Fall 2012
GIS in Water Resources
Section 1

Term Project:
Delineation of Subglacial Water Catchments of Antarctica

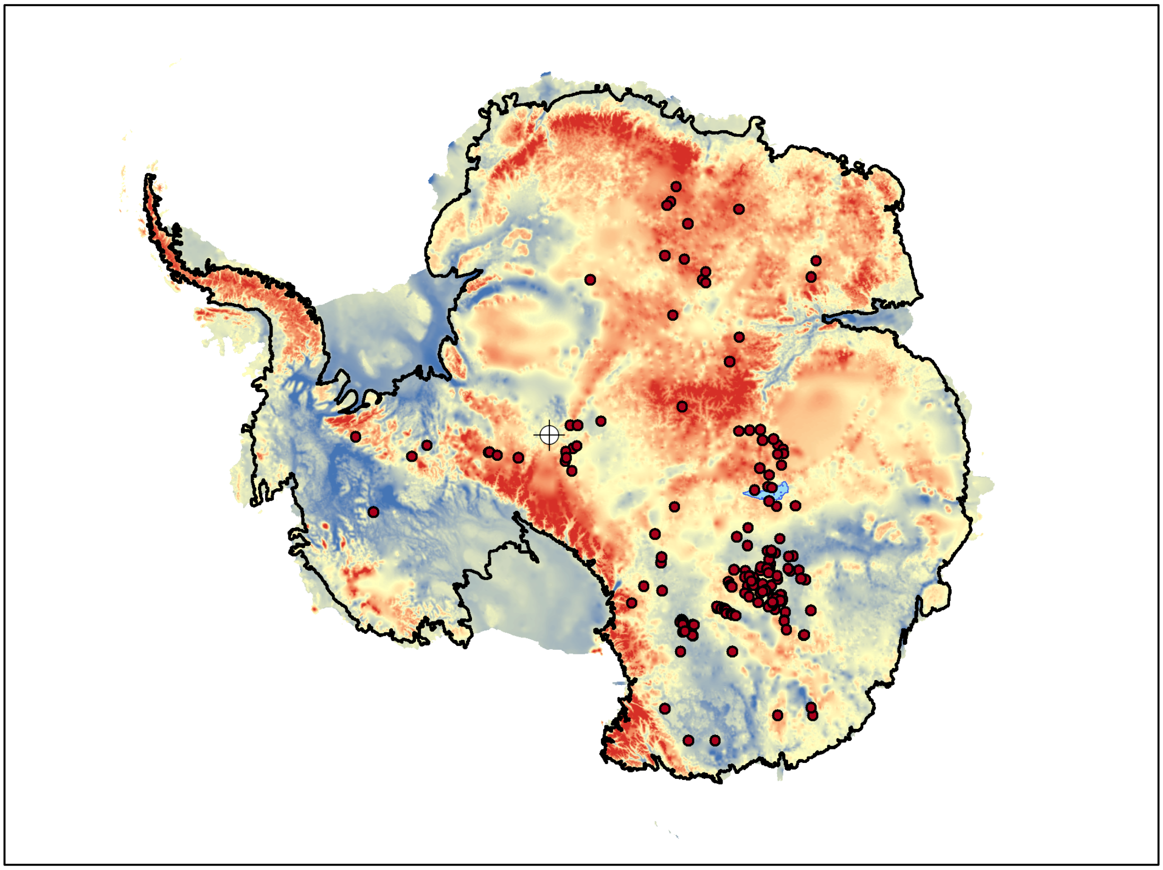

Figure caption: Map of subglacial bed elevation of Antarctica with associated current inventory of subglacial lake locations and grounded ice line (Siegert et al., 2005). Location of South Pole indicated by crosshair. Grounding line data from Scambos et al., 2007.

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Statement of Purpose and Intended Project Goals

As a graduate student studying subglacial water dynamics in Antarctica, I would like to create a database of reference for sub- ice sheet water catchment basins and potential flow paths. My principle area of research is in the study of water that is generated at the base of the ice sheet but usually requires more general knowledge of the overlying ice geography. Having better maps of prominent features across the entire continent would help as office wall print outs, as well as, specific maps of ice and water routing. The main result of this project will be a better understanding of the distribution of potential water networks underneath the continental ice sheet in Antarctica and how they are related to their associated, overlying ice catchments.

This ArcGIS database created by this project would ideally have a generic map of water flow paths based on a modified hydropotential with pressure assumptions stemming from the overlying ice. The maps that would come out of this project would contain various layers (previously mentioned) of water catchments, a map of potential subglacial water flow paths, and a map of subglacial topographic features. All of these data sets could be better visualized if I were to have all of these in a GIS database.

The data used could be from any published data currently available on the Internet. NASA, USGS, the British Antarctic Survey, and others have a great deal of data that are in GIS-ready formats and are available for download on their respective websites. I plan to use the recent BEDMAP2 data (Oct. 2012 release) for this project (Fretwell et al., 2012) because it is the latest and most useful.

Introduction

Understanding of how the Antarctic ice sheet is rapidly changing is of critical importance to society. It has been shown that there is a correlation to the dynamic nature of ice and the presence of water underneath them (Sterns et al., 2008). This presence of water is also very dynamic itself and has been linked to ice sheet surface movement (Fricker et al., 2007). Being able to trace potential flow routing of the subglacial water is immensely useful in predicting ice sheet behavior. While there have been previous attempts to look at the potential preferential flow paths of subglacial water (e.g. Wright et al., 2012), these studies utilized older data and may have been biased incorrectly because of it. This project attempts to start a similar analysis (using the latest data release) but with an explicit, repeatable methodology for others to follow.

Description of Data Sources and Usage

The data obtained for this project are from the latest (October 2012 release) and most anticipated data in Antarctic geographic science, BEDMAP2 published by Fretwell and other in 2012 (http://www.antarctica.ac.uk/bas_research/our_research/az/bedmap2/index.php). The data can be downloaded from a link that can be found from the original publication (*www.the-cryosphere-discuss.net/6/4305/2012/tcd-6-4305-2012.pdf*) into TIF image files and then imported into ArcGIS (see results below). The three different data sets are 1.) a surface elevation map (Figure 2), 2.) a bed elevation map

(Figure 3), and 3.) an ice sheet thickness map (Figure 4). All data are in the WGS84 Polar Stereo Projection. The hope for this work is to take just the data within the coastline to work with because I do not want to work with sub-ice ocean water. After cutting out excess continental shelf data, maps of water pressure potential will be produced. The water pressure potential is a map of areas of where the ice sheet's mass pressurizes water that lies below it. The pressure potential maps will be generated via a methodology assuming that water pressure equals the overburden pressure (Carter et. al., 2009). Given this pressure map, a map of hydraulic head can be created in ArcGIS. Finally, the map of hydraulic head can be used to do basin drainage analysis as done in the "Watershed and stream network delineation" exercise for the CE 394K.3 GIS in Water Resources course.

