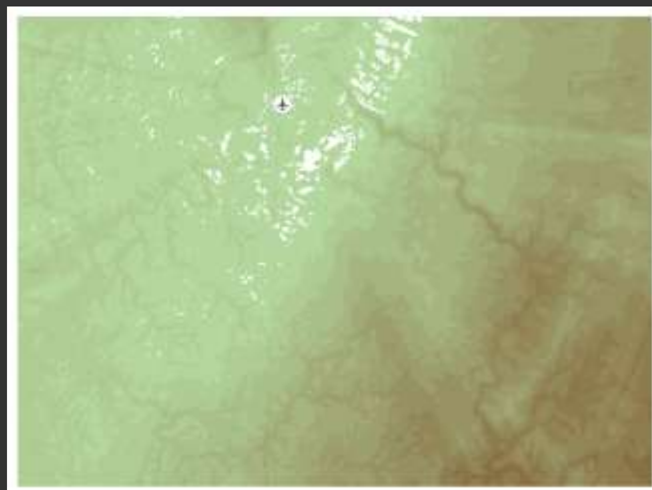
To undertake such an analysis, you will need to provide a vantage point, such as a point location, and a digital terrain surface.

The output will be binary with 1 indicating areas that are visible based on the topography.

Note that this only takes into account topography. If you would like to incorporate above ground features that could impact visibility, you should input a DSM as opposed to a DTM.

More complex visibility analyses can be performed using 3D GIS.

Above Ground Level Raster



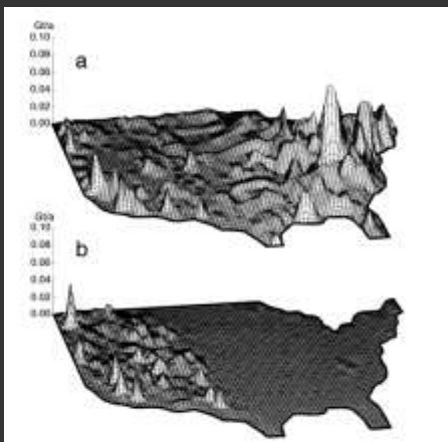
66

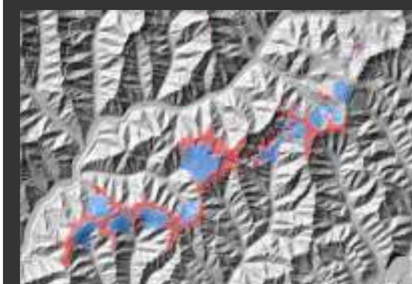
An ancillary output of viewshed analysis is an above ground level raster.

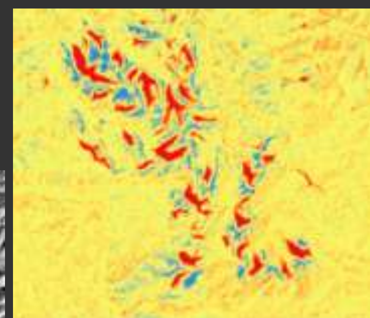
This surface represents the height that must be added to each cell in order for it to be visible from the defined vantage point.

Cut and Fill Analysis

- Subtract DEM surfaces pre- and post- terrain change







Hooke, R.L. (1999). "Spatial distribution of human geomorphic activity in the United States: comparison to rivers," *Earth Surface Processes*, 24: 687-692.

67

Cut and fill analysis allows you to map areas of elevation change by comparing two elevation surfaces.

Cut areas represent elevation loss or areas of excavation whereas fill areas represent areas of fill or elevation gain.

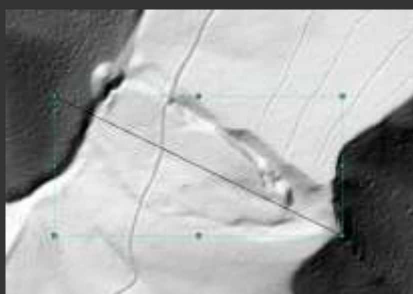
Cut and fill analysis can be impacted by the error and quality of the input digital elevation data. Misregistration between the datasets can be an issue.

