Lahars from Cotopaxi Volcano in Ecuador

Final Project GEO327G

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GIS & GPS Applications in Earth Science
Fall 2021

Dr. Mark Helper

Problem formulation

Cotopaxi Volcano is located 50 km south of Quito, Ecuador's capital, and 31 km northeast of the city of Latacunga. Historical eruptions have leveled the city of Latacunga three times with massive lahars. Now the city is larger than ever with 175,000 inhabitants. The most recent eruption occurred in 2015 and raised awareness to the impending danger this volcano presents. As an Ecuadorian, I want to understand the extent of the area that would be affected if Cotopaxi entered a period of high eruptive activity and triggered lahars/mud flows. To accomplish the goal of my project, I will use ArcMap to generate Multiple-Ring Buffers along the main discharge routes from Cotopaxi and compare the areas to the ones on a hazards map published by the USGS in 1978, then explain how and why these differ.

Data collection and Data preprocessing

To start, I needed Digital Elevation Model data of this specific region in Ecuador. This data can be obtained from the USGS Earth Explorer. You simply enter the website > Zoom to the location you desire data for > click "Use Map" when your desired area is on the screen > Data Sets at the bottom of the screen > Digital Elevation > SRTM > SRTM 1 Arc-Second Global > Results > then Download the GeoTIFF file

With the new TIF file in ArcMap, I noticed that the downloaded TIFF file of this zone of Ecuador is too large for what I needed. Therefore, I needed to create a polygon to select the Study Area (outlined in blue below in *Figure 1*) by right clicking on the TIF file>Edit Features> Start Editing > Create Features > Polygon and drawing it to the desired Study Area.

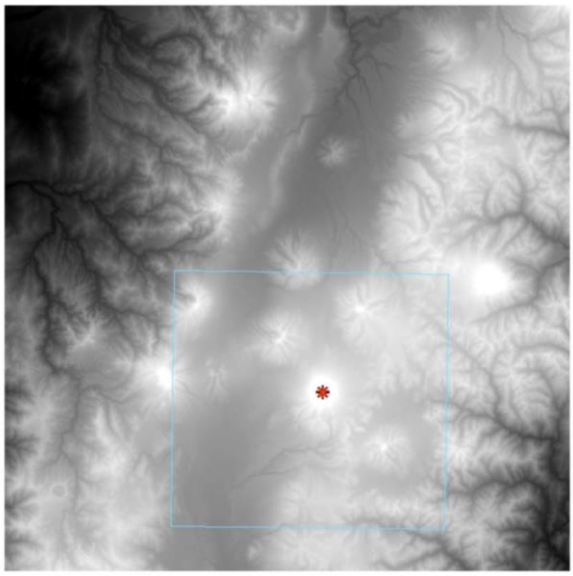

Figure 1 - ASTER GDEM of Quito and its outskirts (including Cotopaxi shown with the red asterisk)

With the desired Study Area drawn, I used the tool 'Extract by Mask' and with the TIFF file as the input layer, the Study Area polygon as the mask, and extract. The result is a clipped portion of the TIFF file to the Study Area that I selected

Now its important to create a Hillshade in order to visualize the terrain around Cotopaxi and depict where there are hills and where there are gorges/valleys.

To create a Hillshade, I used the clipped Study Area TIFF file and opened the 'Hillshade' tool. Since the horizontal units are in decimal degrees and the vertical units are in meters, use a z factor of 0.000009 to convert (shown in *Figure 2)*. I kept the default azimuths.

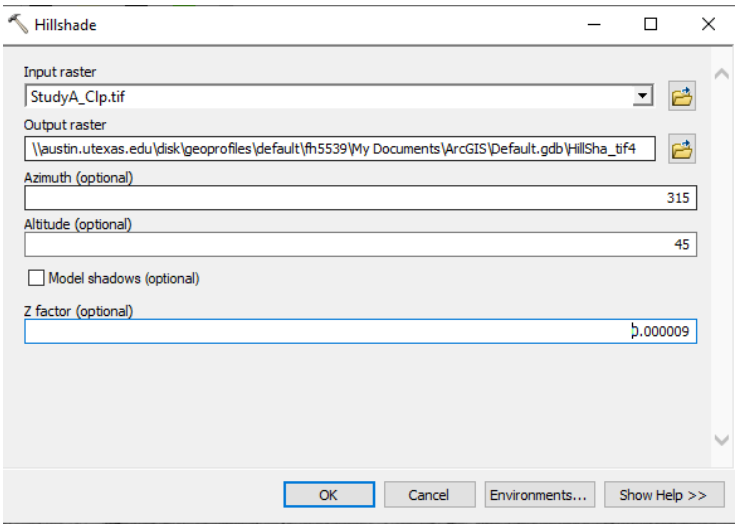

Figure 2

Hydrographic Network around Cotopaxi

Due to the lack of hydrographic information near or on Cotopaxi, I resorted to using my Digital Elevation Model data to generate a river network around Cotopaxi. I used a video on YouTube by Dody Setiawan as a guide, it is simple, straightforward, and just excellent. Here is the link: https://www.youtube.com/watch?v=tnO5zABBbnk

I used the Hydrology toolbox in the Spatial Analyst Tools and it went in the order of the video:

1. Fill (using the DEM as the input)
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5. Be sure to symbolize the value of 0 as 'Hollow'.
6. Stream Order (using the calculated data above 10000 as the 'Input Stream Raster' and the Flow Direction as the 'Input Flow Direction Raster'), use the 'STRAHLER' method.
7. Finally, use the Stream to Feature tool to convert the raster into a vector. I just used the standard river symbology and this is the only layer I kept in my map.

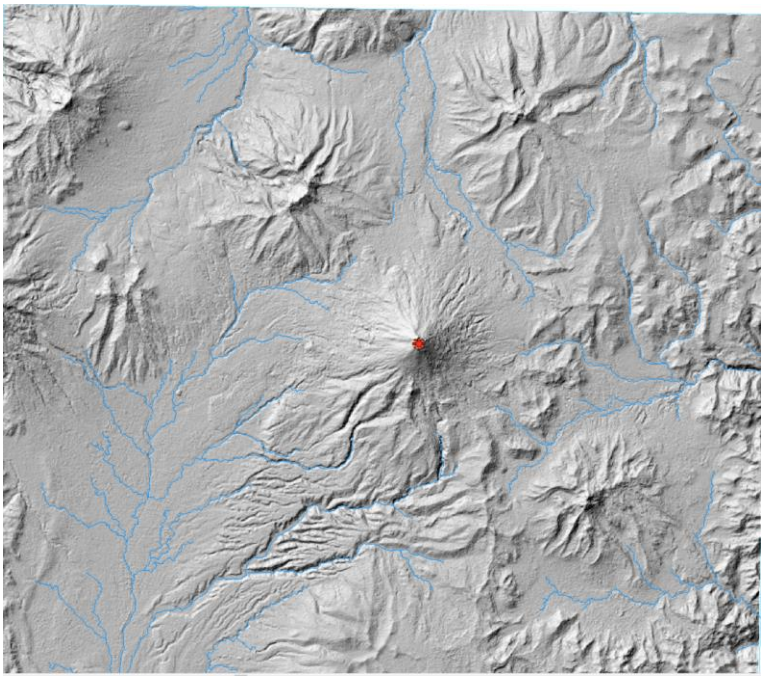


Figure 3 - Ta-da! River and stream network!

Now that I had a river network set for my map, I had to clip the rivers to show only the ones that flow down from Cotopaxi, and therefore cause lahars.

This step required nothing complicated, just drawing a weirdly-shaped polygon (*Figure 4*) and clipping with the 'Clip (Analysis)' tool (*Figure 5)*!

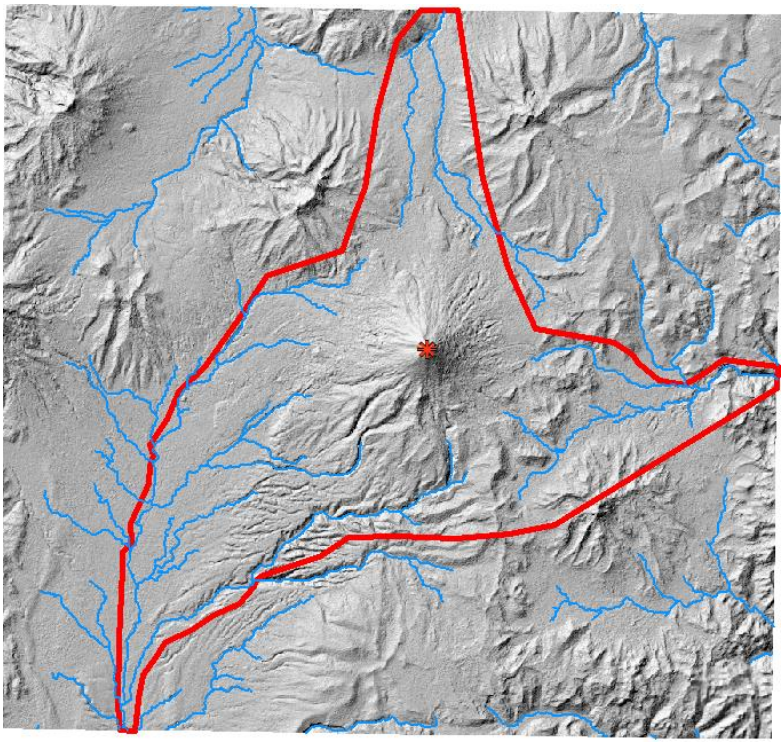
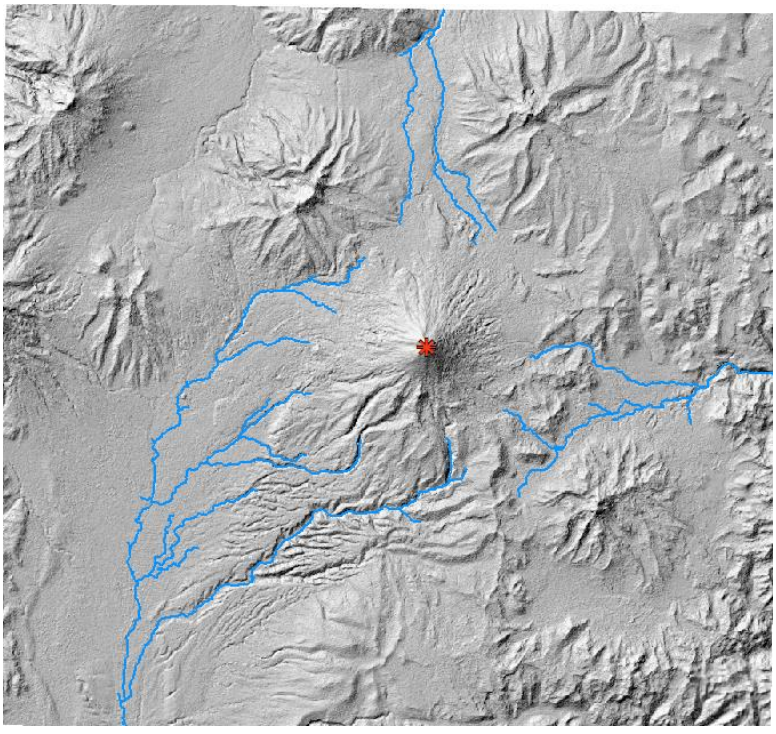