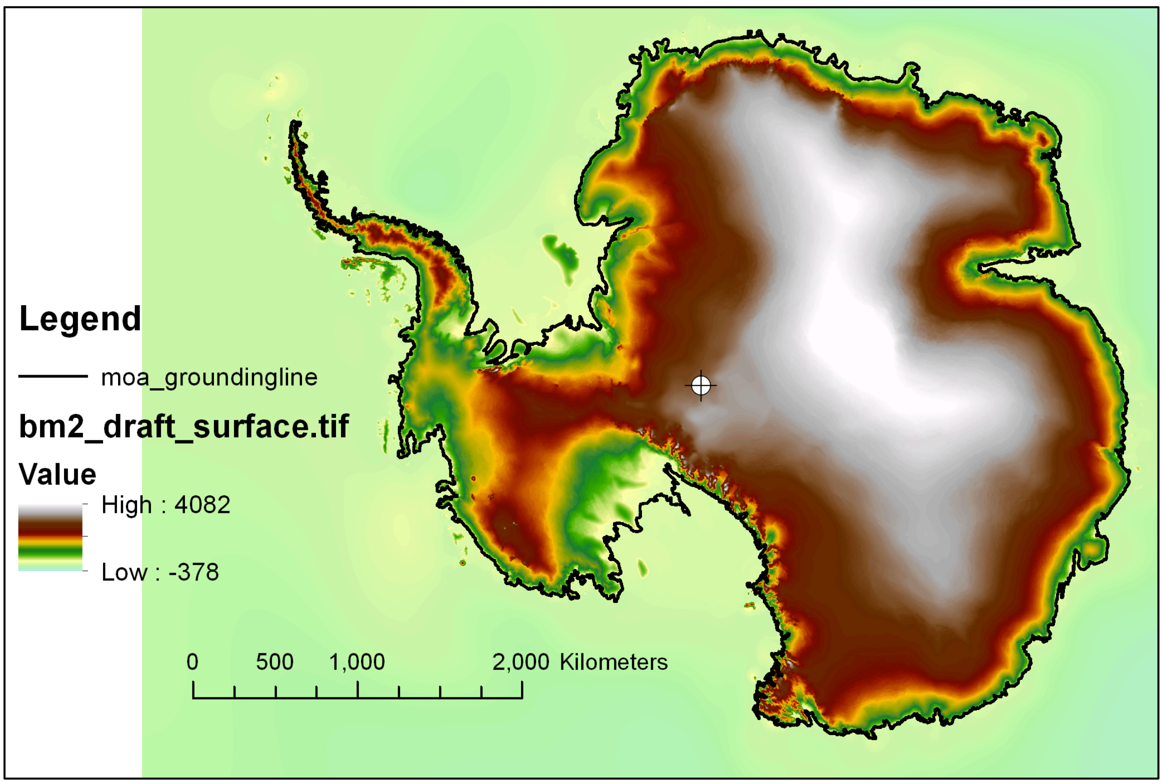


Figure 2. BEDMAP2 Surface topography (expressed in meters). NASA MODIS-derived ice sheet grounding line is shown. Modelbuilder step details are shown in box above. Location of South Pole indicated by crosshair.

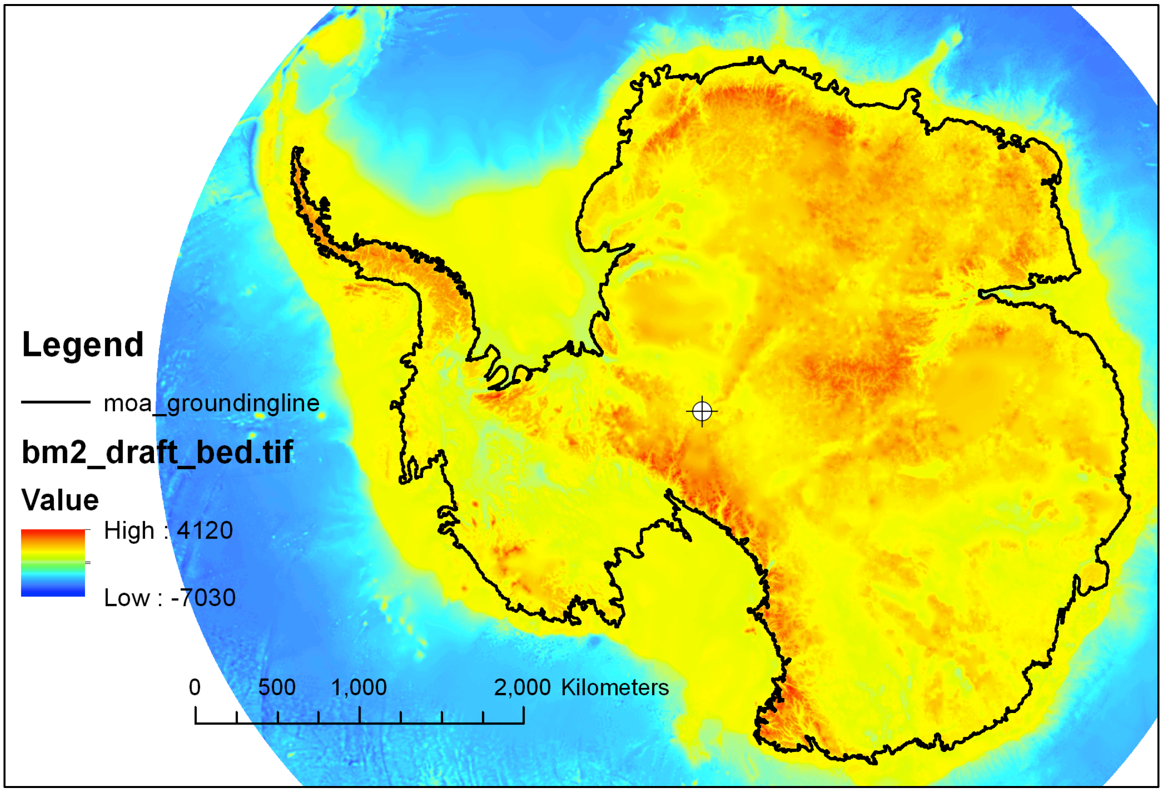


Figure 3. BEDMAP2 Bed topography (expressed in meters). NASA MODIS-derived ice sheet grounding line is shown. Modelbuilder step details are shown in box above. Location of South Pole indicated by crosshair.