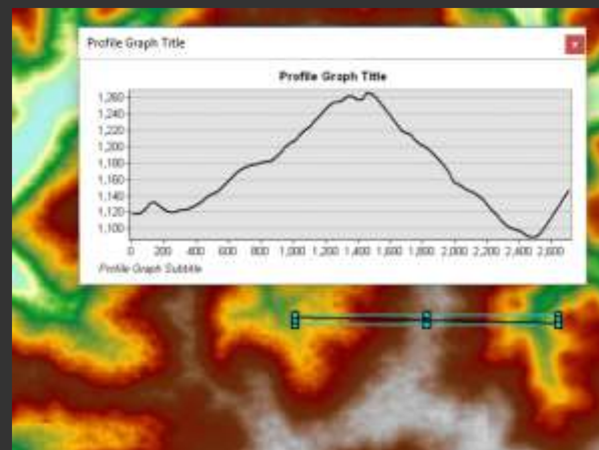
If you compare two DEMs, they should use the same vertical datum and units and both represent ellipsoidal or orthometric heights.

Topographic change can result from natural processes or human-induced alterations. Hooke (1999) suggests that humans move more material than rivers!

Profiles

- ❖Available with 3D Analyst
- ❖Can export to a table





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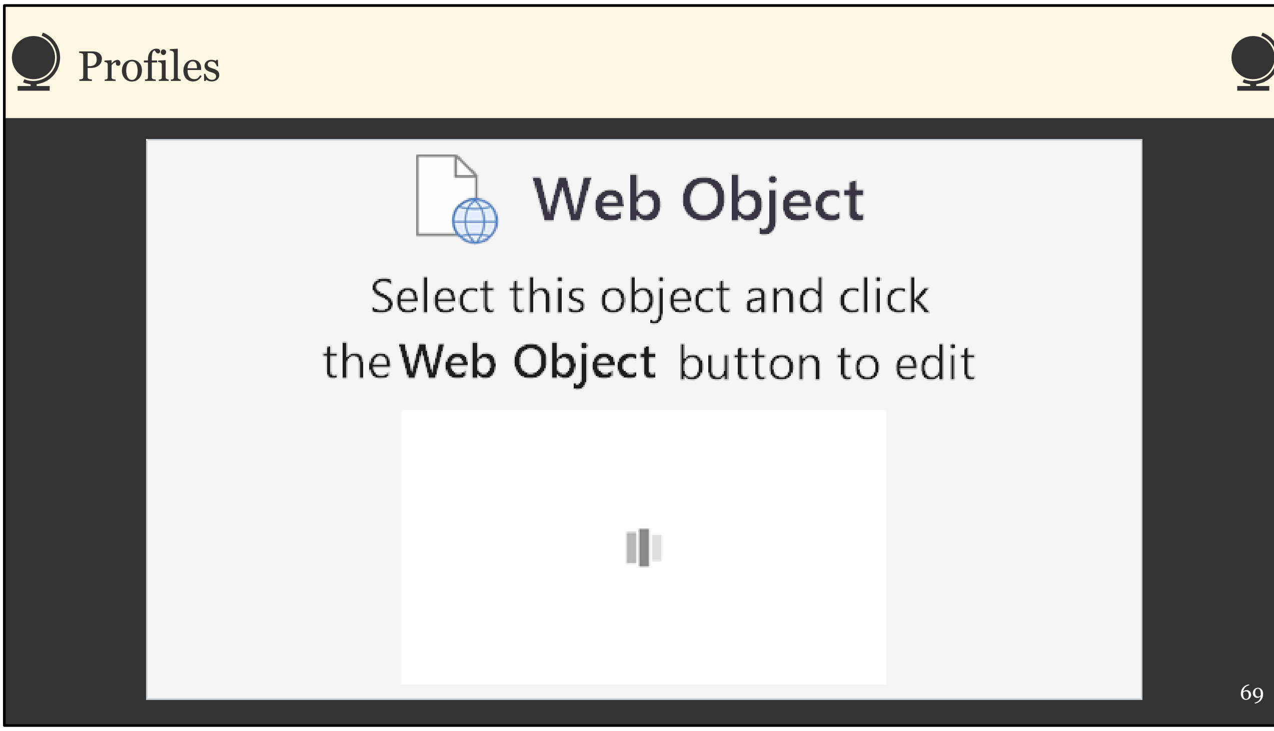
You can generate profiles to extract elevation values along a transect, line, or path.