Figure 5 - Rivers in my area of interest polygon in red



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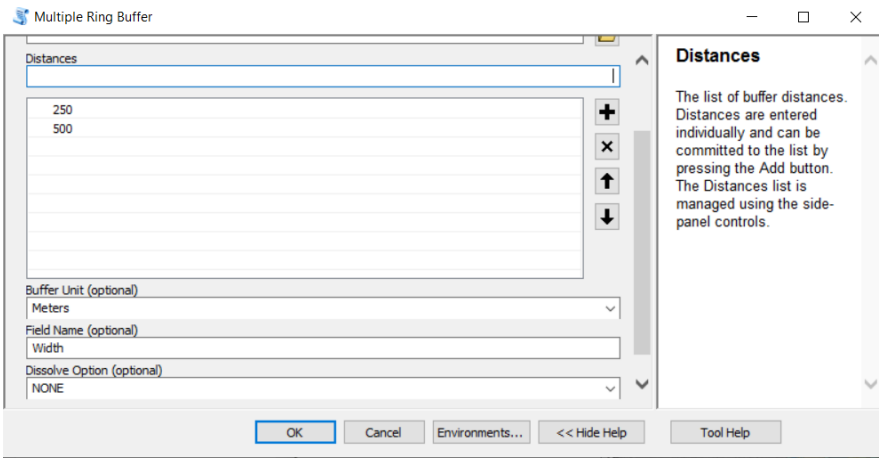

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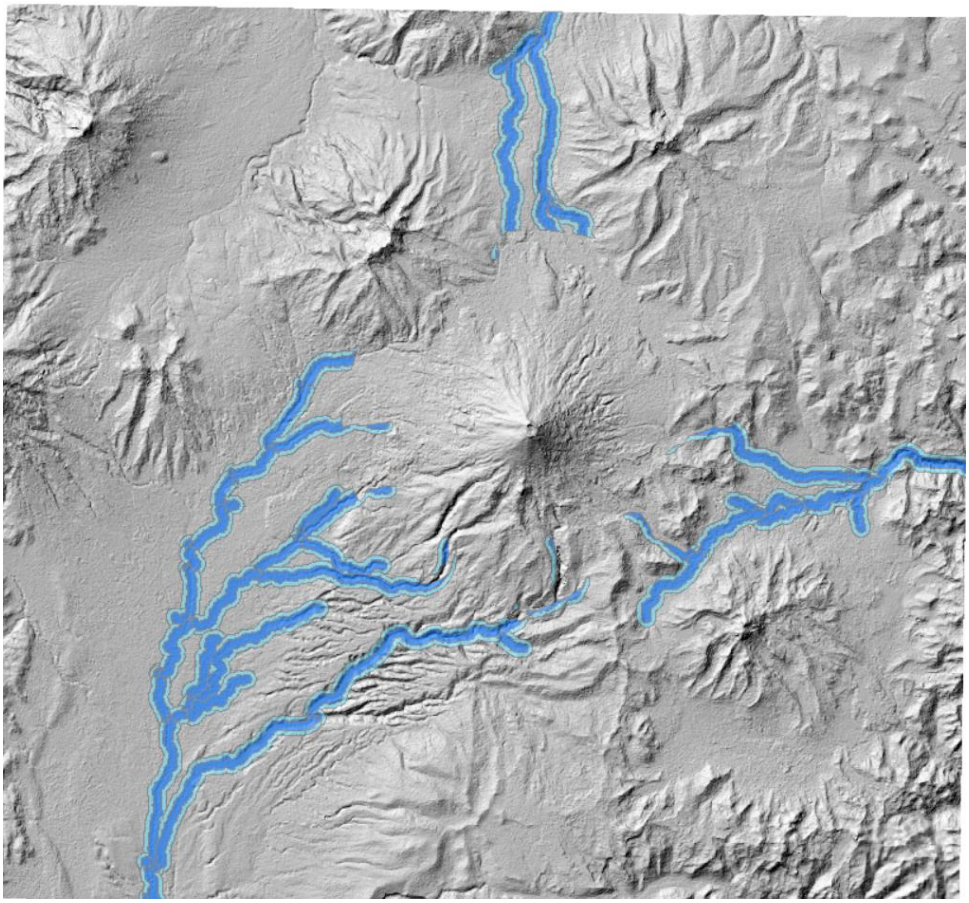

Figure 7 – Multiple Ring Buffer Lahars

Georeferencing a 1978 USGS Cotopaxi Hazards Map

First, I got this map from the USGS publication: *Reconnaissance map of potential volcanic hazards from Cotopaxi Volcano, Ecuador* https://doi.org/10.3133/i1072, specifically the Plate-1 pdf. It maps the potential hazards that would occur if Cotopaxi erupts and its glaciers/snow cover melt. The map analyses ashfall and designates three lahar hazard zones: Maximum, Severe, and Lesser. The 'Maximum' hazard zone is all of the volcano's slopes on a ~10.5 km radius from the summit. This zone includes pyroclastic flows, lava flows, and blocks/bombs, which are not likely in the other zones. Second, the 'Severe' hazard zone is made up of valley floors and areas of lower elevation to which mudflows flow towards after coming down from Cotopaxi. Finally, the 'Lesser' hazard zone is marked as an extension of the 'Severe' zone and it is only affected if there are abnormally large mudflows (1 kilometer+ in width). Map from the USGS can be found here.

Since this is a PDF file, I needed to georeference and digitize the hazard zones shown in this map.

First, I converted the USGS PDF file to JPEG in an online converter (get the highest definition). Then I imported it into ArcMap and set the Projected Coordinate System to UTM Zone 17S as you can see that the USGS map has UTM coordinates and Ecuador is in zone 17 with Cotopaxi being south of the Equator.

Next, I used the PDF to see the specific coordinates and use the Georeferencing tool > Add control points > Click on the point twice > Open the Link table after the point is set and edit the data under the X Map and Y map columns (*Figure 8)* to match the coordinates in the ones printed on the USGS map image. Select 4 points and change their X Map and Y Map coordinates accordingly.

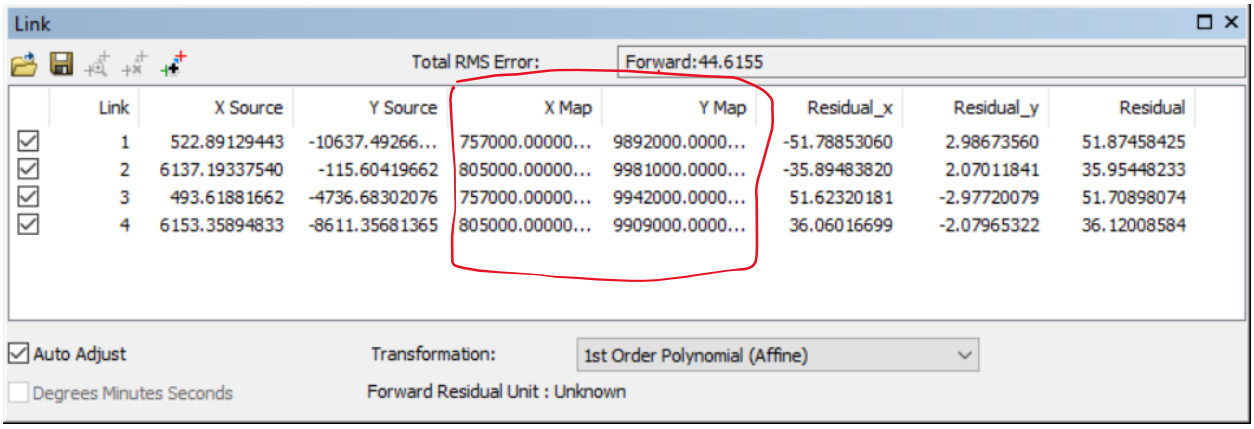

Figure 8 - Georeferencing Link Table

After this, I was ready to start digitizing the map as it now has coordinates set and is georeferenced. To digitize first you have to create three new Feature Classes: Maximum, Severe, and Lesser Hazard Zones. Right Click on the Geodatabase > New > Feature Class > Label the name to what degree of lahar it is (Maximum, Severe and Lesser) > Select the Projected Coordinate System > UTM > WGS1984 > Southern Hemisphere > WGS_1984_UTM_Zone_17S > Accept default tolerance > Finish. Now I could start tracing new polygons in each hazard zone to create a digital version of the USGS map. After long hours of tedious work and loss of eyesight, I accomplished this, shown in *Figure 9*.