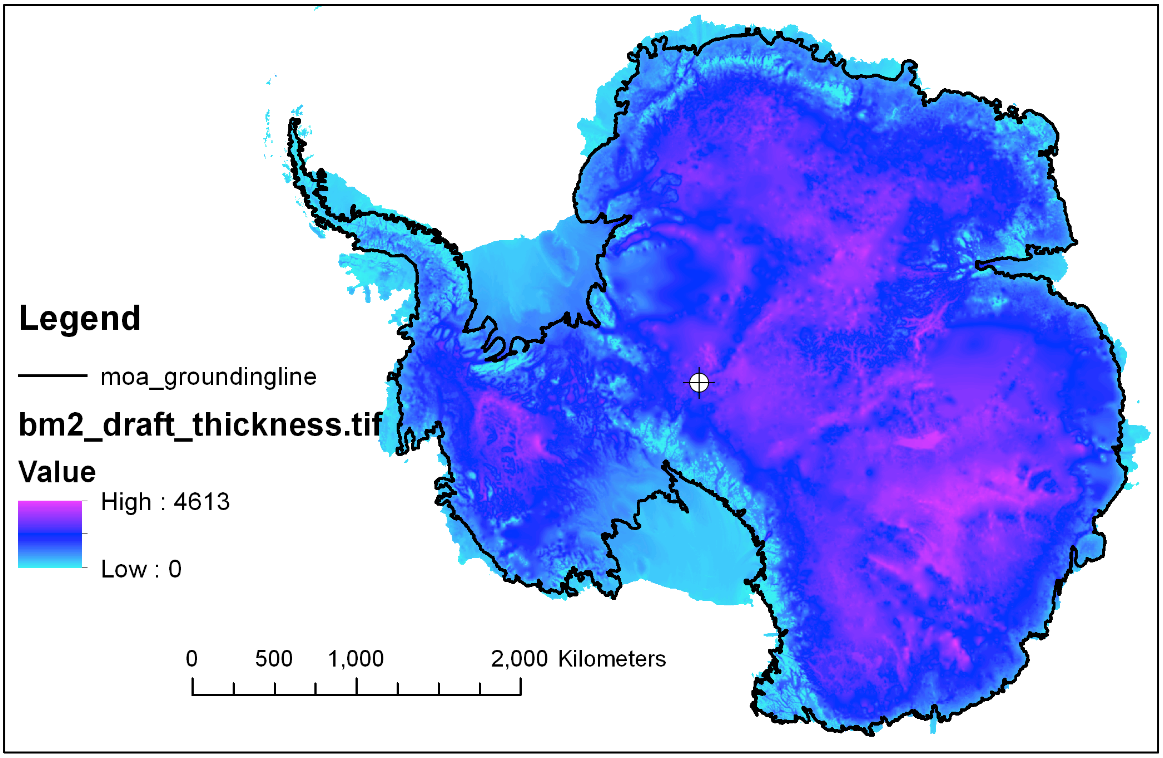


Figure 4. BEDMAP2 ice sheet thickness (expressed in meters). NASA MODIS-derived ice sheet grounding line is shown. Modelbuilder step details are shown in box above. Location of South Pole indicated by crosshair.

Overview of process for generating results for this project

In order to design a repeatable processing flow for this study a new tool was created using the ModelBuilder in ArcGIS. One model takes a topographic surface map and calculates the pressure potential and hydraulic head (the elevation above a given datum to which pressurized water would rise) based on a modified Shreve water pressure potential (seen below as Eq. 1; Shreve, 1972).

(1) P = (rho_i * g * z) + (rho_w * g * b)

(2) H = P / (rho_w * g)

Where P is the water pressure potential, H is the hydraulic head, g is the gravitational acceleration, rho_i and rho_w are respectively the densities of pure ice and fresh water, z is the ice thickness, and b is the bed elevation. This formulation assumes for sake of simplification that water pressure equals the ice overburden pressure. The ArcGIS ModelBuilder flow chart of this work is in Figure 5A. The other model calculates stream networks and watershed basin delineations based on either the result of the previous model (hydraulic head) or any another other elevation map. The ArcGIS ModelBuilder flow chart of this work is in Figure 5B. The specifics of each of the computational steps in ArcGIS are listed in the following sections.

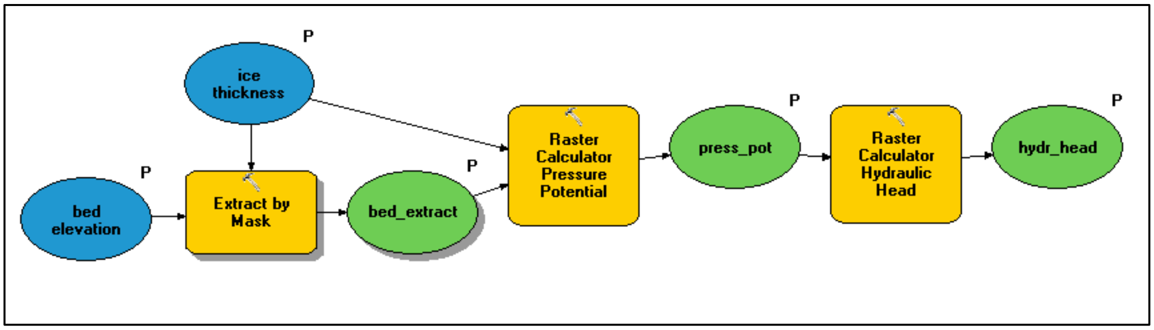


Figure 5A. ArcGIS Modelbuilder flow chart for calculating hydraulic head.

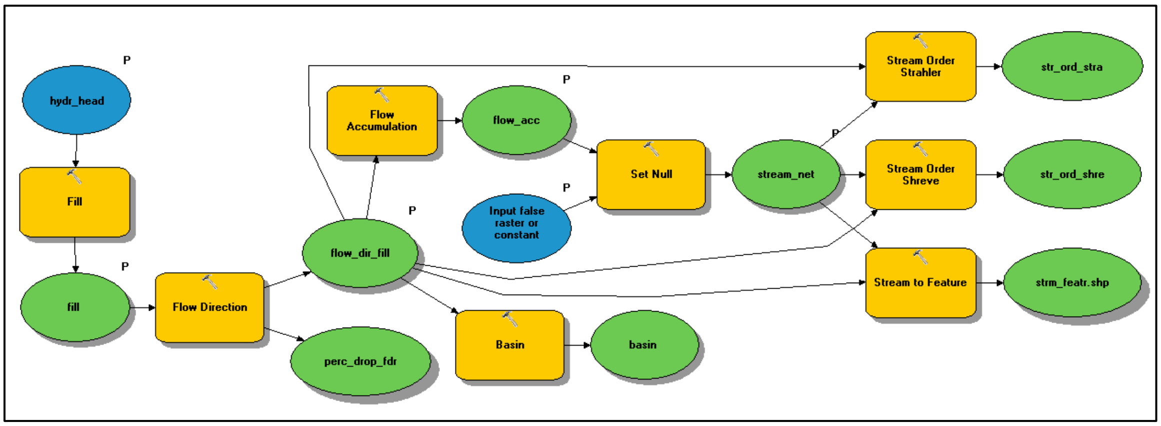


Figure 5B. ArcGIS Modelbuilder flow chart for delineating streams and basins given hydraulic head (or any topographic elevation raster).

Procedural Workflow Details:

Extract data for watershed delineation

Because each of the input datasets contain different margin lengths, it is necessary to extract only the data needed for this modeling. Specifically, the surface topography and bed elevation data contain values that exceed the coasts of Antarctica by a great distance, any distance of which is unnecessary for modeling preferential subglacial water flow paths. The Extract by Mask tool in ArcGIS was used to cut out only the bed elevation data that lies within the ice sheet thickness raster. The result of this can be seen in Figure 6.