A profile is generated based on the raster cell values that intersect the path.

Once a profile is generated, graphs can be created and the results can be exported as tables for further analysis in other software packages.



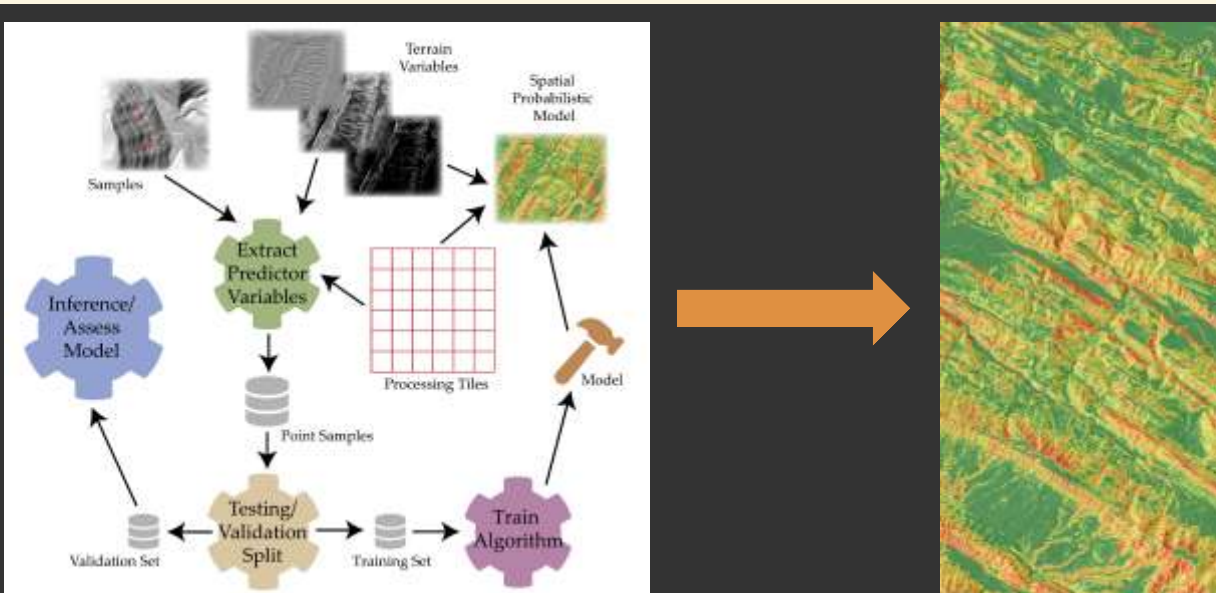
This web app makes use of an ESRI service that allows the user to generate an elevation profile. Give it a try.

Flood Inundation Prediction

70

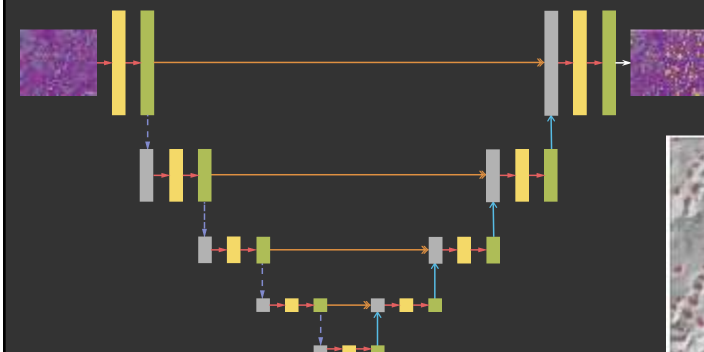
Digital terrain data and their derivatives have a variety of use cases. For example, they are important for mapping and defining the extent of flood-prone areas.