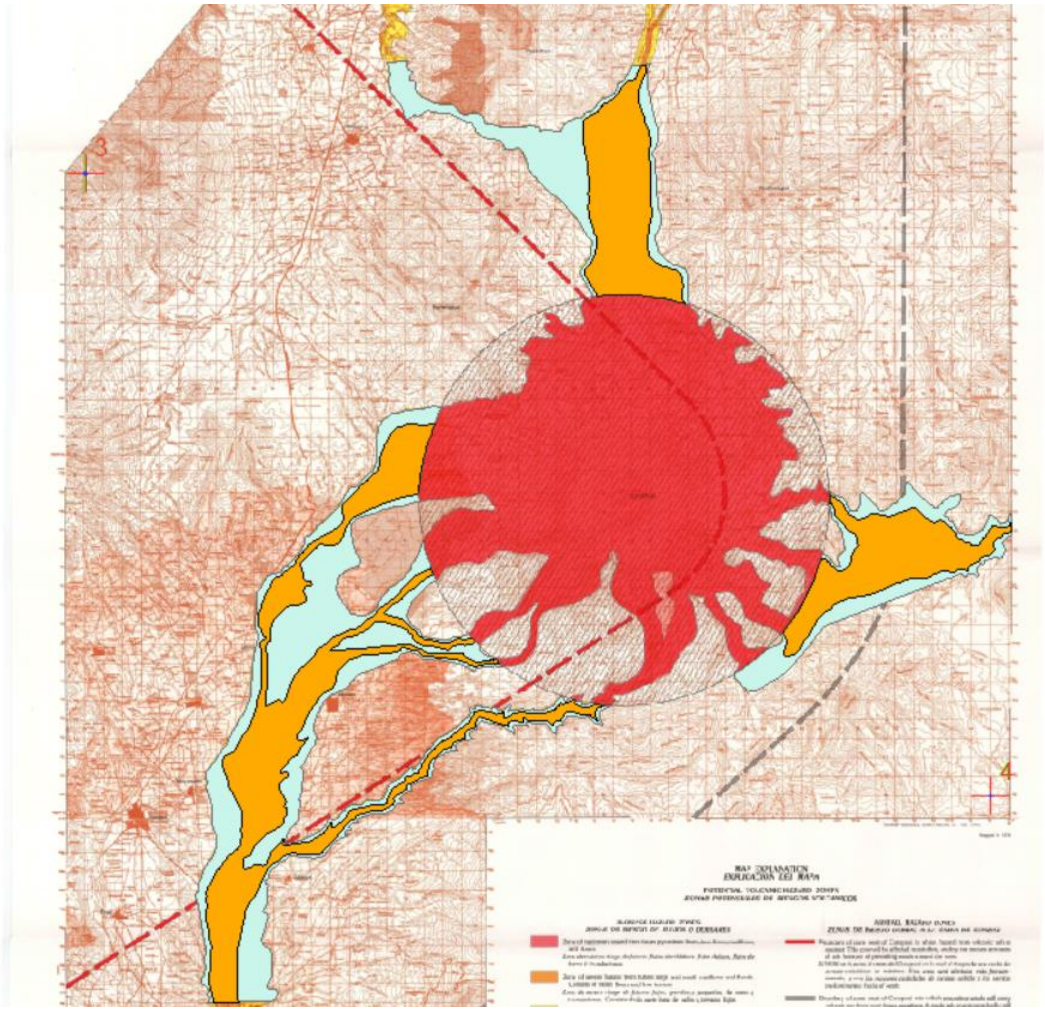

Figure 9 - Digitized hazard zones shown in red, orange, and light blue, with the Georeferenced USGS hazard map below. In the upper left corner, you can see the Link (+ sign) used to georeferenced it.

Comparing USGS Lahar Areas to the Multiple Ring Buffer areas made with ArcMap

Now that I have digitized the USGS Hazards map, I can compare the areas the USGS designates as 'Potential Volcanic-Hazard Zones' to the areas from the Multiple Ring Buffers I created using the tool in ArcMap, and which are based on the hydrographic information around Cotopaxi. To calculate these areas, I first opened the attribute table, created a new Field with the 'Table Options' menu and named the Field "Area". Then, in the attribute table, right click on the new "Area" field heading, select 'Calculate Geometry', select "Area" under the Property drop down menu, make sure the units are Square Meters, and click OK and Yes on all the messages. Area is now calculated for the buffers! Time to compare. Use the "Statistics" button after right-clicking to find the sum of the areas.

One last correction I made is erasing a portion of my lahars that went up the mountain slope into what the USGS calls the 'Maximum Hazard Zone', considering lahars in this area would not be useful for my comparison as there are almost no inhabitants here and its in the national park, no urban areas here. Using the 'Erase' tool in ArcMap, I erased the Multiple Ring Buffers I created that went inside the Maximum Hazards zone (red zone). *Figures 10 and 11* show the difference.

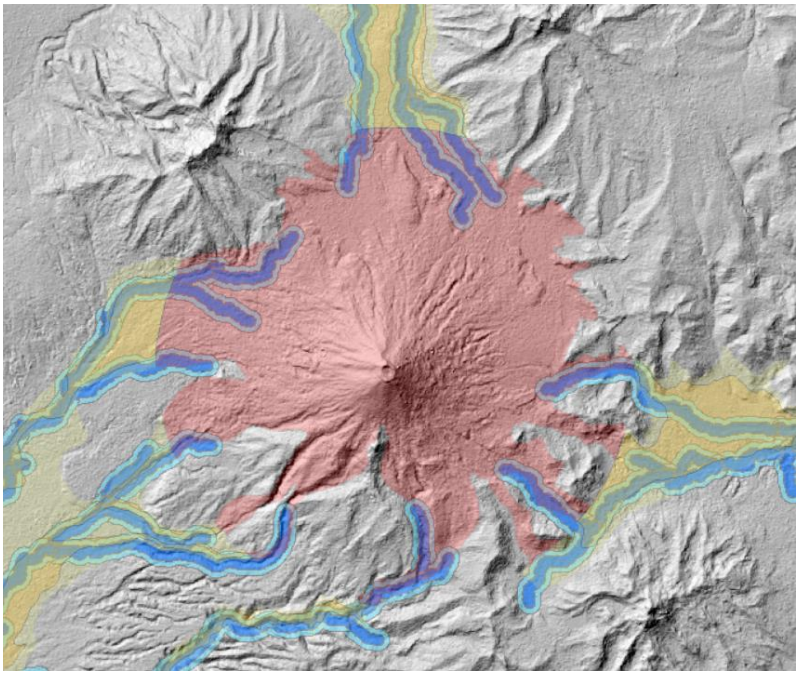

Figure 10 - Multiple Ring Buffers go into the USGS Maximum Hazard (red) zone, adding unnecessary area to the lahar area calculation

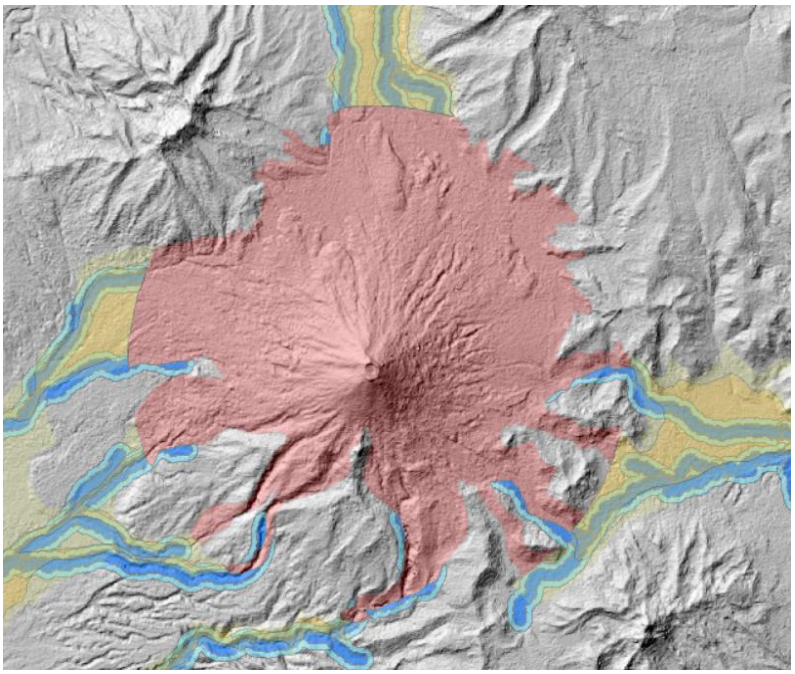

Figure 11 - With the Erase tool, the Multiple Ring Buffers are no longer in the red zone, making comparisons more accurate

Data Table

Below is a table showing the areas from the digitized USGS map, the Multiple Ring Buffers I created using ArcMap, and just for extra comparison the same Multiple Ring Buffers *without* using the Erase tool.

Zone	Area in square meters	Area in square kilometers
USGS Digitized Map Data		
Maximum Hazard Zone (Red)	**263,202,603**	**263.2**
Severe Hazard Zone (Orange)	**143,414,191**	**143.4**
Lesser Hazard Zone (Yellow)	**127,241,640**	**127.2**
Total Area (Severe + Lesser)	**270,655,831**	**270.7**
Multiple Ring Buffer made with ArcMap		
500m wide Lahar (Dark Blue)	**129,740,749**	**129.7**
250m wide Lahar (Light Blue)	**109,751,504**	**109.8**
Total Area	**239,492,253**	**239.5**
Multiple Ring Buffer made with ArcMap (without the Erase tool)		
500m wide Lahar	**161,734,117**	**161.7**
250m wide Lahar	**140,508,177**	**140.5**
Total Area	**302,242,294**	**302.2 (over 60 km^2 more!)**

Analysis and Conclusion

As seen above the total area designated by the USGS to be a 'Hazard Zone' adds up to 270.7 square kilometers, whereas the total area of the Multiple Ring Buffers is 239.5 square kilometers. This 31.2 square kilometer difference comes as a result of two very different methods of mapping the possible lahar flows from Cotopaxi.