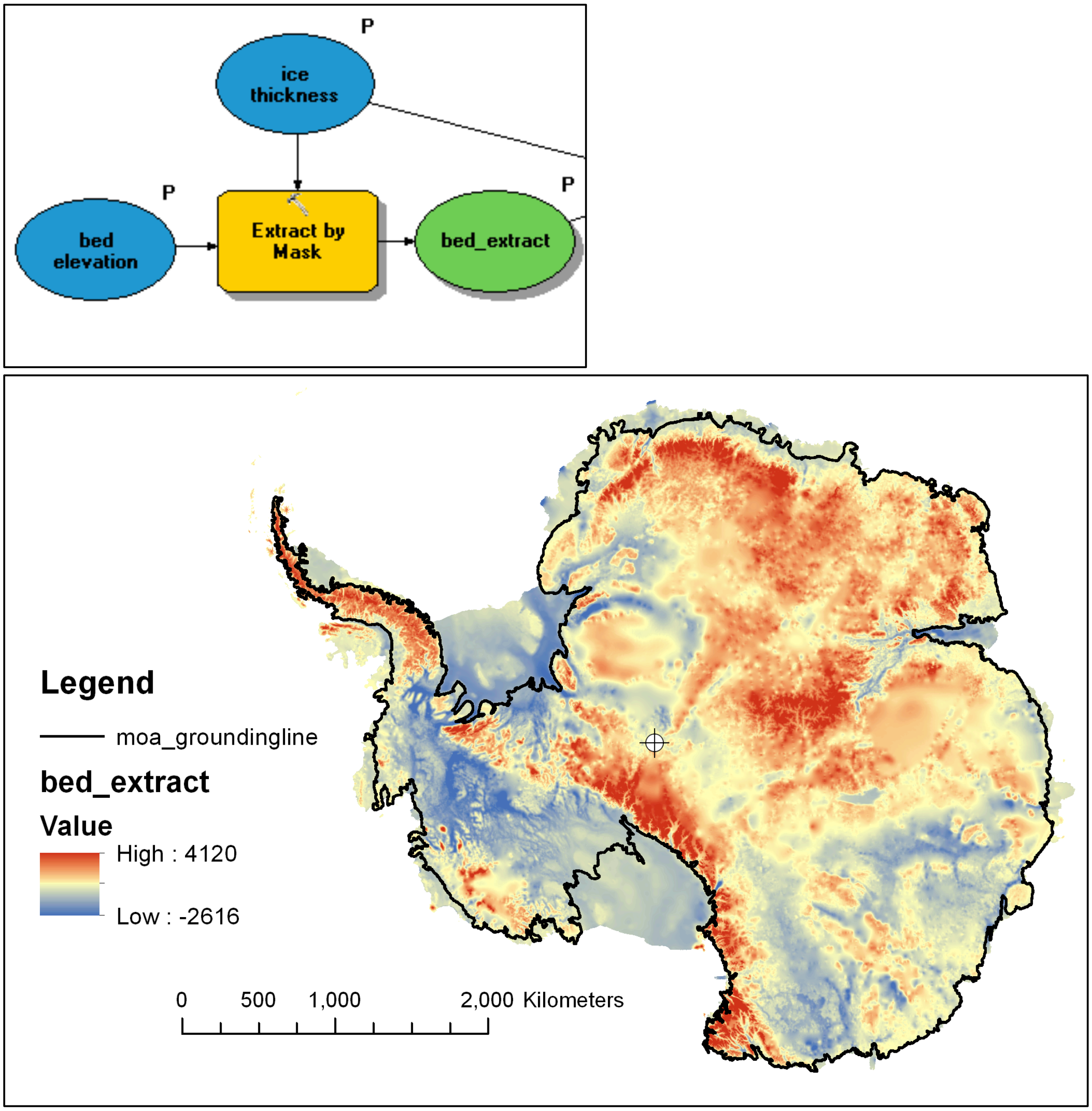


Figure 6. Extracted bed topography (expressed in meters). NASA MODIS-derived ice sheet grounding line is shown. Modelbuilder step details are shown in box above. Location of South Pole indicated by crosshair.

Calculate pressure potential and hydraulic head

If using a hydraulic head elevation map as opposed to an elevation map containing bed topography, the next step is to calculate Equation 1 given the extracted bed topography (output from the previous step) and ice thickness rasters as inputs. The resulting water pressure potential map can be seen in Figure 7. The second part of this is to take the water pressure potential output and input into Equation 2 to get out the hydraulic head elevation map (see Figure 8 for result). Both of these operations use the ArcGIS Raster Calculator to perform the calculations for both Equations 1 and 2.

