



Terrain and Satellite Imagery in Madre de Dios, Peru

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Introduction

Informal and small-scale gold mining of alluvial (water-deposited) sediments has been increasing rapidly in the Madre de Dios region of Peru (Figure 1), spurred by high global prices for gold (Álvarez et al. 2011; Swenson et al. 2011). Gold mining of current and relict river channels in Madre de Dios is causing environmental destruction and mercury contamination, due to the miners' use of mercury to amalgamate gold from sediments (Álvarez et al. 2011; Swenson et al. 2011). Mining activities can impact the geomorphology and sedimentation characteristics of river systems (Pickup and Marshall 2009; James 1999). For my master's research, I hope to investigate how the fluvial geomorphology of certain river reaches in Madre de Dios has been impacted because of mining activities.

Purpose of Project

The purpose of this term project is to gather available data sources for Madre de Dios, Peru. The goal is to obtain multi-temporal satellite imagery of my study area of interest to determine if mining areas visibly increase through time. In addition, I will use the ASTER digital elevation model (DEM) to conduct hydrologic terrain analysis for the region.

Data Sources

For satellite imagery, I downloaded Landsat 4-5 Thematic Mapper (TM) images from the USGS Global Visualization Viewer (<http://glovis.usgs.gov/>). I used Landsat 4-5 TM images because I was able to find images over a long period of time. The Landsat 4 satellite was launched in 1982, and the Landsat 5 satellite was launched in 1984 (USGS 2003). Imagery from these satellites also has consistent resolution (30 meters) through time. The Thematic Mapper sensor receives 7 separate spectral bands. (USGS 2003)

GIS data useful for hydrologic terrain analysis in the Madre de Dios region are hard to find compared to the data that are available in the United States. One source of information, the SRTM Hydrosheds data, is based on the SRTM 90-meter DEM, but I wanted to use a higher resolution DEM for hydrologic terrain analysis. I used the ASTER GDEM 2 (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model Version 2), which is derived from the Terra Spacecraft and has a 1 arc-second by 1 arc-second resolution (30X30 meters at the equator). I downloaded this DEM from the NASA Reverb ECHO website (http://testbed.echo.nasa.gov/reverb/#utf8=%E2%9C%93&spatial_map=satellite&spatial_type=rectangle). Version 2, used in this project, was released in October 2011, and contains fewer errors compared with ASTER GDEM version 1.

In my search for data from the Peruvian government, I found a shapefile of the Peruvian watersheds from their Ministry of the Environment

(<http://geoservidor.minam.gob.pe/geoservidor/download.aspx>) to use in my project. However, I was unable to find good streamline data for the region from the Peruvian government.

Figure 1: Study Area. The specific area of interest is outlined in red.

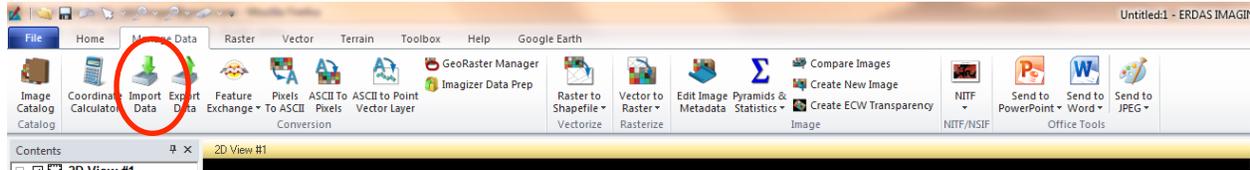


Assessment of Multi-temporal Satellite Imagery

To compare changes in mined areas, I downloaded dry season Landsat 4-5 TM images of my study area (path, row: 3, 69). I was able to obtain images relatively free from cloud cover from 12 July 1986, 23 July 1996, 6 July 2006, 13 September 2011. The rasters come as .tif files, with each spectral band as a separate file. The rasters are geo-referenced and projected into WGS1984 UTM Zone 19N (World Geodetic System 1984 Universal Transverse Mercator Zone 19N).

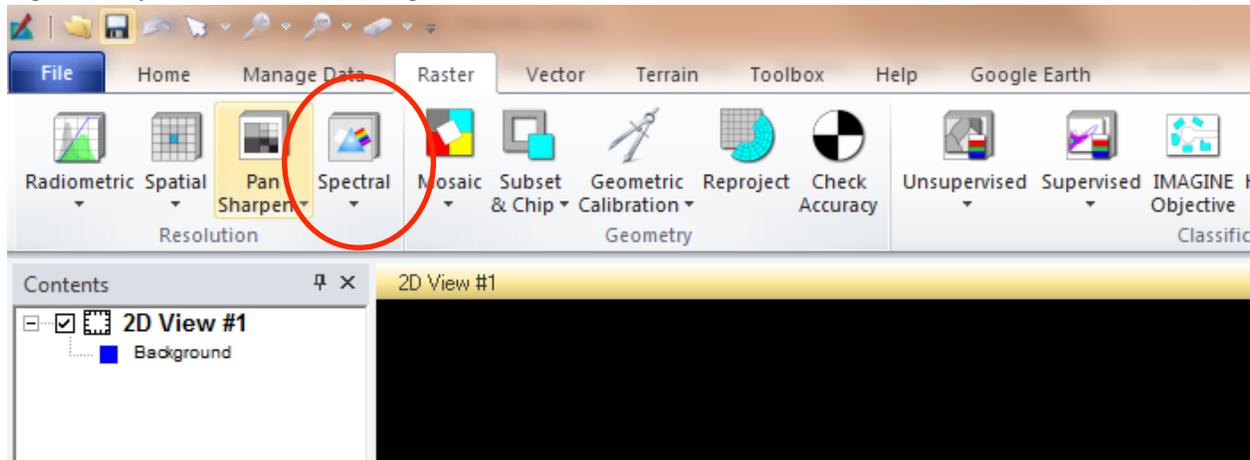
I used ERDAS Imagine software to stack the band layers into one file to view the imagery. To do this, I first converted the .tif files to .img (imagine) files by using the **Import Data** tool in Imagine (Figure 2).