My approach of creating Multiple Ring Buffers following the rivers and streams that flow down from Cotopaxi is a lot simpler than the USGS's method. My method involves simply plotting rings around a specific point (river pathway in this case) with a specific radius set. For this analysis I set the lahar width to be a total of 250 and 500 meters, this width is followed throughout the river's path. The problem with this is that the width cannot be the same along all the path due to topography. There are steep slopes coming down from the mountain and water drainage pathways have formed deep gorges where lahars could not possibly be 500 meters wide with such steep slopes. Moreover, another topographical factor that is not considered when setting the fixed buffer distance from the river is that when the gorges end and it reaches the valley below, the lahar, with all its accumulated momentum and speed, will start to spread out and cover more area. You can clearly see this in the USGS hazard areas. When the lahars come down from the mountain, they are thinner, but when they reach flatter ground they get a lot wider. This is where I believe the main discrepancy is between my buffer areas and the USGS hazard area. In the flatter ground, their area is much wider than the buffer I created, making the USGS's areas more accurate than mine. The USGS can produce these more accurate areas as they are using the rock record, historical records of where the lahars flow, and can also input topography as a defining factor of where and how the lahars can flow.

It is very intriguing to compare two very different approaches to mapping the same thing. Multiple Ring Buffers are an effective, simple, method of showing where lahars would flow, but they are not as accurate as they do not follow topography, just the path of the river. The USGS model uses far more complicated sets of data to reach its conclusion of where the hazard zones would be and therefore it is indeed more accurate than my method. A possible improvement to my method would be using slope maps or higher resolution imagery in order to get more accurate results that follow topography closer, like the USGS map does. I was limited by the data I could obtain from this part of the world. In terms of area there is a difference of an area the size of twenty-two Zilker Parks, a considerable amount. This means that my results could not be used to accurately depict the area that would be affected by the lahars, but for the purposes of this project I am very satisfied with how they turned out and I enjoyed being able to compare them.

Cotopaxi Hazards Map

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Final Project
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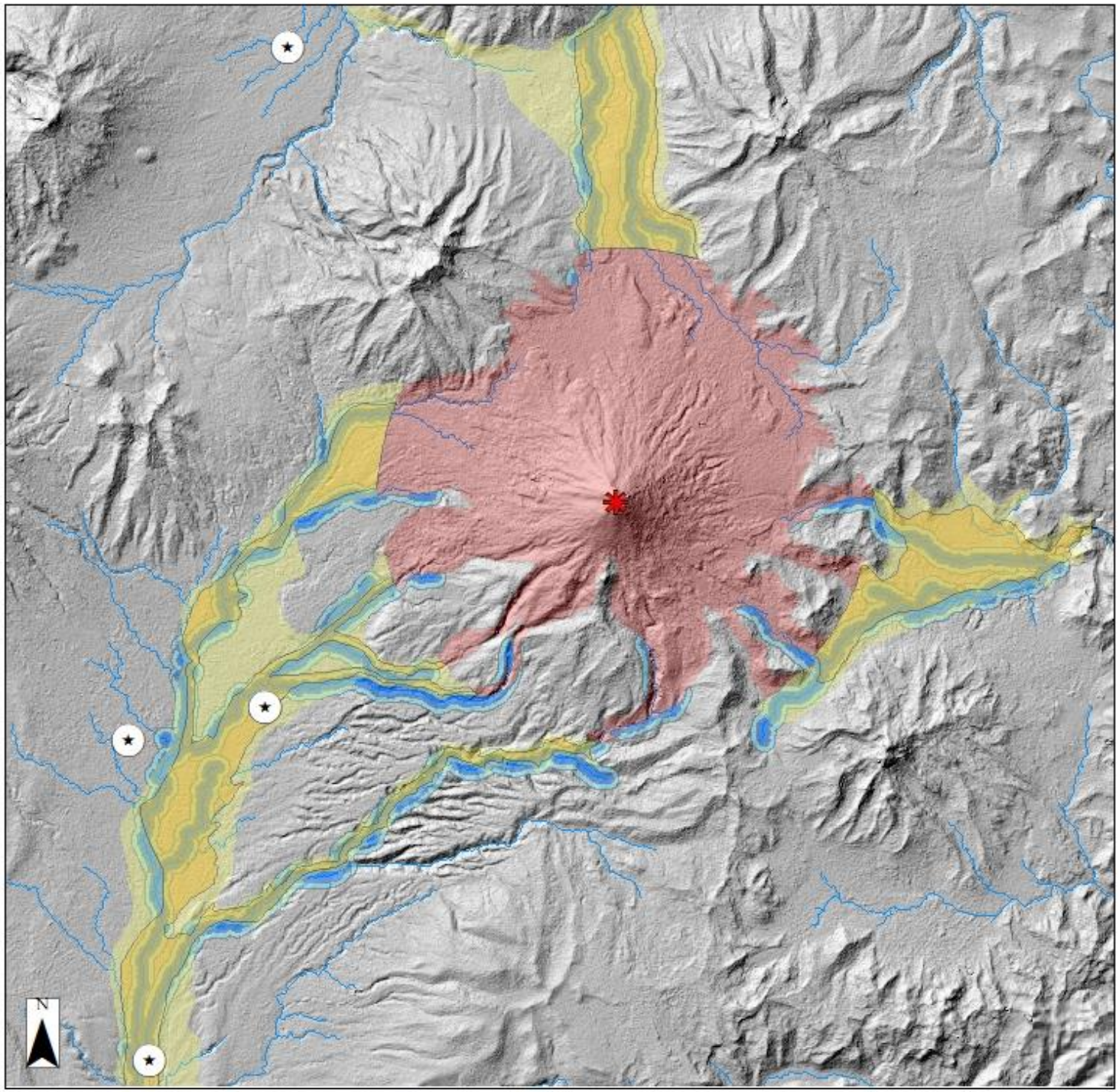


Legend

- Cities
- Cotopaxi Summit
- USGS Maximum Hazard Zone
- USGS Severe Hazard Zone
- USGS Lesser Hazards Zone

Multiple Ring Buffer

Lahar Width in meters

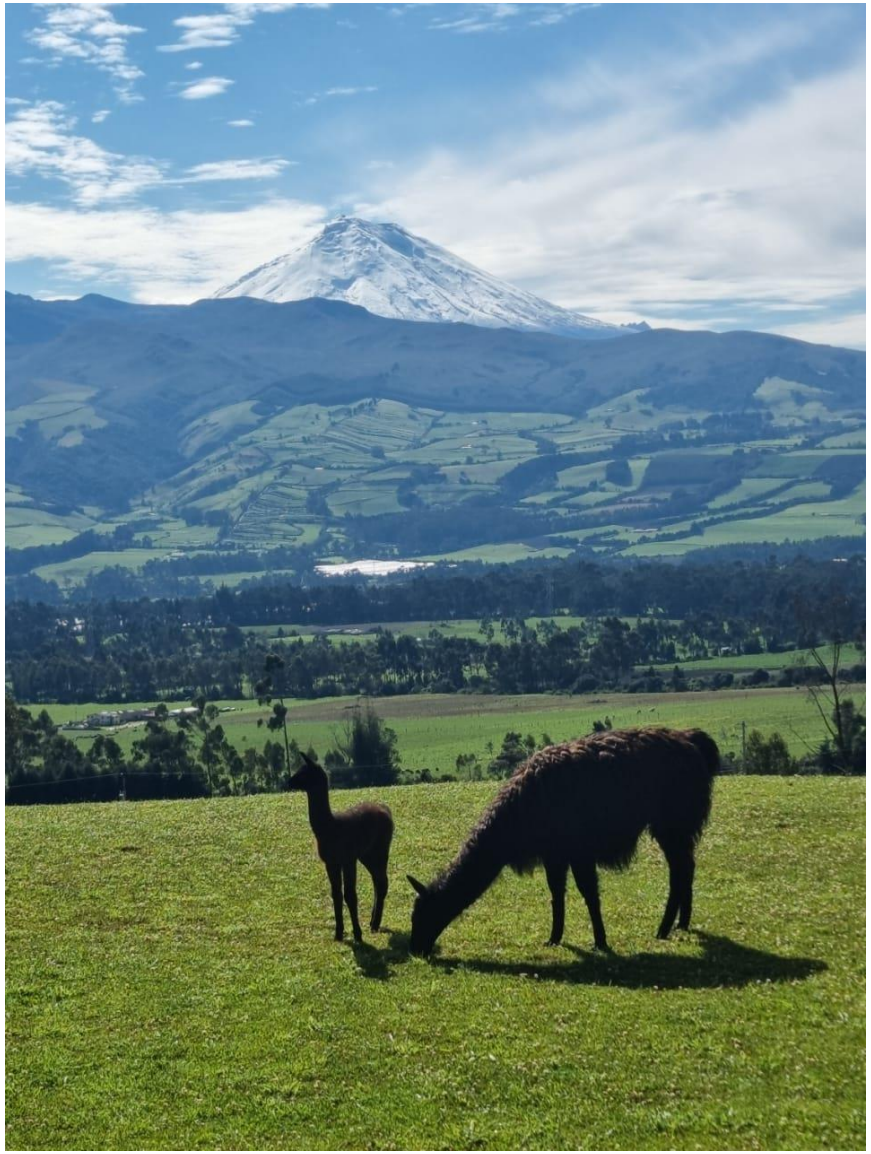
- 250
- 500
- Rivers

Coordinate System: WGS 1984 UTM Zone 17S
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000.0000
False Northing: 10,000,000.0000
Central Meridian: -81.0000
Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter