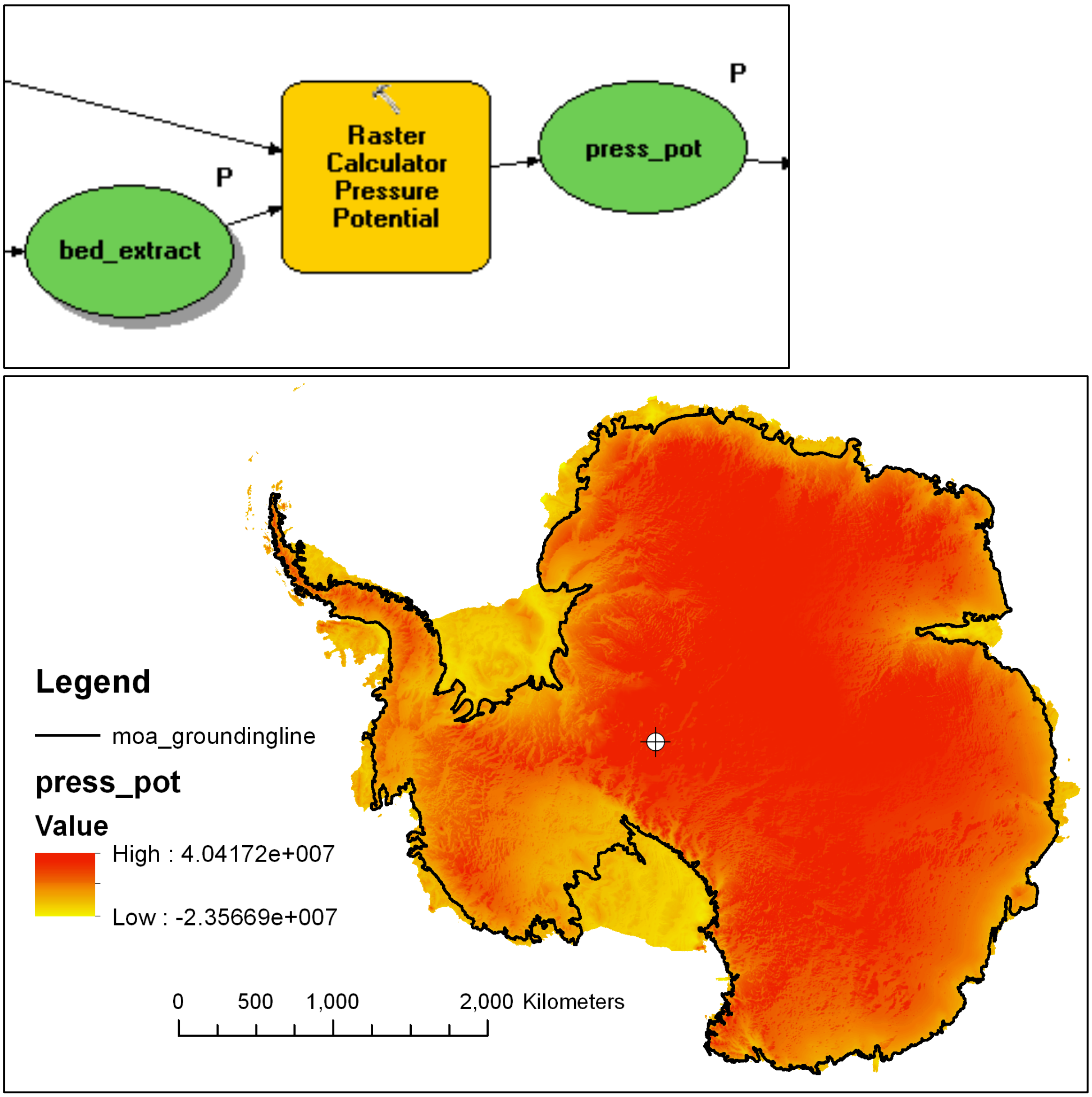


Figure 7. Potential water pressure (expressed in Pascals). NASA MODIS-derived ice sheet grounding line is shown. Modelbuilder step details are shown in box above. Location of South Pole indicated by crosshair.

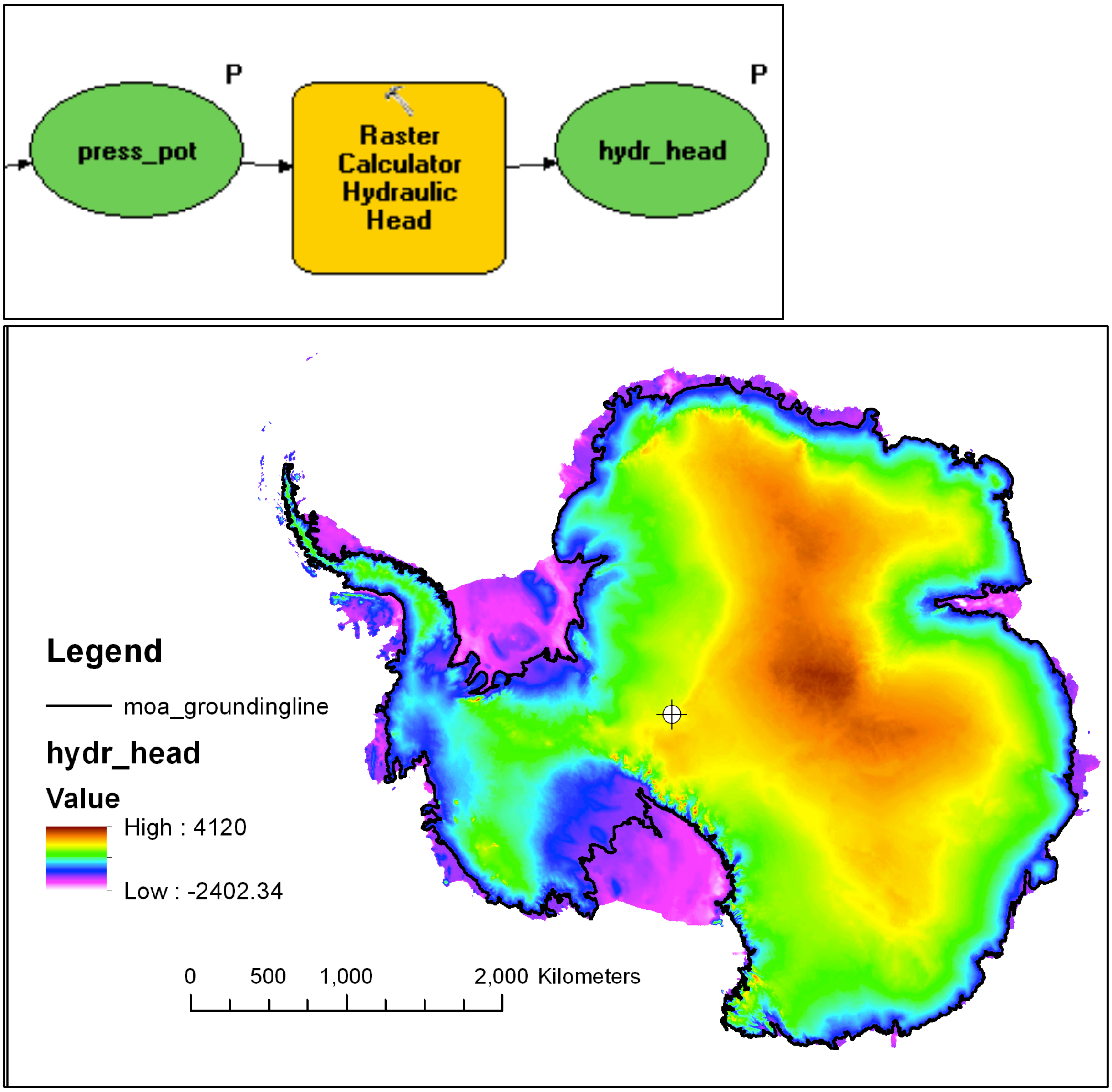
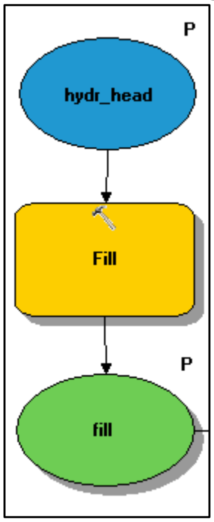


Figure 8. Hydraulic head (expressed in meters). NASA MODIS-derived ice sheet grounding line is shown. Modelbuilder step details are shown in box above. Location of South Pole indicated by crosshair.

Fill sinks

In order for ArcGIS's flow direction and accumulation algorithms to function properly, there must be no sinks present. This is so that water can route out of the domain from all points, otherwise there would be ponding. Using the ArcGIS Fill tool, a raster map of hydraulic head elevation is produced. The resulting output can be viewed in Figure 9.