Figure 2: Import Data in ERDAS Imagine



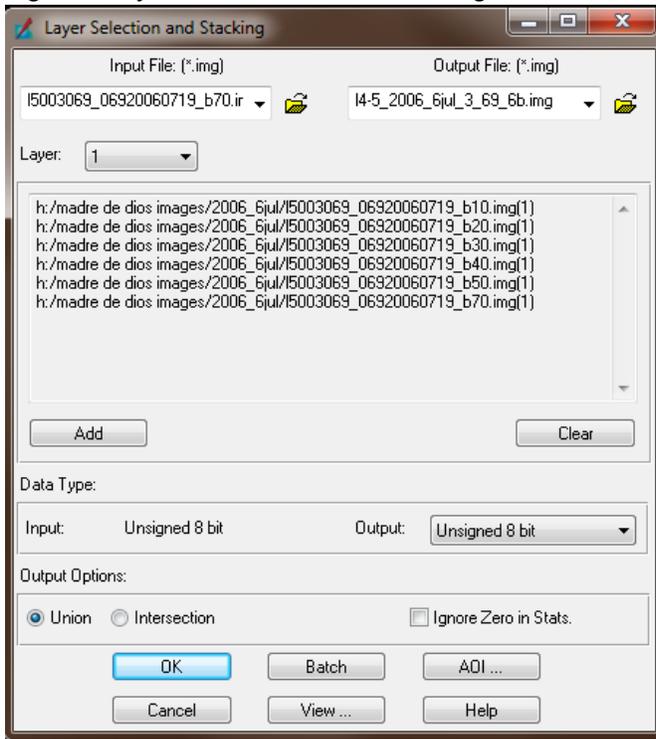
Then, to stack the layers, click on **Spectral** and then **Layer Stack** (Figure 3).

Figure 3: Layer Stack in ERDAS Imagine



I stacked bands 1-5 and 7 because they are at the same spatial resolution (30 meters). I did not include band 6 (thermal infrared) because it has a spatial resolution of 120 meters. It is important to stack the bands in order (1-5, 7) for future computations (e.g., computing NDVI) (Figure 4).

Figure 4: Layer Stack bands in ERDAS Imagine



After stacking the layers, the 4 Landsat images are ready to be viewed. I first projected the images using the ArcGIS **Project Raster** tool. I projected them into the WGS 1984 UTM Zone 18S (World Geodetic System 1984 Universal Transverse Mercator Zone 18S).

Figures 5-8 show the satellite imagery through time, displaying bands 5, 4, 3. The area outlined in red in each of the figures is a large mining area called Huapetuhe (Swenson et al 2011). I am now able to visually identify that the extent of mining has increased through time since 1986. In addition, I am able to visually determine that the fluvial geomorphology of the Puquiri River has changed since 1986 (e.g., the channel has become wider and there is a greater amount of sedimentation).