References:

Miller, C. D., Mullineaux, D. R., & Hall, M. L. (1978). *Reconnaissance map of potential volcanic hazards from Cotopaxi Volcano, Ecuador* (Rep.). DOI: https://doi.org/10.3133/i1072

Setiwan. D. (April 4, 2014). *How to generate river network using DEM data* [Video] YouTube. https://www.youtube.com/watch?v=tnO5zABBbnk



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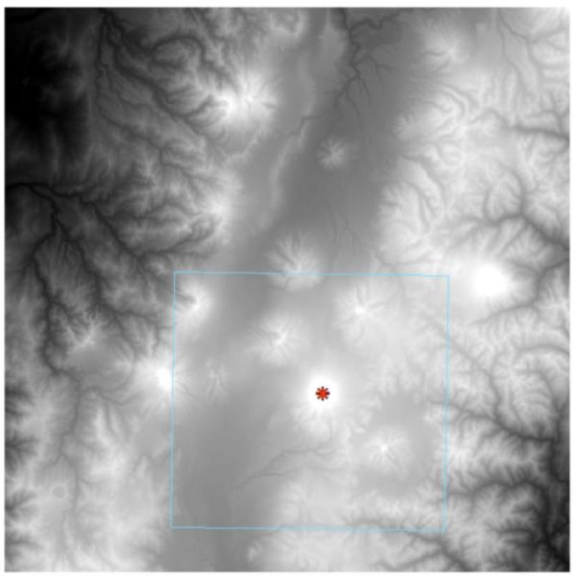

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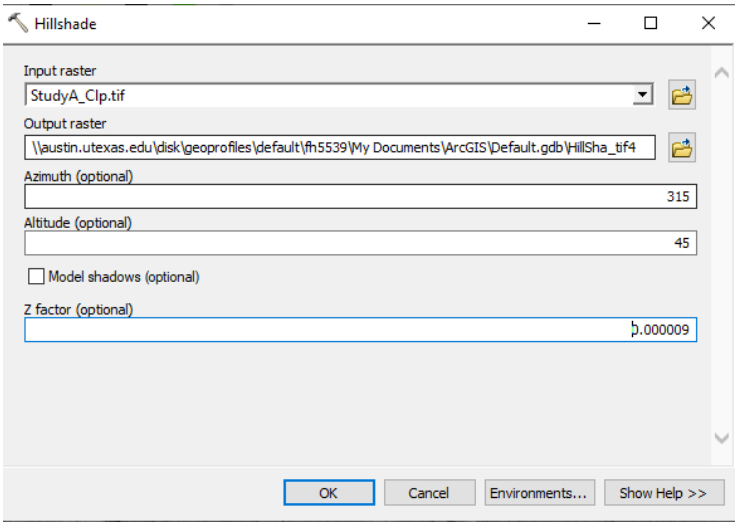

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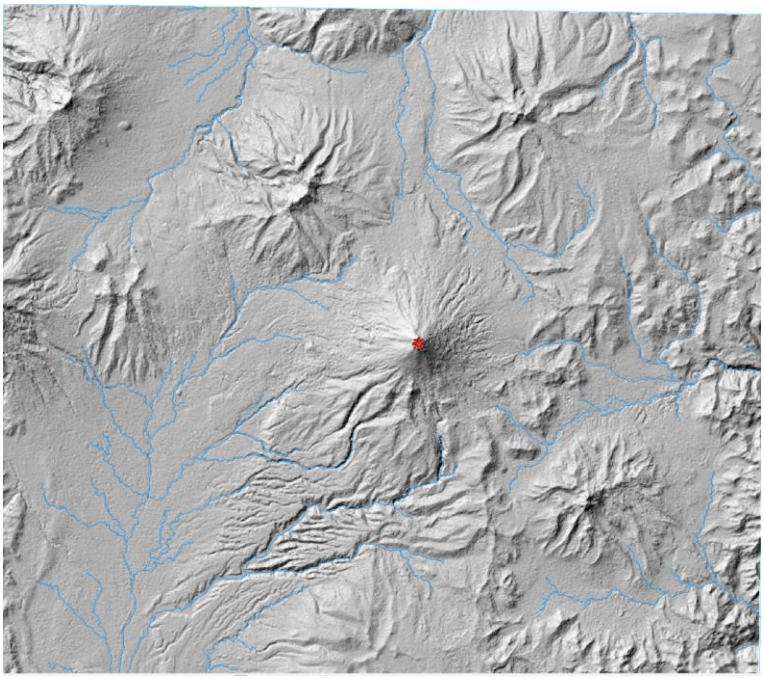

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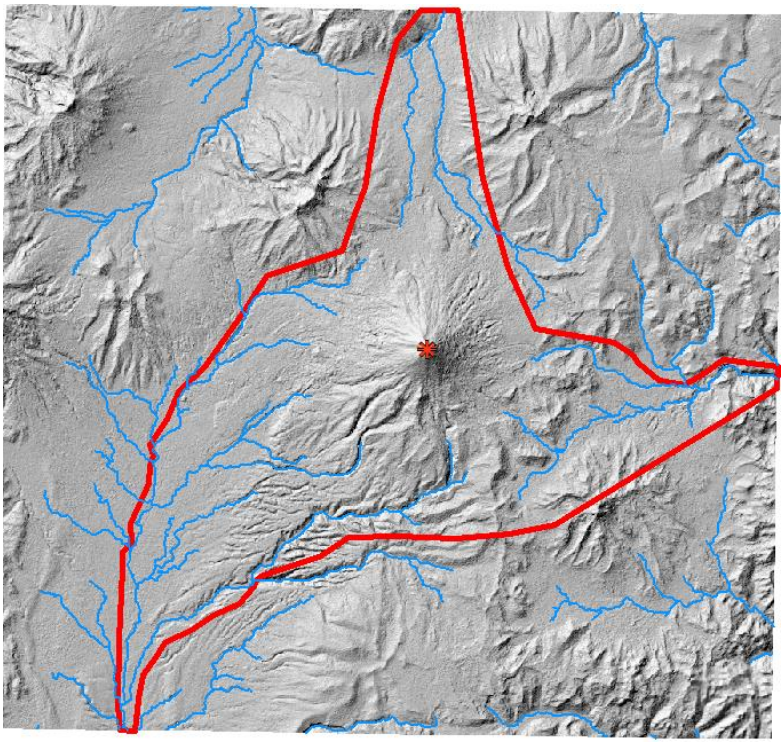

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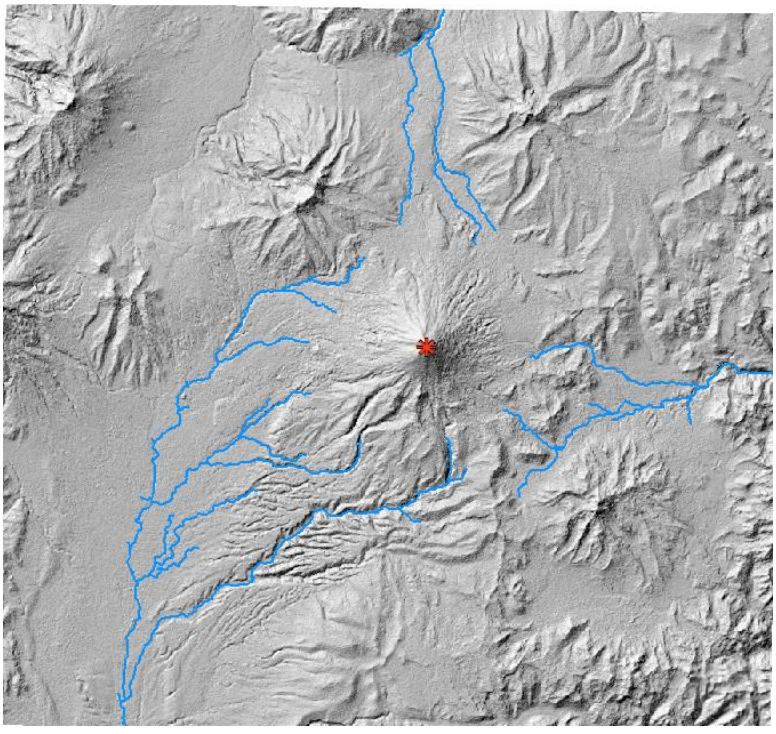

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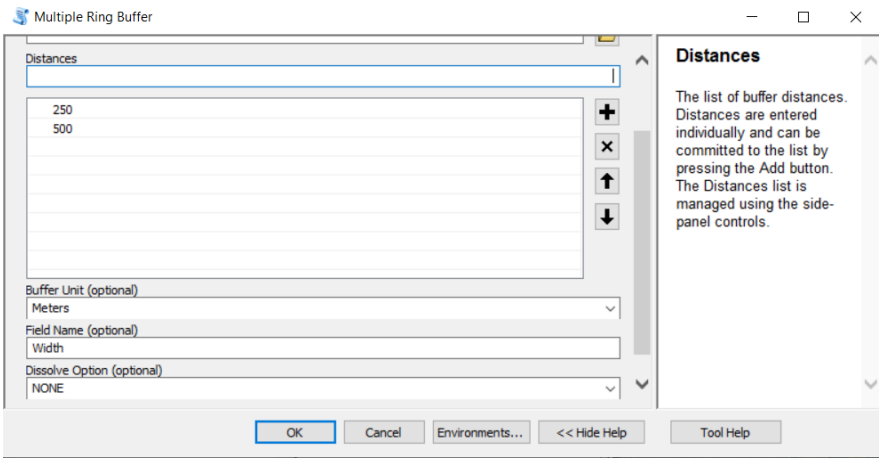