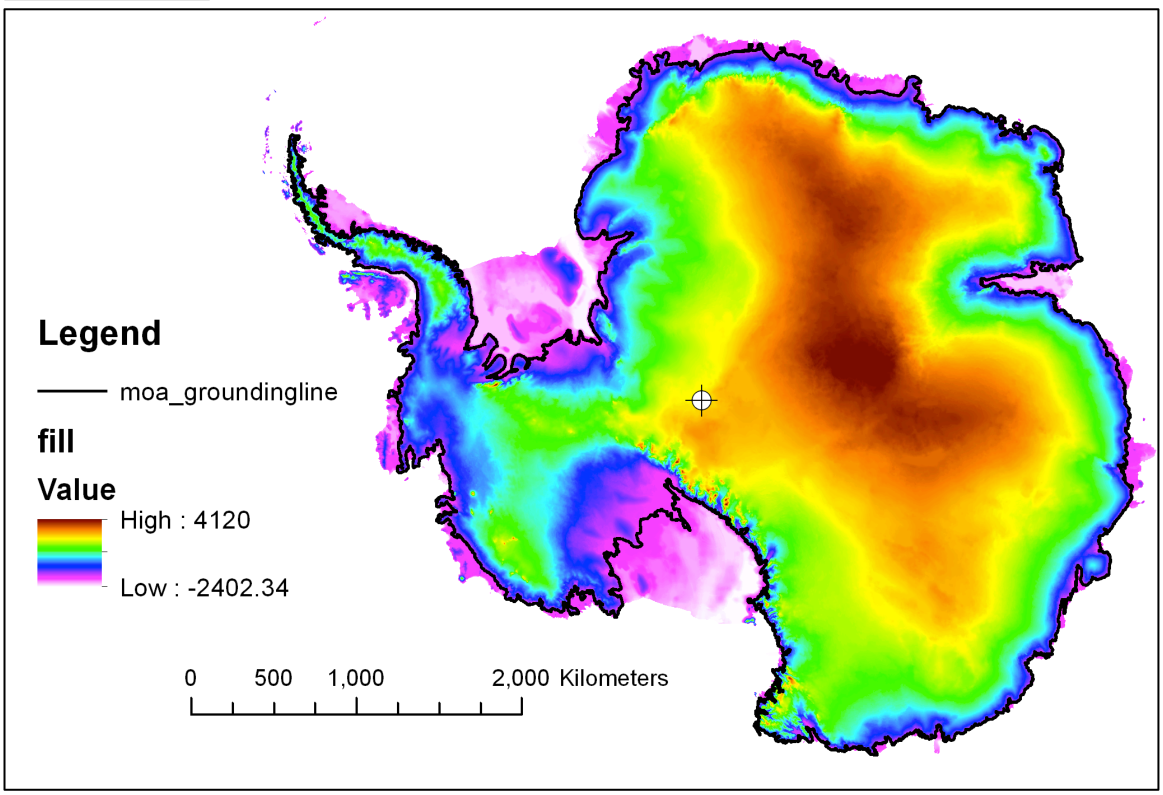


Figure 9. Filled hydraulic head (expressed in meters). NASA MODIS-derived ice sheet grounding line is shown. Modelbuilder step details are shown in box above. Location of South Pole indicated by crosshair.

Calculate flow direction raster

Before a stream network can be found, a raster of the direction of flow from each cell to another (of 8 total) around it is needed for the entire dataset. This is accomplished using the ArcGIS Flow Direction tool with the Fill map (from the previous step) as input. This map gives each cell in the raster a number corresponding to the direction of flow from one cell to another adjacent to it. It utilizes the D8 algorithm (see ArcGIS manual, Tarboton et al., 1991) to accomplish this. The result of this step can be viewed in Figure 10.

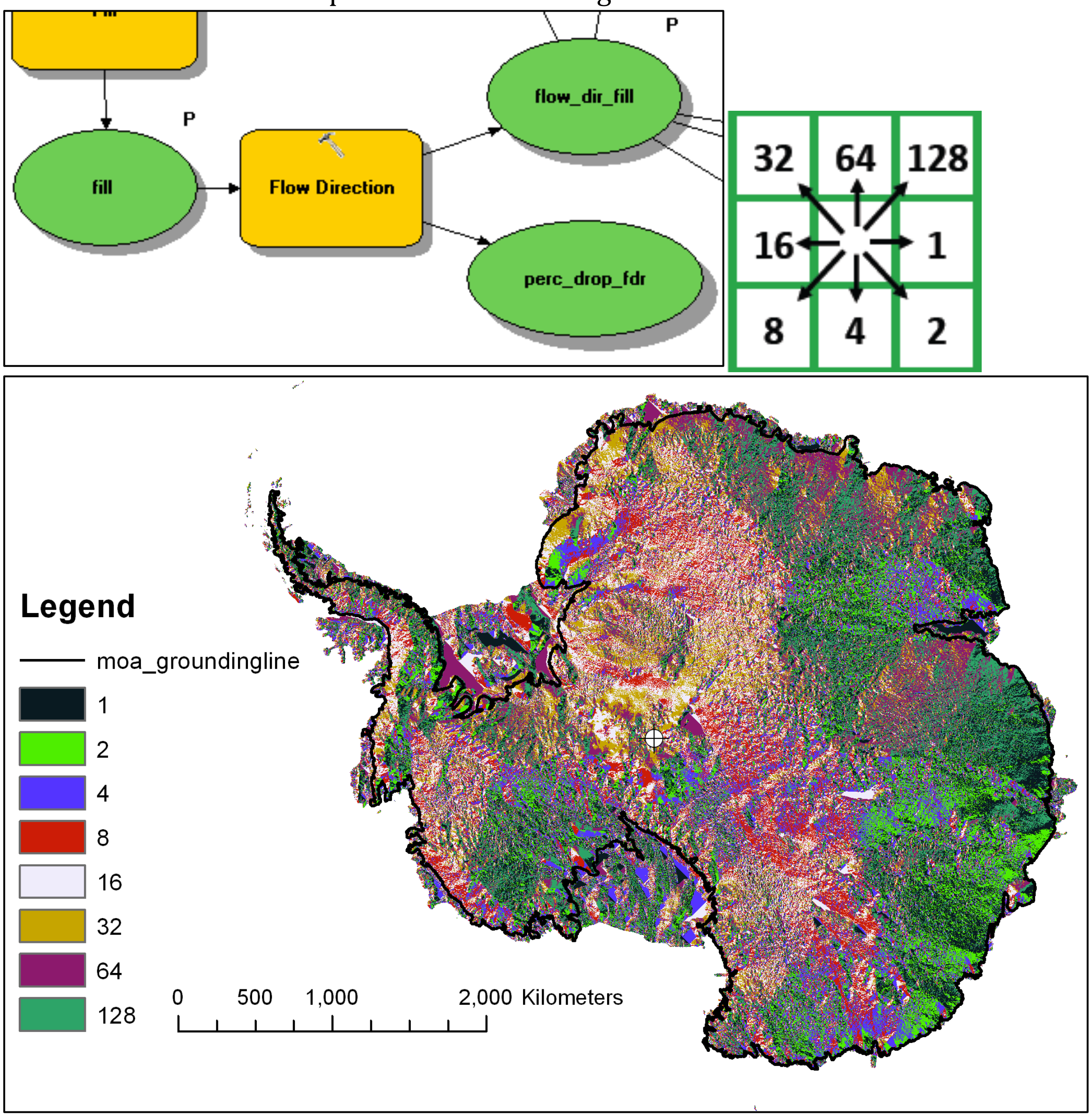


Figure 10. Flow direction raster (index square above). NASA MODIS-derived ice sheet grounding line is shown. Modelbuilder step details are shown in box above. Location of South Pole indicated by crosshair.