Figure 5: 12 July 1986 satellite image

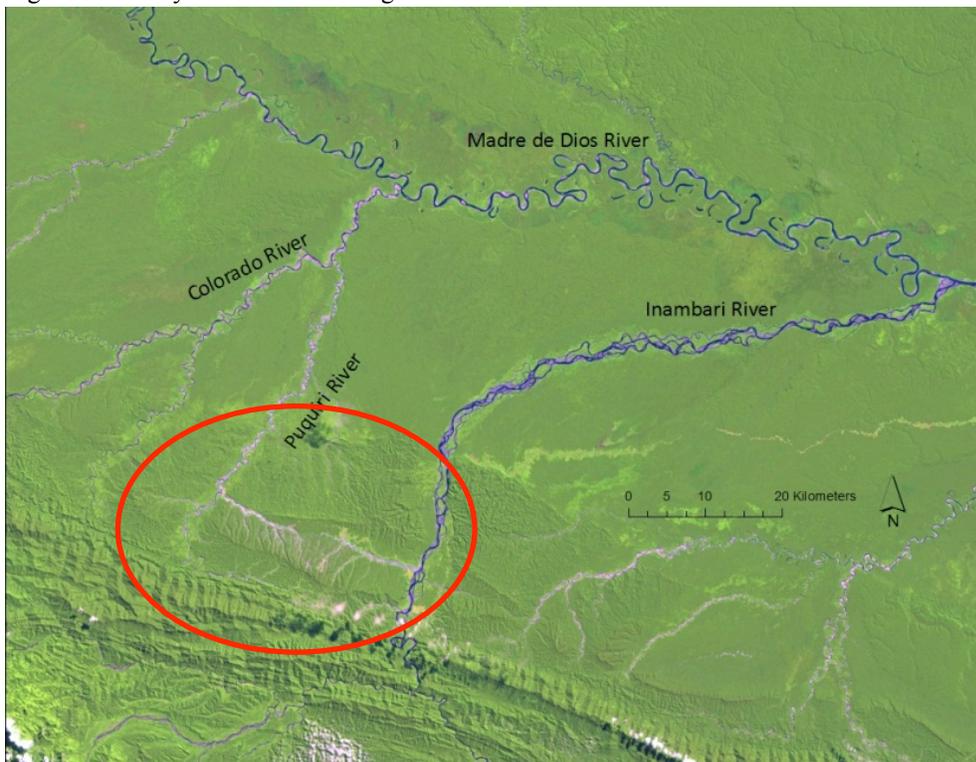


Figure 6: 23 July 1996 satellite image

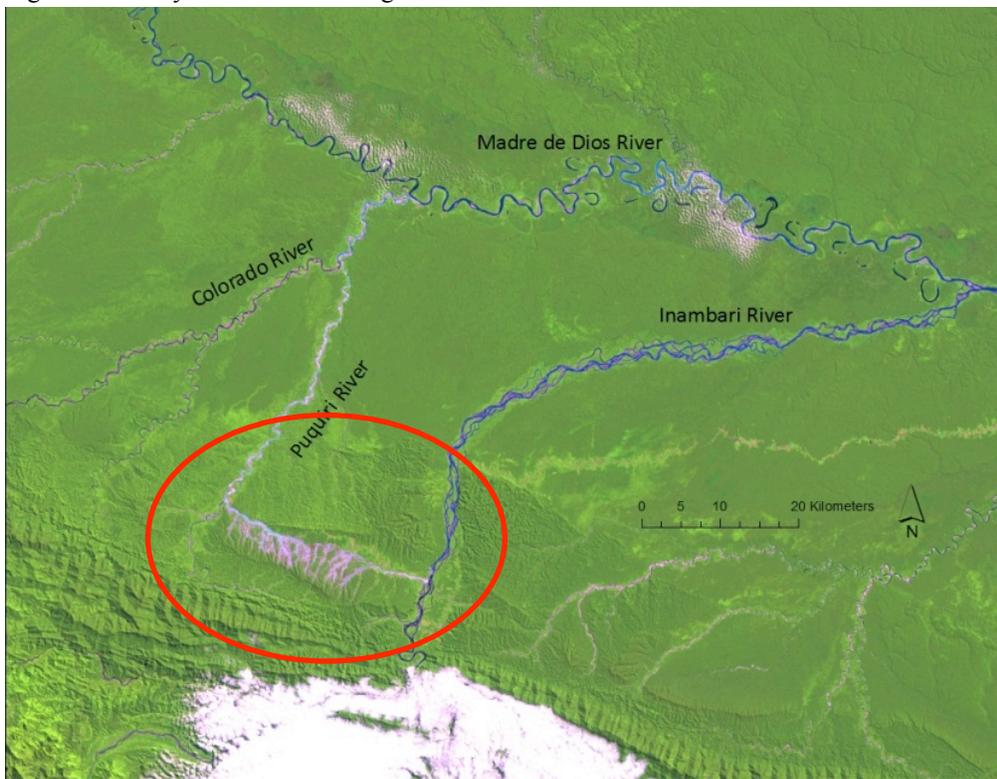


Figure 7: 6 July 2006 satellite image

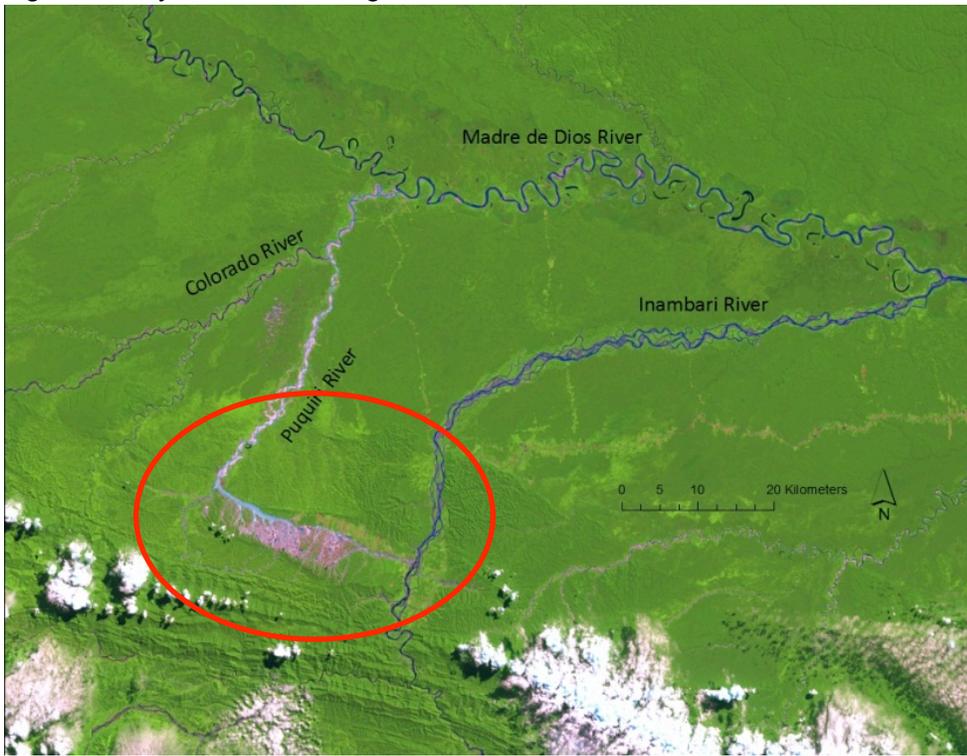
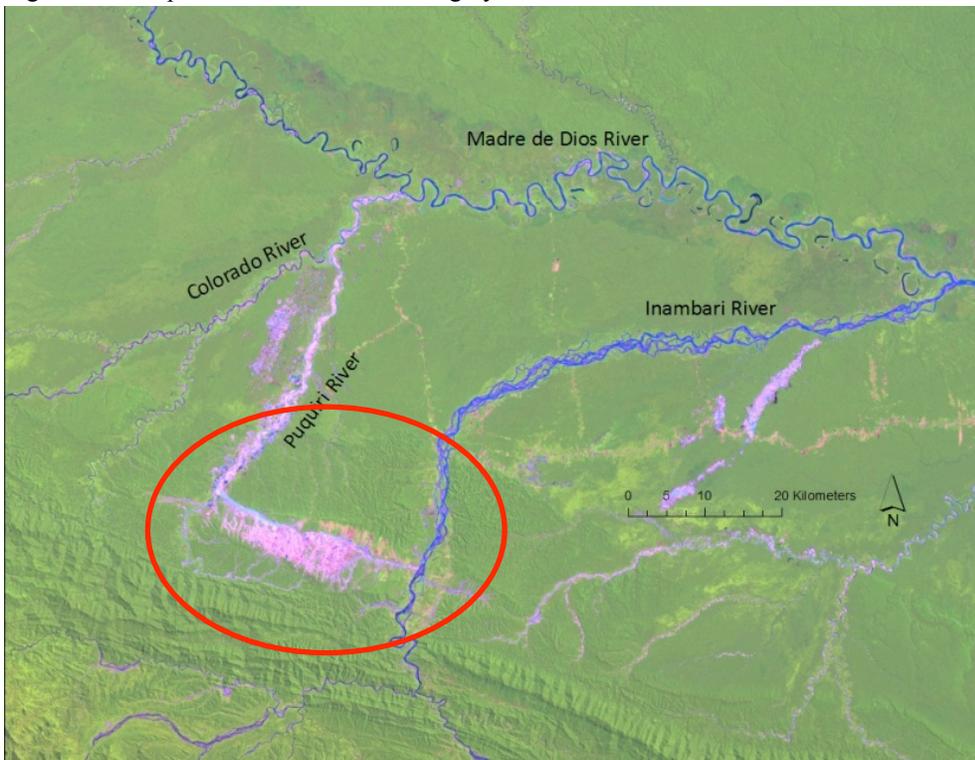