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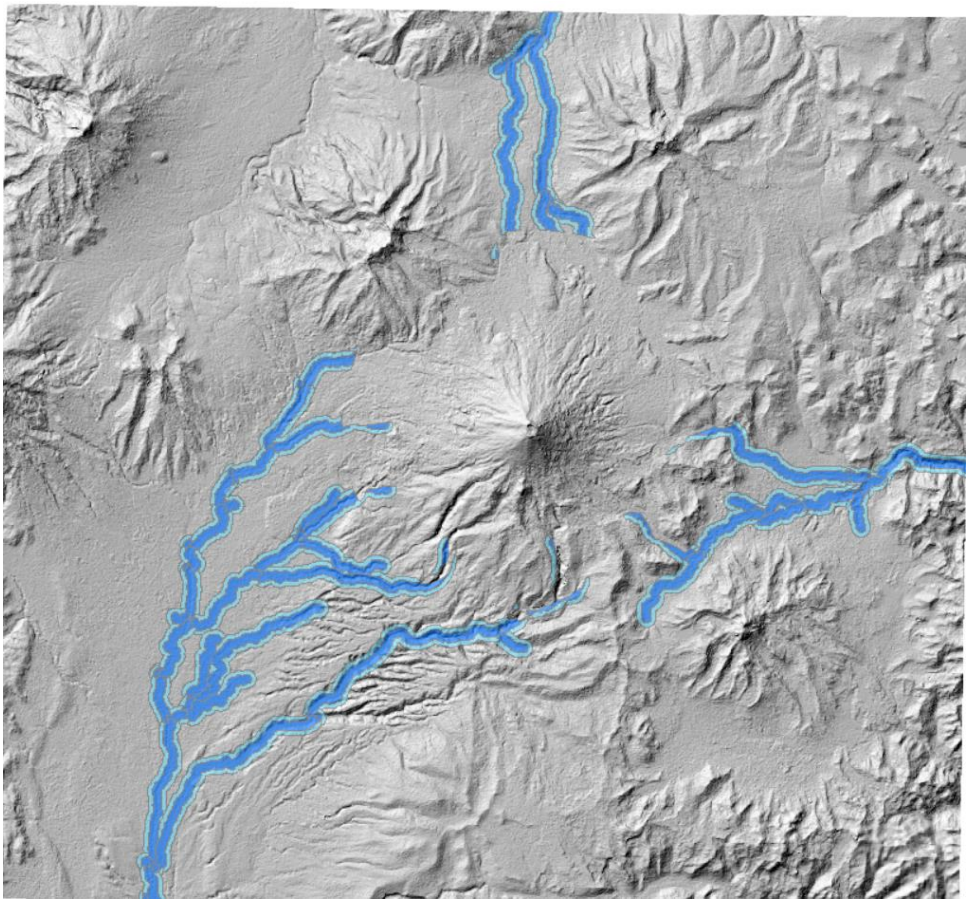

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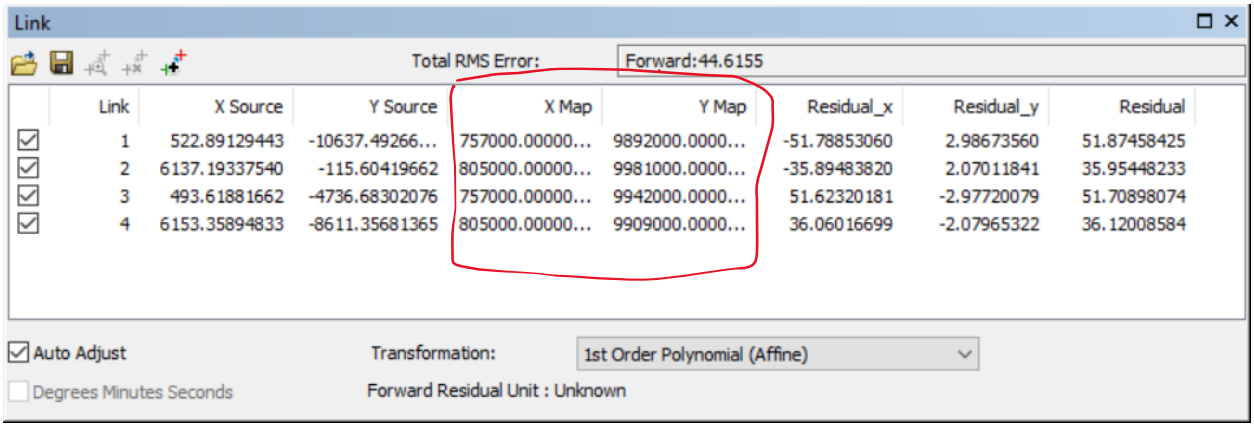

Figure 8 - Georeferencing Link Table

After this, I was ready to start digitizing the map as it now has coordinates set and is georeferenced. To digitize first you have to create three new Feature Classes: Maximum, Severe, and Lesser Hazard Zones. Right Click on the Geodatabase > New > Feature Class > Label the name to what degree of lahar it is (Maximum, Severe and Lesser) > Select the Projected Coordinate System > UTM > WGS1984 > Southern Hemisphere > WGS_1984_UTM_Zone_17S > Accept default tolerance > Finish. Now I could start tracing new polygons in each hazard zone to create a digital version of the USGS map. After long hours of tedious work and loss of eyesight, I accomplished this, shown in *Figure 9*.

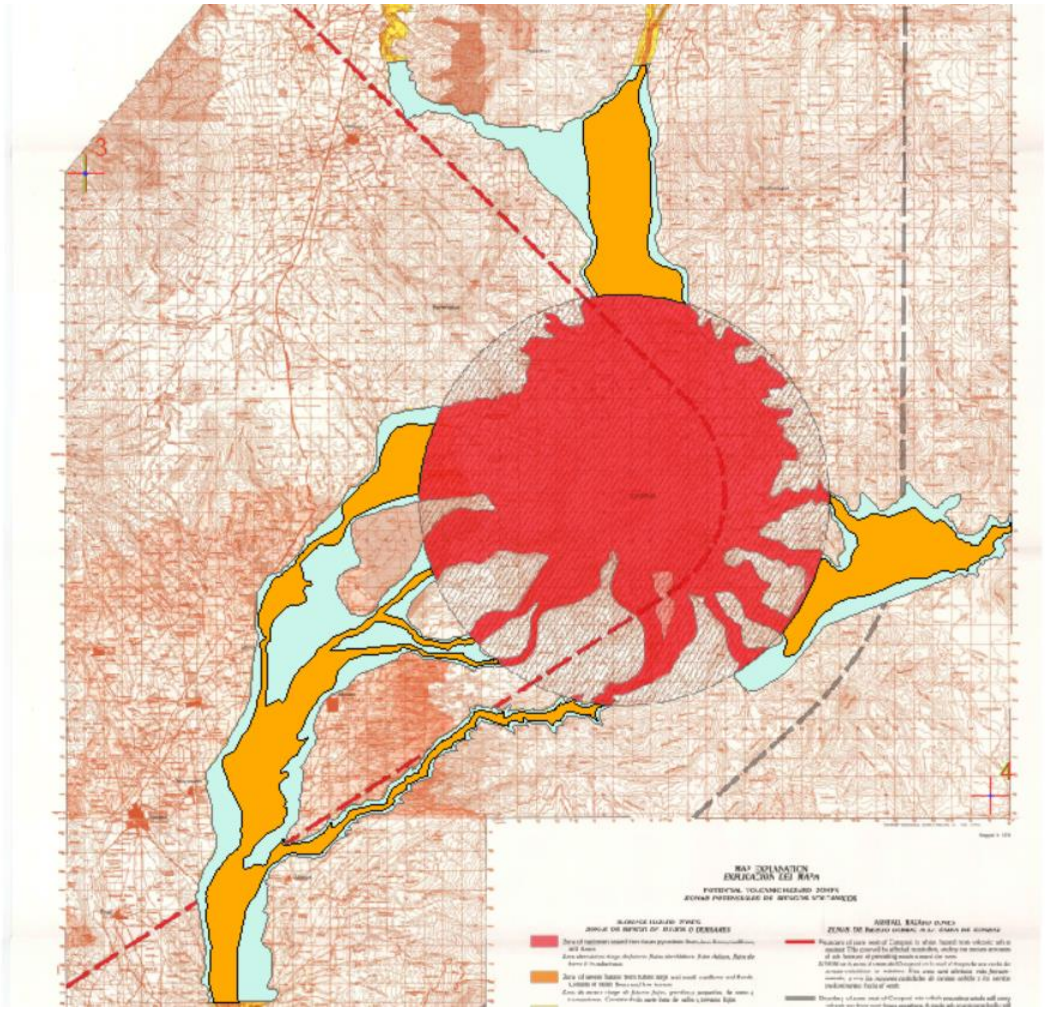

Figure 9 - Digitized hazard zones shown in red, orange, and light blue, with the Georeferenced USGS hazard map below. In the upper left corner, you can see the Link (+ sign) used to georeferenced it.

Comparing USGS Lahar Areas to the Multiple Ring Buffer areas made with ArcMap

Now that I have digitized the USGS Hazards map, I can compare the areas the USGS designates as 'Potential Volcanic-Hazard Zones' to the areas from the Multiple Ring Buffers I created using the tool in ArcMap, and which are based on the hydrographic information around Cotopaxi. To calculate these areas, I first opened the attribute table, created a new Field with the 'Table Options' menu and named the Field "Area". Then, in the attribute table, right click on the new "Area" field heading, select 'Calculate Geometry', select "Area" under the Property drop down menu, make sure the units are Square Meters, and click OK and Yes on all the messages. Area is now calculated for the buffers! Time to compare. Use the "Statistics" button after right-clicking to find the sum of the areas.

One last correction I made is erasing a portion of my lahars that went up the mountain slope into what the USGS calls the 'Maximum Hazard Zone', considering lahars in this area would not be useful for my comparison as there are almost no inhabitants here and its in the national park, no urban areas here. Using the 'Erase' tool in ArcMap, I erased the Multiple Ring Buffers I created that went inside the Maximum Hazards zone (red zone). *Figures 10 and 11* show the difference.