Sum previous for flow accumulation

One final step to perform before finding the stream network is to sum up the previous flow direction raster values to produce a flow accumulation raster. This raster will also serve as the input to calculating the various stream orders. The ArcGIS tool used is Flow Accumulation and its result may be viewed in Figure 11.

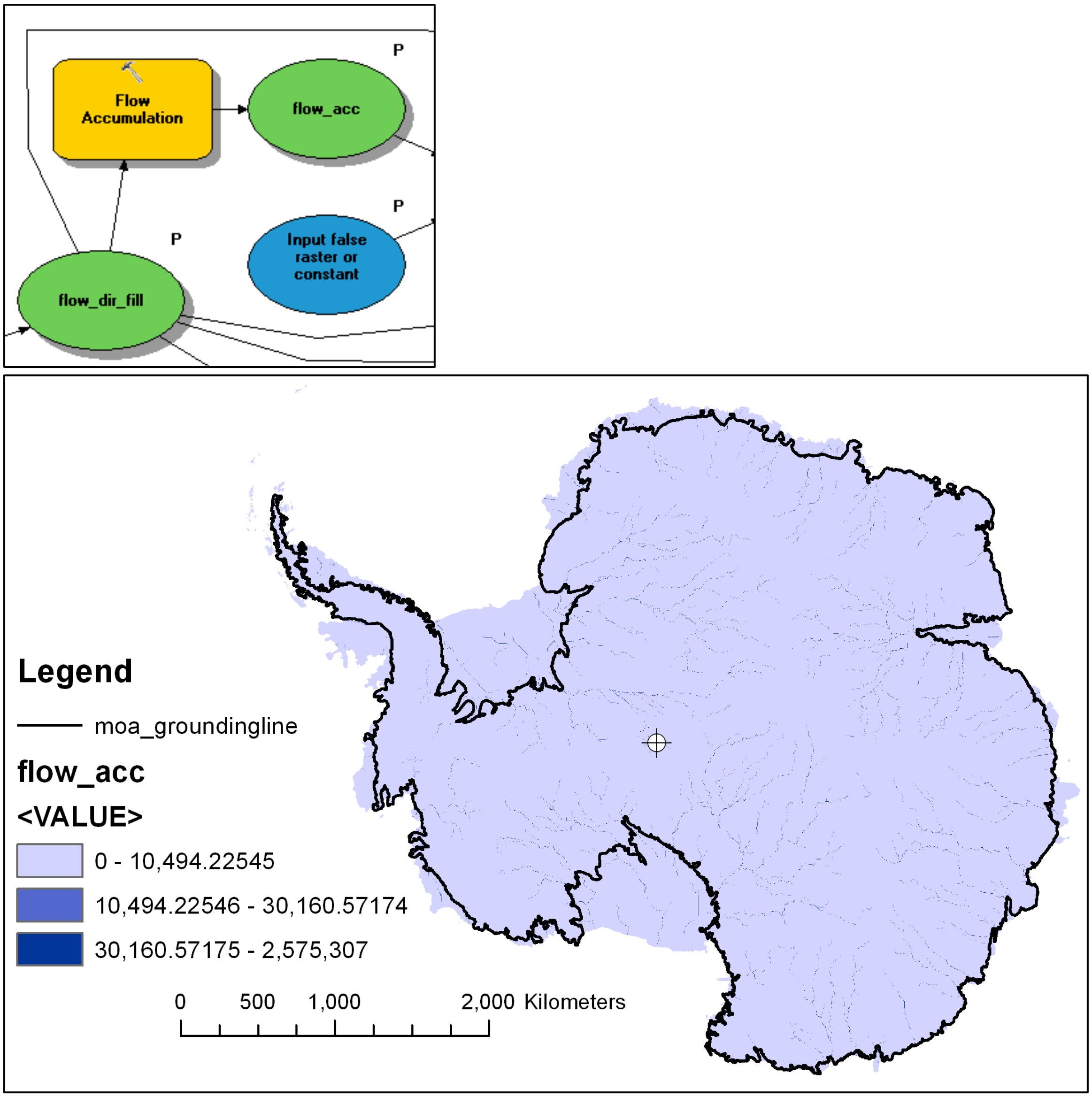


Figure 11. Flow accumulation raster (expressed as number of total contributing cells). NASA MODIS-derived ice sheet grounding line is shown. Modelbuilder step details are shown in box above. Location of South Pole indicated by crosshair.

Define stream network

Using the flow accumulation raster and the ArcGIS Set Null tool, a method to define stream network can be created. The Set Null tool is used to find where cells are significantly carrying flow enough to be registered as part of a stream network and given a value and if not significant enough, the cells are assigned NoData. This resulting stream raster is used as the input for the ArcGIS Stream to Feature tool, which is used to convert the previous output into a shapefile (viewable in Figure 12). Taking this further, stream order of the network can be applied by the ArcGIS Stream Order tool. Approaches to defining order by both Shreve and Strahler methodologies (see ArcGIS manual) are viewable in Figure 13.