Figure 8: 13 September 2011 satellite imagery



Hydrologic Terrain Analysis using ASTER GDEM

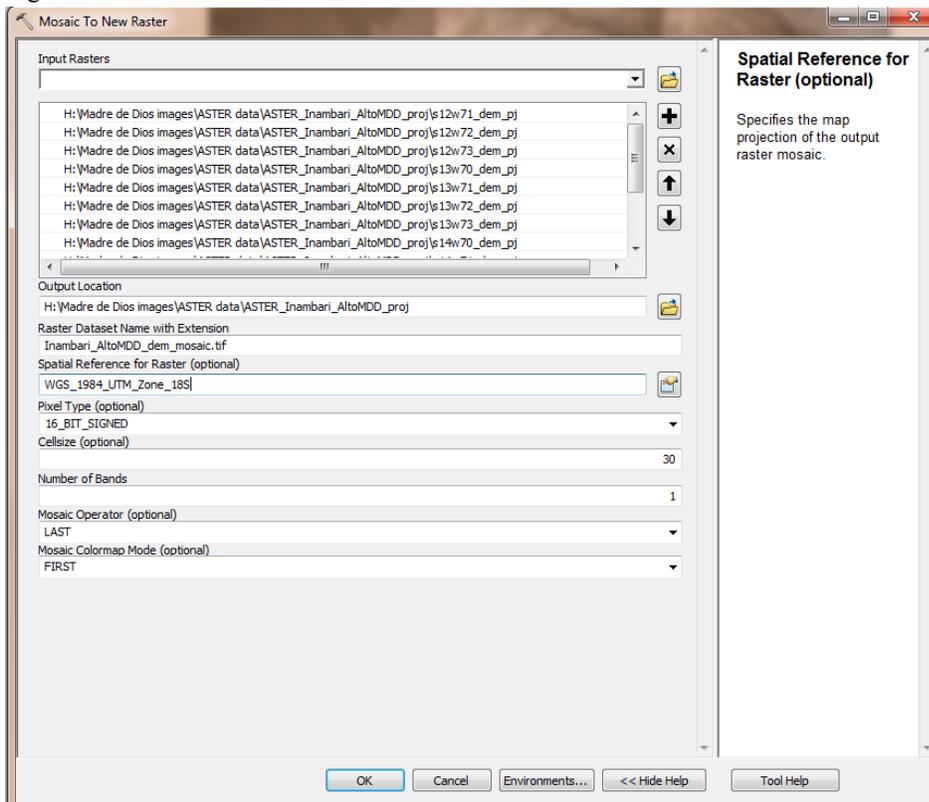
My study area of interest spans two larger watersheds, the Inambari watershed and the Alto Madre de Dios watershed. Because of this, I will conduct hydrologic terrain analysis for both large watersheds.

Data Setup

The ASTER GDEM comes as 1° by 1° tiles, thus I downloaded all the tiles that contain at least part of the Inambari and Alto Madre de Dios watersheds (14 tiles). The DEM is not projected, but it is referenced to WGS 1984. In ArcGIS, my first step was to project each of the 14 tiles into WGS 1984 UTM Zone 18S using the **Project Raster** tool. Using the tool, I set the output cell size as 30 meters and used the bilinear resampling technique.

All 14 of the raster datasets are separated, so I need to mosaic them together to form one raster dataset using the **Mosaic to New Raster** tool (Figure 9). Because the raster datasets have a 16-bit signed pixel type, in the **Mosaic to New Raster** tool I set the pixel type to 16_Bit_Signed. I also set the file extension as a .tif, the cell size as 30, and the number of bands as 1.

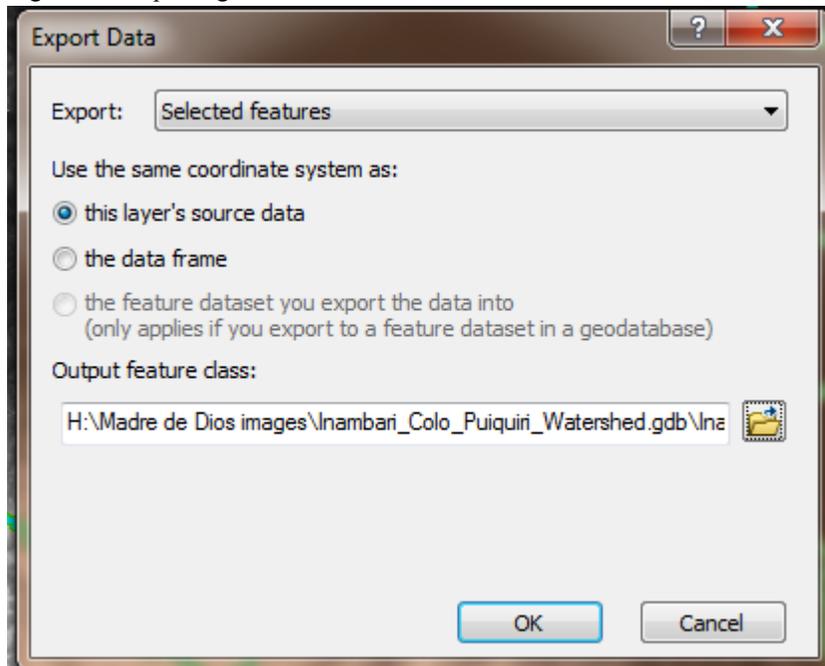
Figure 9: The Mosaic to New Raster Tool in ArcGIS



To speed up processing time because the area is large, I used the shapefile of watersheds from the Peruvian Ministry of the Environment to extract the portion of the DEM that was of interest. The Peruvian watersheds shapefile was already projected into WGS 1984 UTM Zone 18S.