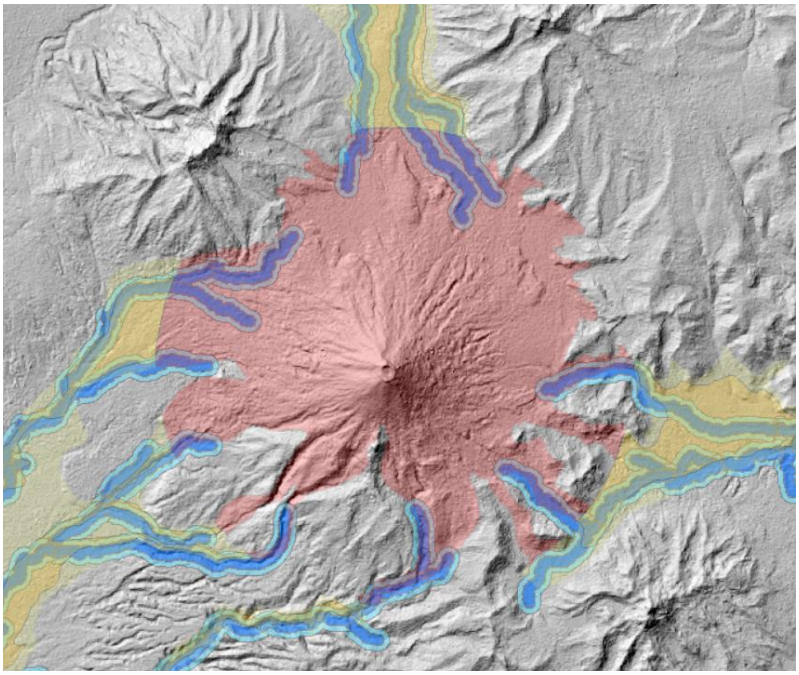

Figure 10 - Multiple Ring Buffers go into the USGS Maximum Hazard (red) zone, adding unnecessary area to the lahar area calculation

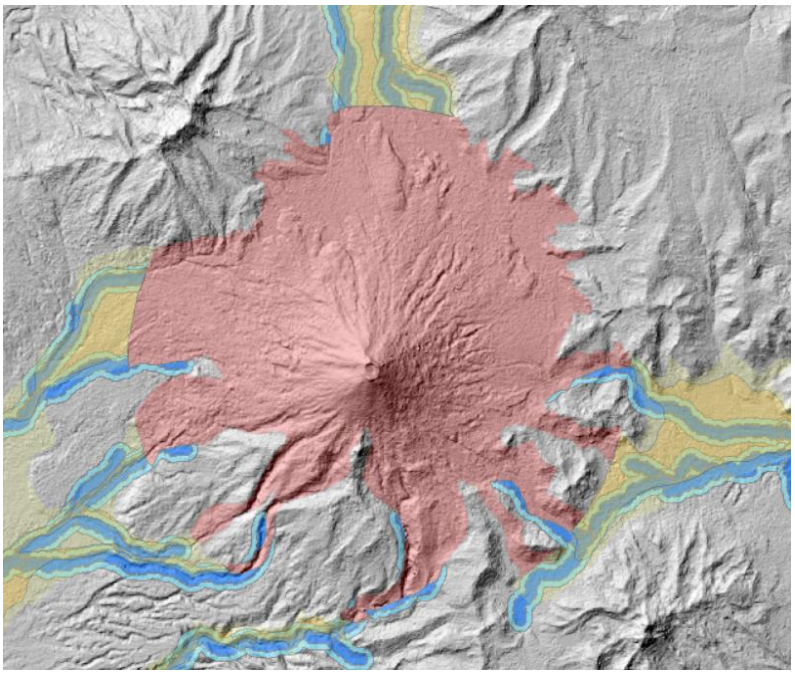

Figure 11 - With the Erase tool, the Multiple Ring Buffers are no longer in the red zone, making comparisons more accurate

Data Table

Below is a table showing the areas from the digitized USGS map, the Multiple Ring Buffers I created using ArcMap, and just for extra comparison the same Multiple Ring Buffers *without* using the Erase tool.

Zone	Area in square meters	Area in square kilometers
USGS Digitized Map Data		
Maximum Hazard Zone (Red)	**263,202,603**	**263.2**
Severe Hazard Zone (Orange)	**143,414,191**	**143.4**
Lesser Hazard Zone (Yellow)	**127,241,640**	**127.2**
Total Area (Severe + Lesser)	**270,655,831**	**270.7**
Multiple Ring Buffer made with ArcMap		
500m wide Lahar (Dark Blue)	**129,740,749**	**129.7**
250m wide Lahar (Light Blue)	**109,751,504**	**109.8**
Total Area	**239,492,253**	**239.5**
Multiple Ring Buffer made with ArcMap (without the Erase tool)		
500m wide Lahar	**161,734,117**	**161.7**
250m wide Lahar	**140,508,177**	**140.5**
Total Area	**302,242,294**	**302.2 (over 60 km^2 more!)**

Analysis and Conclusion

As seen above the total area designated by the USGS to be a 'Hazard Zone' adds up to 270.7 square kilometers, whereas the total area of the Multiple Ring Buffers is 239.5 square kilometers. This 31.2 square kilometer difference comes as a result of two very different methods of mapping the possible lahar flows from Cotopaxi.

My approach of creating Multiple Ring Buffers following the rivers and streams that flow down from Cotopaxi is a lot simpler than the USGS's method. My method involves simply plotting rings around a specific point (river pathway in this case) with a specific radius set. For this analysis I set the lahar width to be a total of 250 and 500 meters, this width is followed throughout the river's path. The problem with this is that the width cannot be the same along all the path due to topography. There are steep slopes coming down from the mountain and water drainage pathways have formed deep gorges where lahars could not possibly be 500 meters wide with such steep slopes. Moreover, another topographical factor that is not considered when setting the fixed buffer distance from the river is that when the gorges end and it reaches the valley below, the lahar, with all its accumulated momentum and speed, will start to spread out and cover more area. You can clearly see this in the USGS hazard areas. When the lahars come down from the mountain, they are thinner, but when they reach flatter ground they get a lot wider. This is where I believe the main discrepancy is between my buffer areas and the USGS hazard area. In the flatter ground, their area is much wider than the buffer I created, making the USGS's areas more accurate than mine. The USGS can produce these more accurate areas as they are using the rock record, historical records of where the lahars flow, and can also input topography as a defining factor of where and how the lahars can flow.

It is very intriguing to compare two very different approaches to mapping the same thing. Multiple Ring Buffers are an effective, simple, method of showing where lahars would flow, but they are not as accurate as they do not follow topography, just the path of the river. The USGS model uses far more complicated sets of data to reach its conclusion of where the hazard zones would be and therefore it is indeed more accurate than my method. A possible improvement to my method would be using slope maps or higher resolution imagery in order to get more accurate results that follow topography closer, like the USGS map does. I was limited by the data I could obtain from this part of the world. In terms of area there is a difference of an area the size of twenty-two Zilker Parks, a considerable amount. This means that my results could not be used to accurately depict the area that would be affected by the lahars, but for the purposes of this project I am very satisfied with how they turned out and I enjoyed being able to compare them.

Cotopaxi Hazards Map

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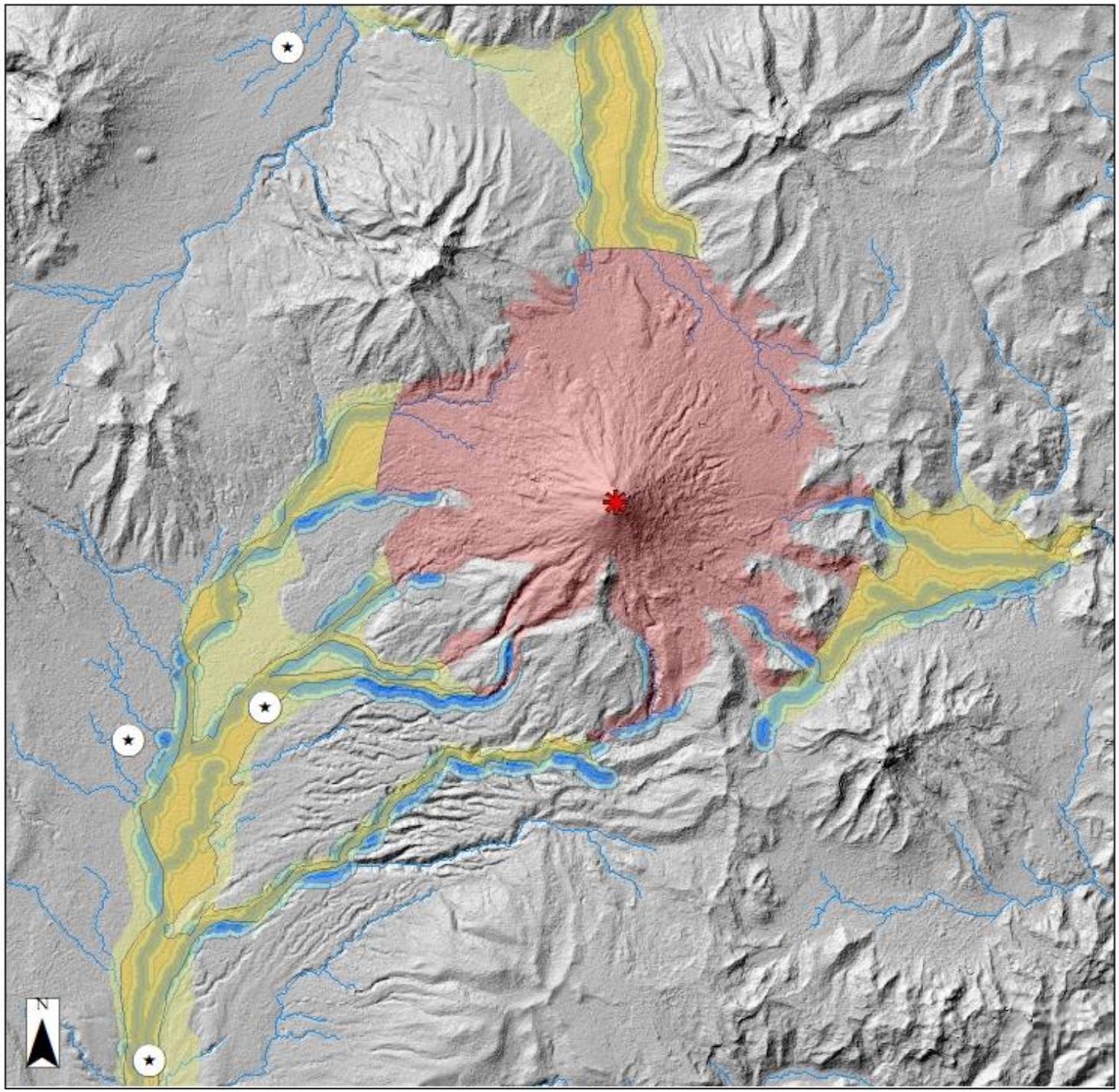
Final Project
Fall 2021