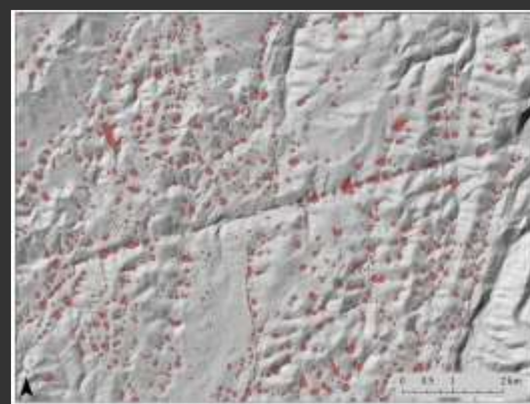
Landslide Susceptibility Modeling



Digital terrain data and machine learning methods are a common means to estimate landslide occurrence or landslide susceptibility at cell locations.

Geomorphic Feature Extraction





Modern deep learning methods, such as semantic segmentation convolutional neural networks (CNNs) are being applied to the extraction of geomorphic features or landforms from LSP predictor variables.

Digital Terrain Analysis In ArcGIS Pro

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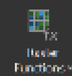
The following exercise can be completed using the provided example data.

Terrain Visualization: Shaded Relief

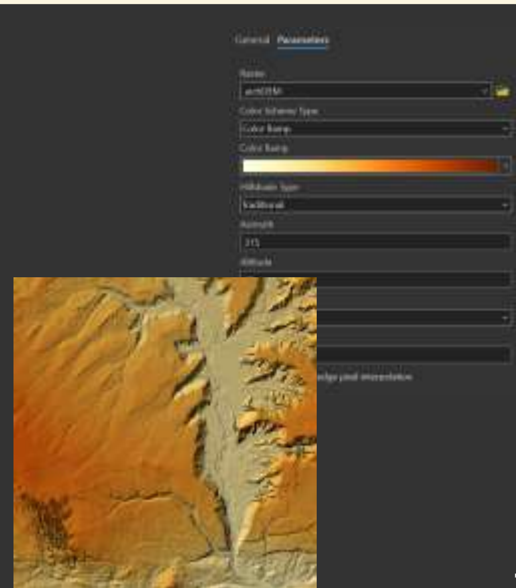
1. Navigate to the arches map.
2. Navigate to the Analysis Tab and click the <u>Raster Functions</u> icon. This will open the Raster Functions Pane.



3. In the Raster Functions Pane, select the Shaded Relief Tool within the <u>Surface</u> tools.

4. Configure the tool as follows then select <u>Create new layer</u> to execute the process.
   - **Raster** = archDEM
   - **Color Ramp** = *choose a color ramp you think is effective*
   - You do not need to change any of the other settings.

The virtual shaded relief raster layer will be added to the map.



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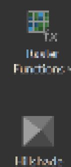
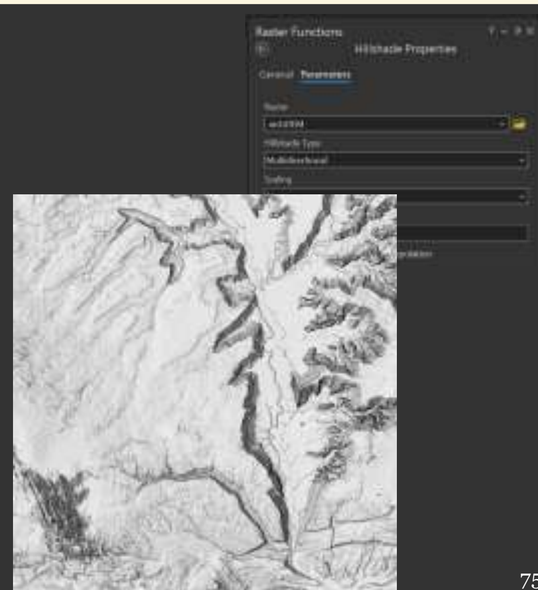
Terrain Visualization: Hillshade

1. Navigate to the Analysis Tab and click the Raster Functions icon. This will open the Raster Functions Pane.
2. In the Raster Functions Pane, select the Hillshade Tool within the Surface tools.
3. Configure the tool as follows then select Create new layer to execute the process.
   - **Raster** = archDEM
   - **Hillshade Type** = *Multidirectional*
   - You do not need to change any of the other settings.