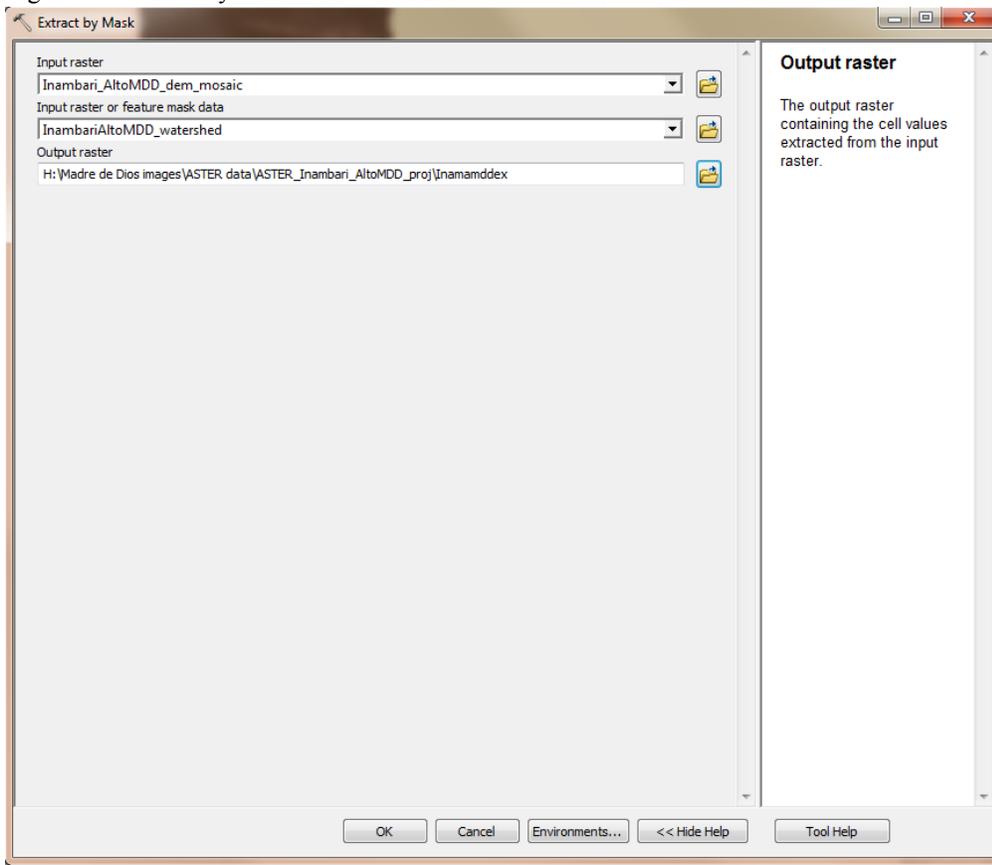
I first selected the Alto Madre de Dios watershed and the Inambari watershed from the attribute table of watersheds shapefile. Then, I right-clicked on the watersheds shapefile in the Table of Contents in ArcGIS and selected **Data/Export Data** to produce a new theme (Figure 10).

Figure 10: Exporting data to create a new theme in ArcGIS



The result was a shapefile of only the Inambari and Alto Madre de Dios watersheds, and I used this shapefile to extract the areas of the DEM that are inside the watersheds. To do this I used the **Extract by Mask** tool (Figure 11).

Figure 11: Extract by Mask tool in ArcGIS



The result is a DEM of the Inambari and Madre de Dios watersheds (Figure 12).

Figure 12: DEM of Inambari and Madre de Dios watersheds



Steps for Hydrologic Terrain Analysis

Hydrologic terrain analysis was then conducted. I did not recondition the DEM with vector stream data, because I did not have reliable stream line data. I did not use the Hydroshed stream information because it was derived from a 90 meter DEM.

I followed the Terrain Flow Information Model presented by Dr. Tarborton in lecture on 22 September. The 5 steps include:

1. Pit removal
2. Flow direction field derivation
3. Flow Accumulation
4. Channels and watersheds
5. Raster to Vector Connection

A pit in a DEM is one or more cells that have no downstream cells around. These pits need to be filled so that the pits do not isolate portions of the watershed and block the drainage flow. To fill the pits in the DEM so that the watershed, I used the **Fill** tool in the Hydrology toolset.

I then used the **Flow Direction** tool to calculate the flow direction for each cell (Figure 13).

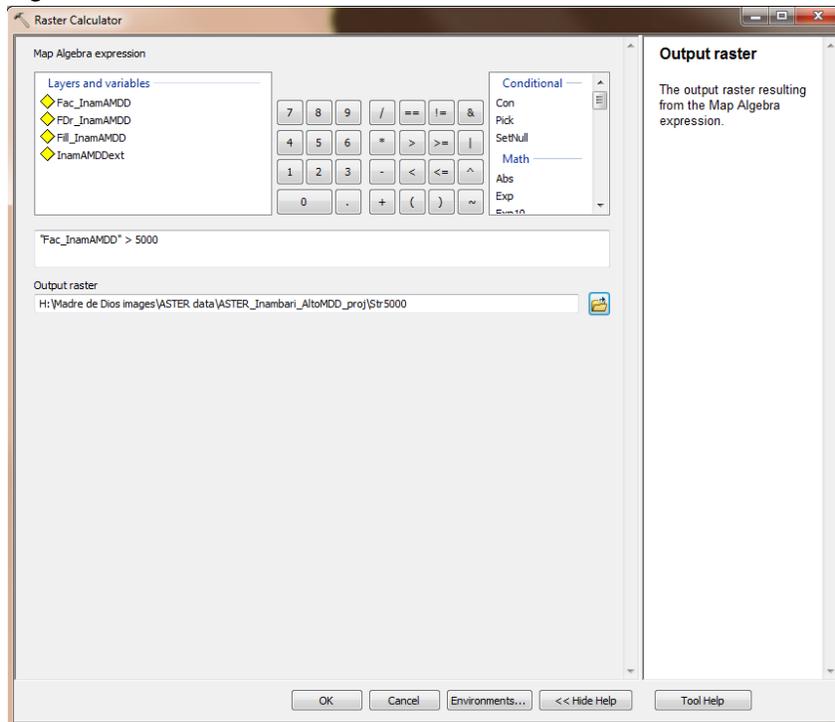
Figure 13: Flow Direction for Inambari and Alto Madre de Dios Watersheds



Using the **Flow Accumulation** tool (and using the flow direction raster as the input raster), I created flow accumulation raster. For each cell, this tool computes how many cells flow into it.