Legend

- Cities
- Cotopaxi Summit
- USGS Maximum Hazard Zone
- USGS Severe Hazard Zone
- USGS Lesser Hazards Zone

Multiple Ring Buffer

Lahar Width in meters

- 250
- 500
- Rivers

Coordinate System: WGS 1984 UTM Zone 17S
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000.0000
False Northing: 10,000,000.0000
Central Meridian: -81.0000
Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter

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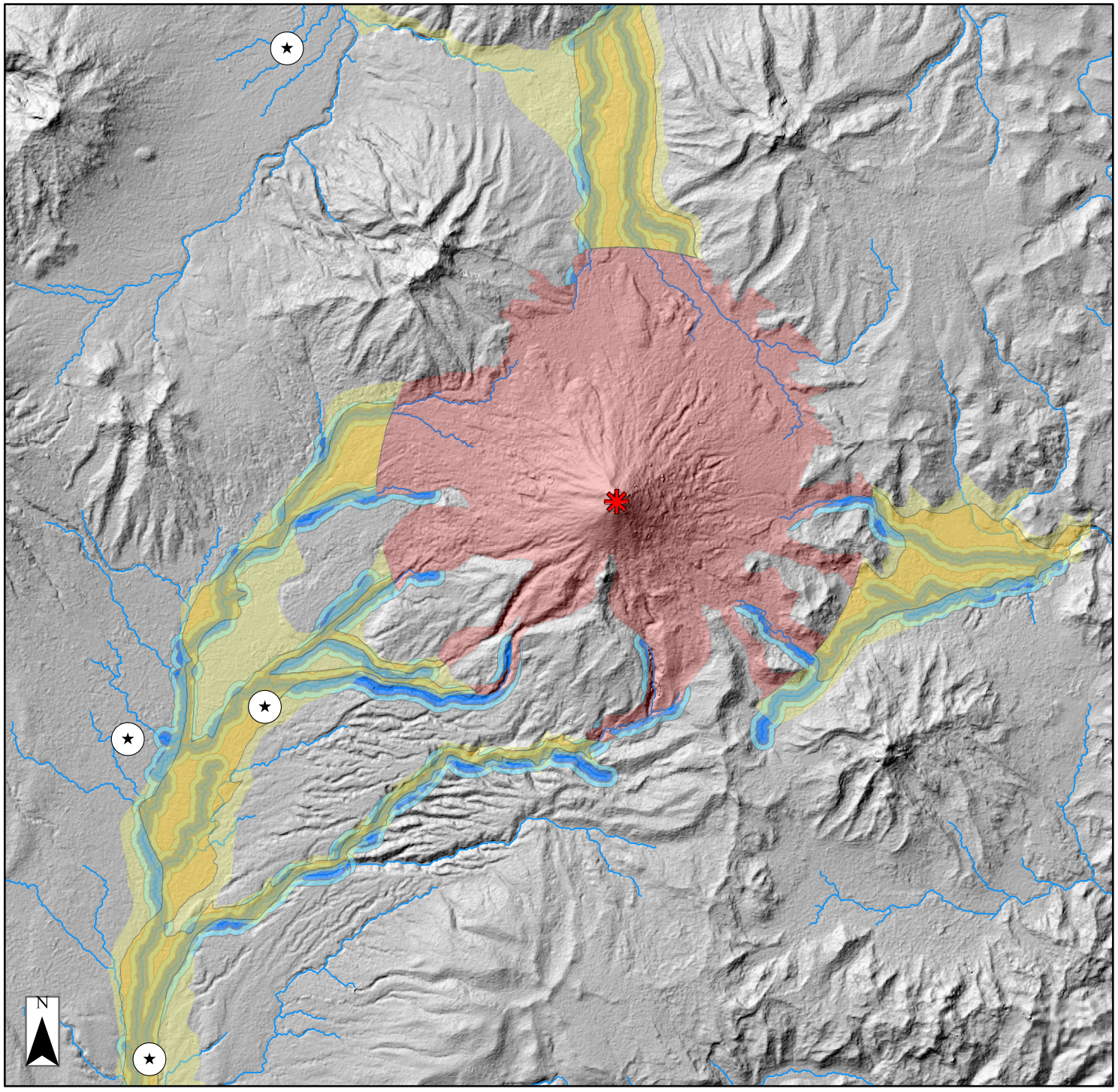

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References:

Miller, C. D., Mullineaux, D. R., & Hall, M. L. (1978). *Reconnaissance map of potential volcanic hazards from Cotopaxi Volcano, Ecuador* (Rep.). DOI: https://doi.org/10.3133/i1072

Setiwan. D. (April 4, 2014). *How to generate river network using DEM data* [Video] YouTube. https://www.youtube.com/watch?v=tnO5zABBbnk

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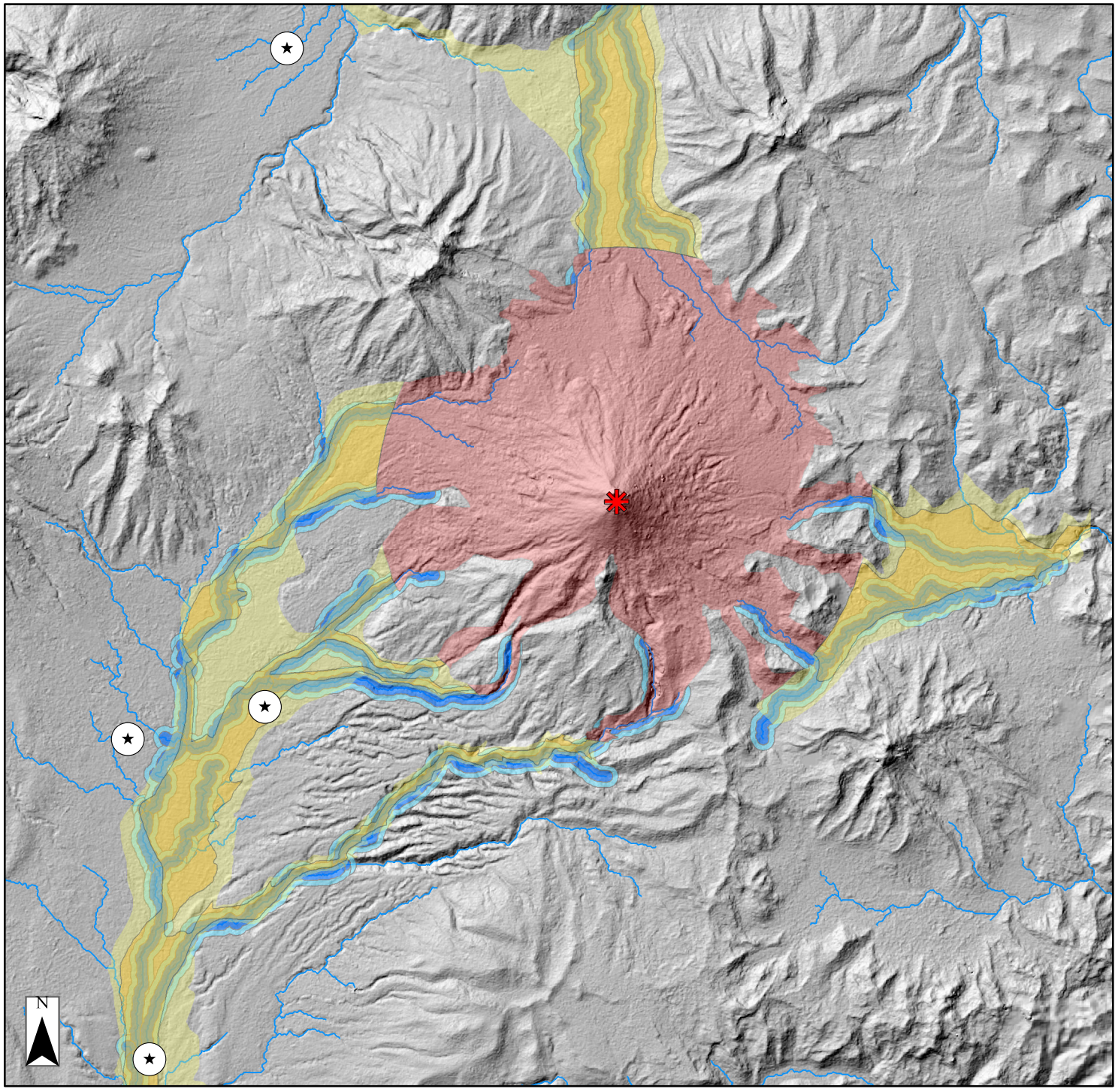

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