The virtual multidirectional hillshade raster layer will be added to the map.





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Terrain Visualization: Hillshade/DEM Overlay

1. Right-click on the arcDEM layer in the Contents Pane the select Symbology. Change the **Color scheme** to a different color ramp that is not simply black-to-white.
2. Drag the archDEM layer to the top of the drawing order in the Contents Pane.
3. Turn off all of the layers in the Contents Pane other than archDEM (which should be at the top) and the generated hillshade (which should be beneath it).
4. With the archDEM layer selected in the Contents Pane, click on the Raster Layer Tab.
5. In the Effects area, change the **transparency** to *40%*.

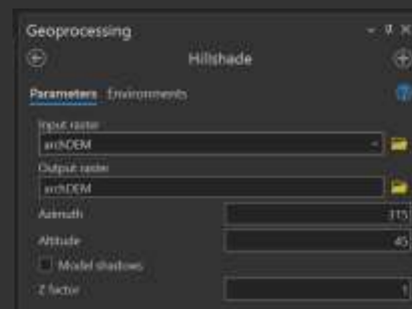
The result should be a tinted shaded relief surface that combines the DEM and hillshade.

Change Environments

1. Using the Environments icon from the Analysis Tab, change the environments as follows:
   - **Extent** = *Same as* archDEM
   - **Cell Size** = Same as archDEM
   - **Mask** = archDEM
   - **SnapRaster** = archDEM

Calculate Hillshade

1. Navigate to the terrainAnalysis map.
2. Use the Hillshade Tool to calculate a hillshade from the archDEM with the following settings:
   - **Input Raster** = archDEM
   - **Output Raster** = archHS
   - **Azimuth** = *315*
   - **Altitude** = *45*
   - **Z factor** = *1*
   - All other setting as default



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Calculate Slope

1. Use the Surface Parameters Tool to calculate topographic slope from the archDEM with the following settings:
   - **Input Surface Raster** = archDEM
   - **Output Raster** = archSLP
   - **Parameter Type** = *Slope*
   - All other setting as default.

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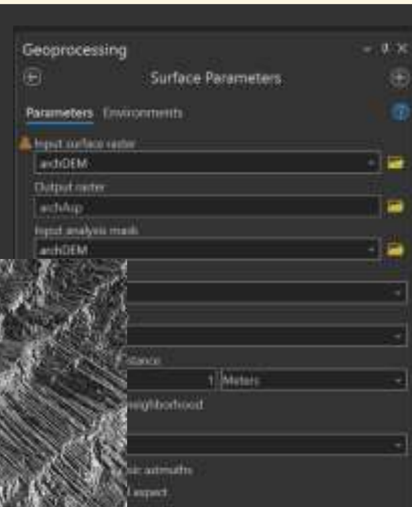
Calculate Aspect

1. Use the Surface Parameters Tool to calculate topographic slope from the archDEM with the following settings:
   - **Input Surface Raster** = archDEM
   - **Output Raster** = archAsp
   - **Parameter Type** = *Aspect*
   - All other setting as default



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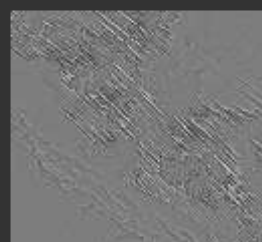
Calculate Topographic Position Index

1. Calculate the average elevation in an 11-cell radius from the archDEM layer using the Focal Statistics Tool.
2. Use Raster Calculator to subtract the mean elevation from the DEM to obtain a topographic position index.