I used the flow accumulation raster to define the streams in the watersheds with the **Raster Calculator**, setting a threshold of 5000 cells to define the streams (Figure 14). I also defined the streams with a threshold of 4000 cells, but it seemed like the 5000-cell threshold worked the best for the landscape.

Figure 14: Raster Calculator used to define streams



The **Stream Links** tool was used to create a raster in which each stream segment has its own identifier. With the stream links raster, the **Watershed** tool delineated the catchments upstream of each stream link (Figures 15 and 16).

Figure 15: Watershed tool used to delineate catchments

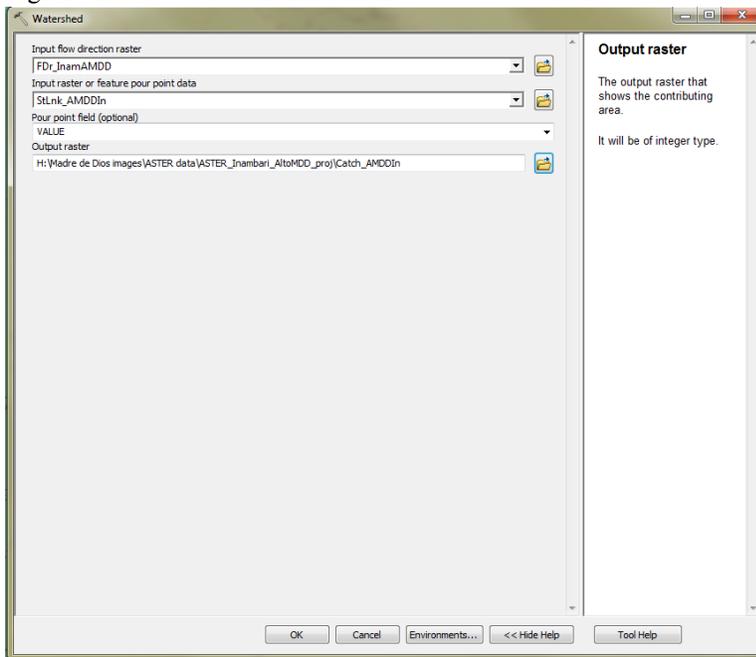
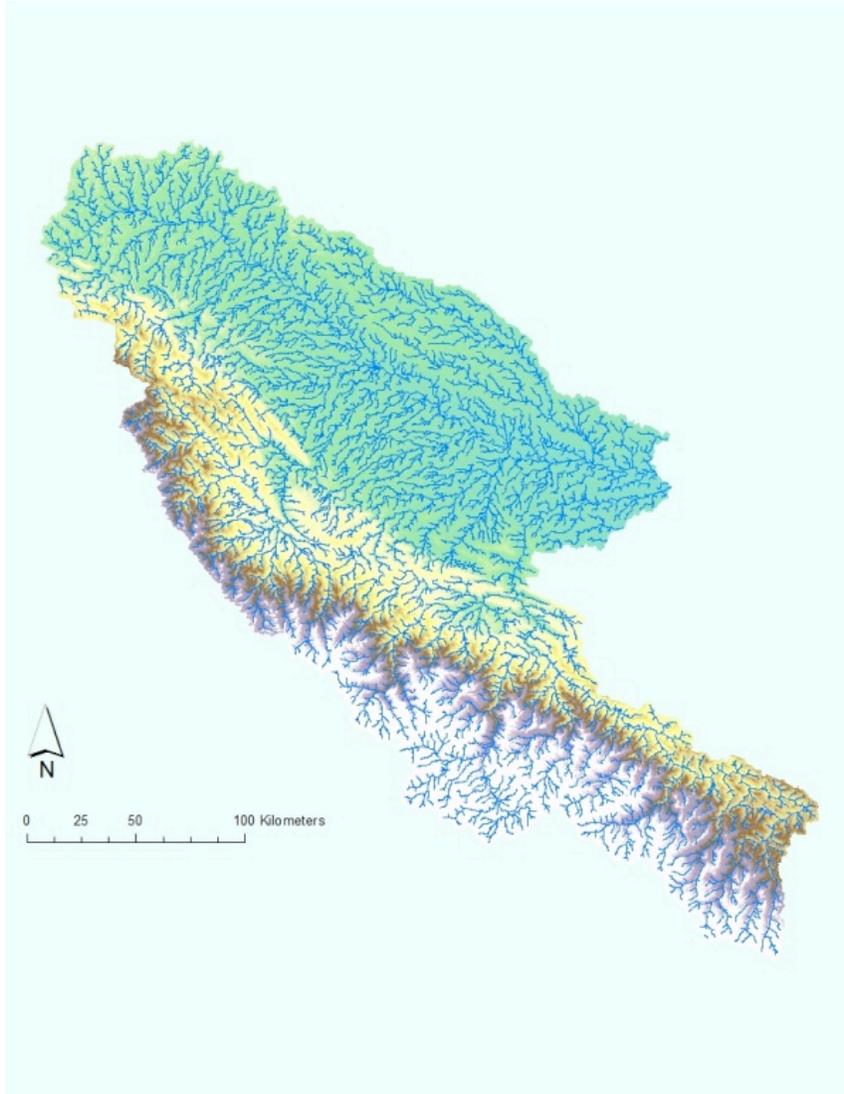


Figure 16: Raster of catchments symbolized with unique colors



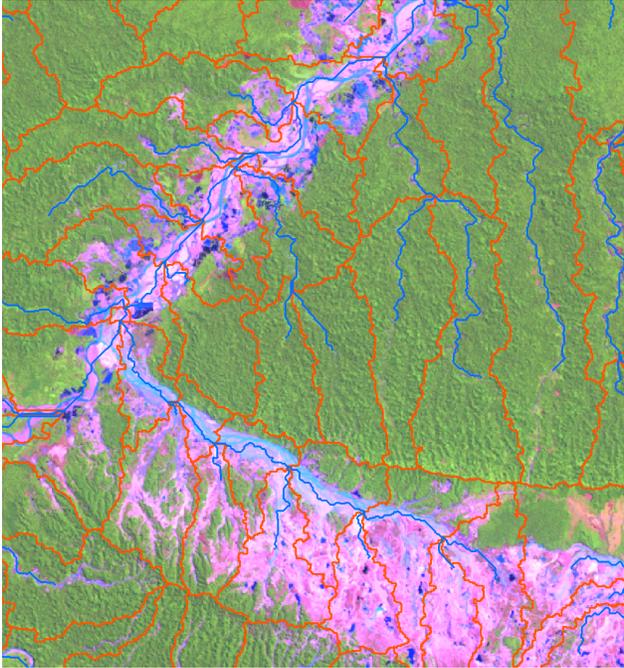
Using the **Stream to Feature** tool, I converted the raster streams to vector data. The result was a map of the drainage lines in the Inambari and Alto Madre de Dios watersheds (Figure 17).

Figure 17: Drainage lines in the Inambari and Alto Madre de Dios watersheds



I also converted the catchments raster to polygons with the **Raster to Polygon** tool. This will be helpful when analyzing which mined areas flow to each stream segment. For example, Figure 18 is a satellite image (Landsat 4-5 TM from 13 September 2011) of a mined area with the drainage lines and catchment polygons.

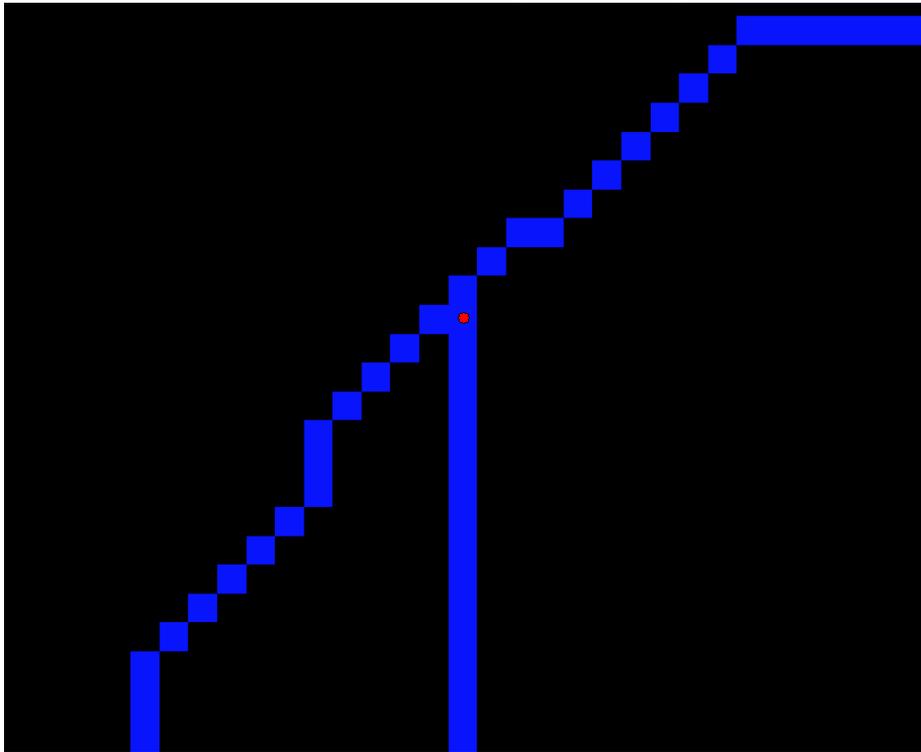
Figure 18: Satellite image (bands 5, 4, 3) showing mined areas, drainage lines, and catchments



Delineating the Puquiri subwatershed within the Alto Madre de Dios watershed

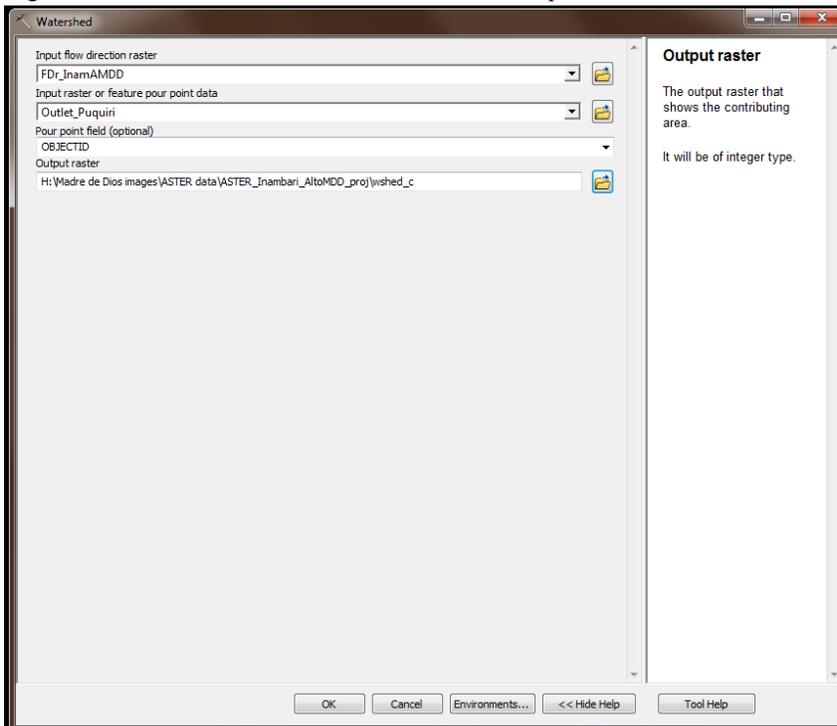
In small Puquiri subwatershed, mining activities have greatly increased since the mid-1980s. I delineated this subwatershed to determine its area and its characteristics. To do this, I created an outlet point as a new feature class. In ArcCatalog, I right-clicked on the location that I wanted to store the feature class and selected **New—Feature Class**. I then followed the prompts to create a new point feature class. As described in Exercise 4, I used the editor tool bar to edit the outlet point feature class. I clicked on the cell that leaves the Puquiri River where it flows into the Colorado River (Figure 19).