Spatial Analyst Tools → Neighborhood → Focal Statistics

Spatial Analyst Tools → Map Algebra → Raster Calculator

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Digital Terrain Analysis In QGIS

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Example Terrain Analysis Tools (Other)

- Processing Toolbox → Raster Analysis → Raster Terrain Analysis
- Processing Toolbox → GDAL → Raster Analysis

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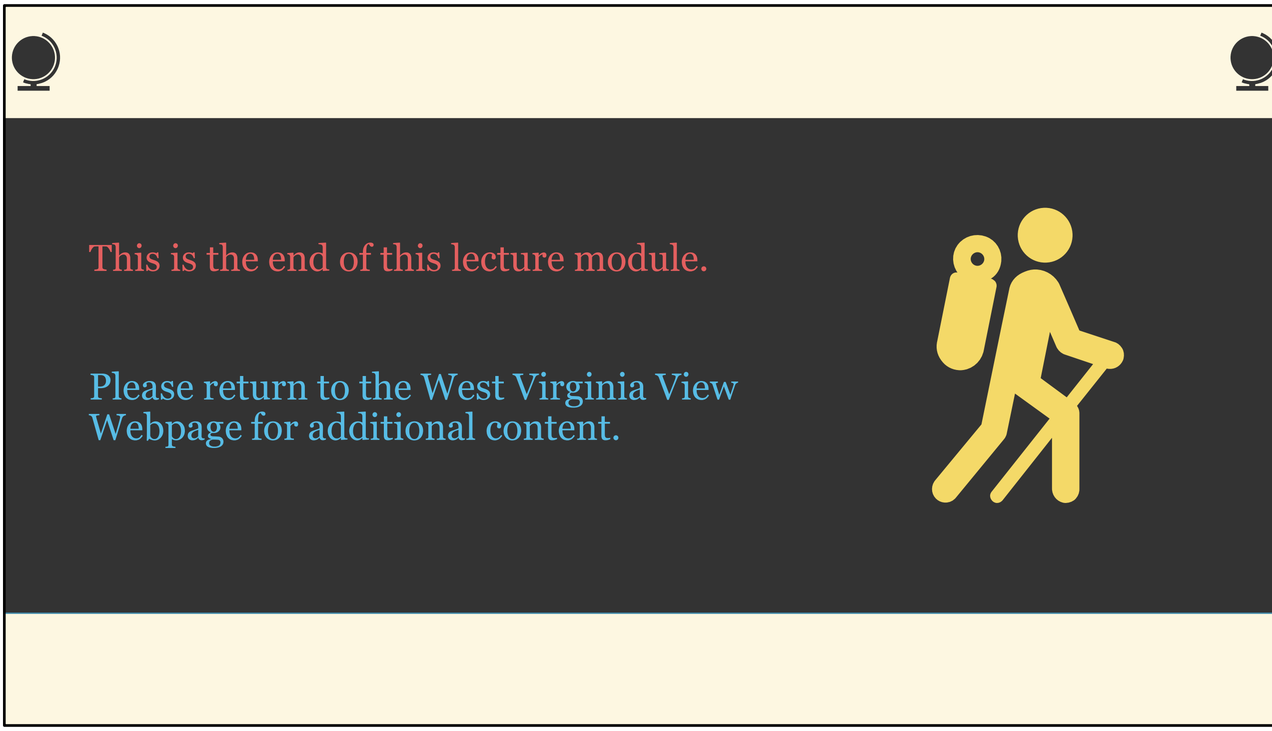
In QGIS, terrain analysis tools are provided in the Raster Analysis → Raster Terrain Analysis and GDAL → Raster Analysis toolboxes.

Make Terrain Derivatives in QGIS

- Use the zermatt project.
- Merge all of the DTMs in the data → Zermatt → dems folder.
- Resample the resulting DTM to a 5 m spatial resolution.
- Calculate the following derivatives from the 5 m DTM: slope and hillshade.



Thanks! Hope you found this useful.