Figure 19: New outlet feature class at the outlet point of the Puquiri River



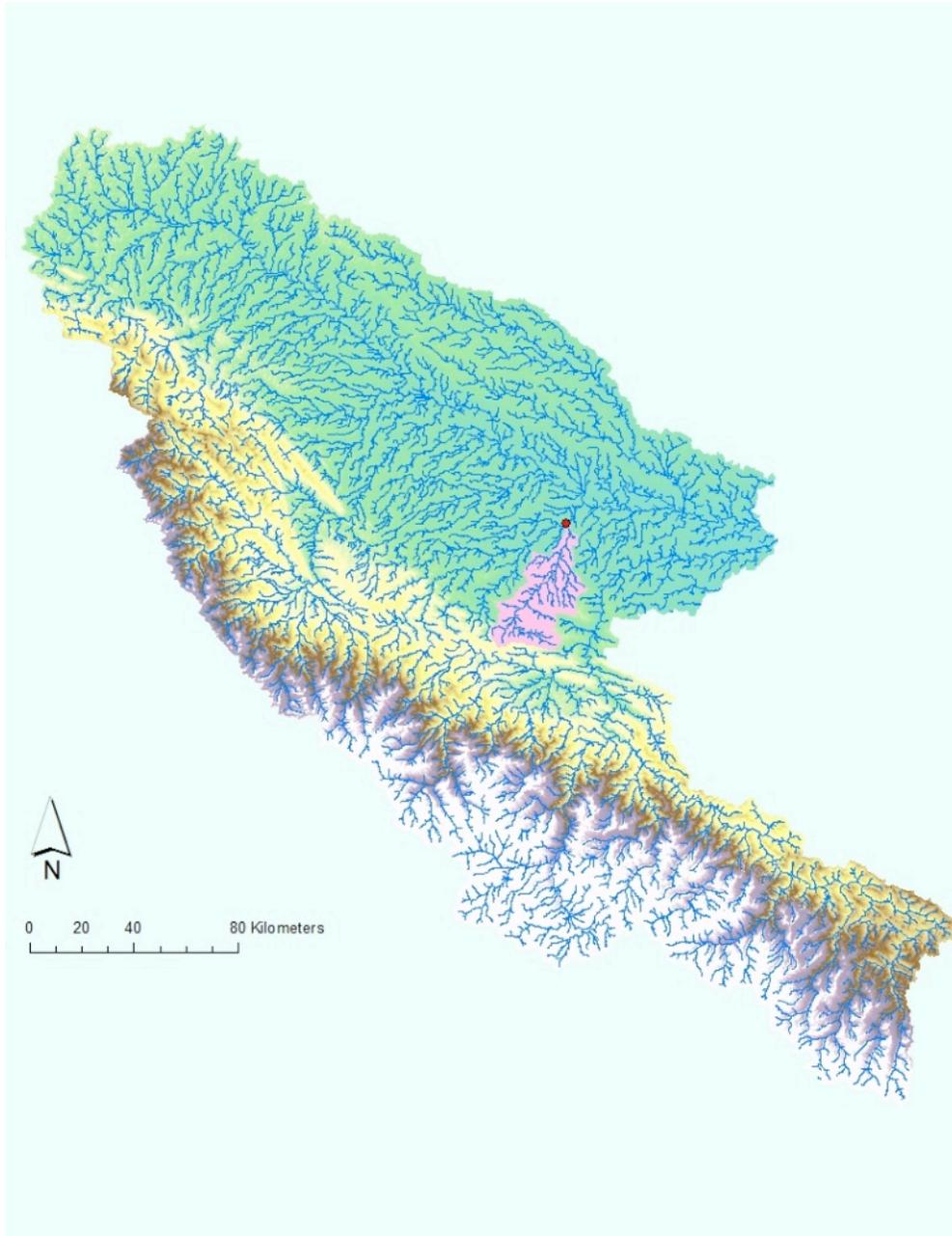
To delineate the subwatershed, I used the **Watershed** tool (Figure 20).

Figure 20: Watershed tool used to delineate the Puquiri subwatershed



This created a raster in which all the values upstream of my outlet point are one, with the other cells having zero values. In Figure 21, the pink area upstream of the outlet point (in red) is the Puquiri subwatershed.

Figure 21: The Puquiri subwatershed in pink below.



Calculating the areas of watersheds and subwatersheds

Through my analysis, I calculated the areas of the Inambari watershed, the Alto Madre de Dios watershed, and the Puquiri subwatershed (Table 1).

Table 1: Area of watersheds in study

| Watershed | Area (km²) |
|---------------------|------------------------------|
| Inambari | 19,837.9 |
| Alto Madred de Dios | 34,760.1 |
| Puquiri | 896.3 |

Future Work and Conclusion

In the future, I will continue to analyze the satellite imagery through time and the elevation data for my study area. I will eventually create geomorphologic maps, identifying geomorphologic units and landforms. Through this term project, I have gathered available information about my study area and characterized some of its physical characteristics.

References

- Álvarez, J., V. Sotero, A.B. Egg, & C.A. Ipenza Peralta. 2011. *Minería aurífera en Madre de Dios y contaminación con mercurio: Una bomba de tiempo*. Peruvian Amazon Research Institute (IIAP) and Peruvian Ministry of the Environment Report. Lima, Peru (in Spanish).
- James, A. 1999. Time and the persistence of alluvium: River engineering, fluvial geomorphology, and mining sediment in California. *Geomorphology* 31: 265-290.
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- Swenson, J.J., C.E. Carter, J. Domec, & C.I. Delgado. 2011. Gold Mining in the Peruvian Amazon: Global Prices, Deforestation, and Mercury Imports. *PLoS ONE* 6: e18875.
- United States Geological Survey (USGS). 2003. *Landsat: A Global Land-Observing Program Fact Sheet 023-03*. Accessed on November 20, 2011 at <http://egsc.usgs.gov/isb/pubs/factsheets/fs02303.html>.