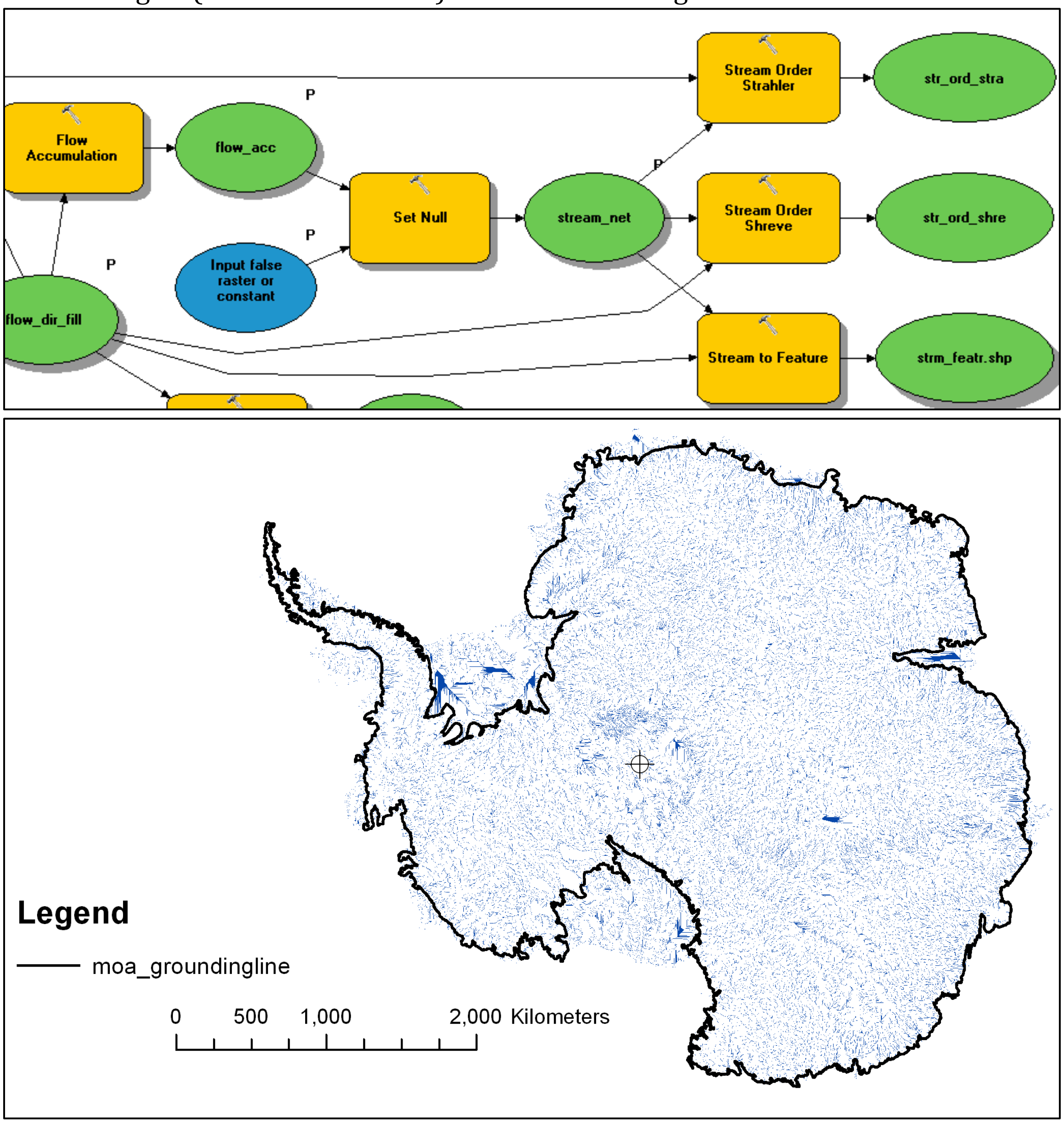


Figure 12. Stream network raster. NASA MODIS-derived ice sheet grounding line is shown. Modelbuilder step details are shown in box above. Location of South Pole indicated by crosshair.

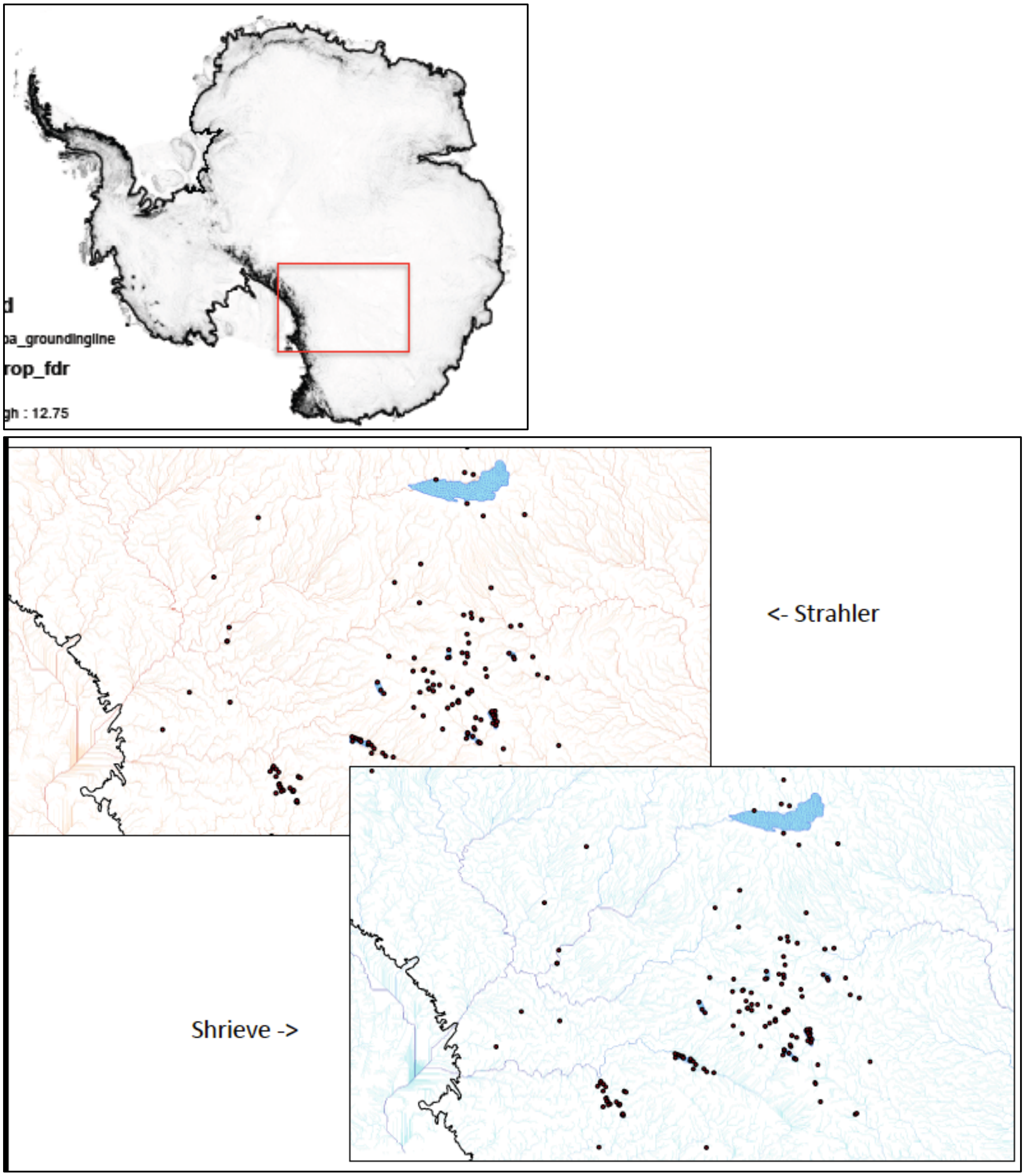


Figure 13. Stream order comparison (Strahler and Shreve methodologies) from inset region indicated above. NASA MODIS-derived ice sheet grounding line is shown. Modelbuilder step details are shown in box above. Location of South Pole indicated by crosshair.

Delineate water catchment basins

Finally, taking the flow direction raster, the water catchment basins for the entire map area can be defined using the ArcGIS Basin tool. This tool assigns regions of related flow to be grouped by unique number and is a level above the watershed classification, which is useful for working datasets at the continent-scale. The result of this step is viewable in Figure 14.

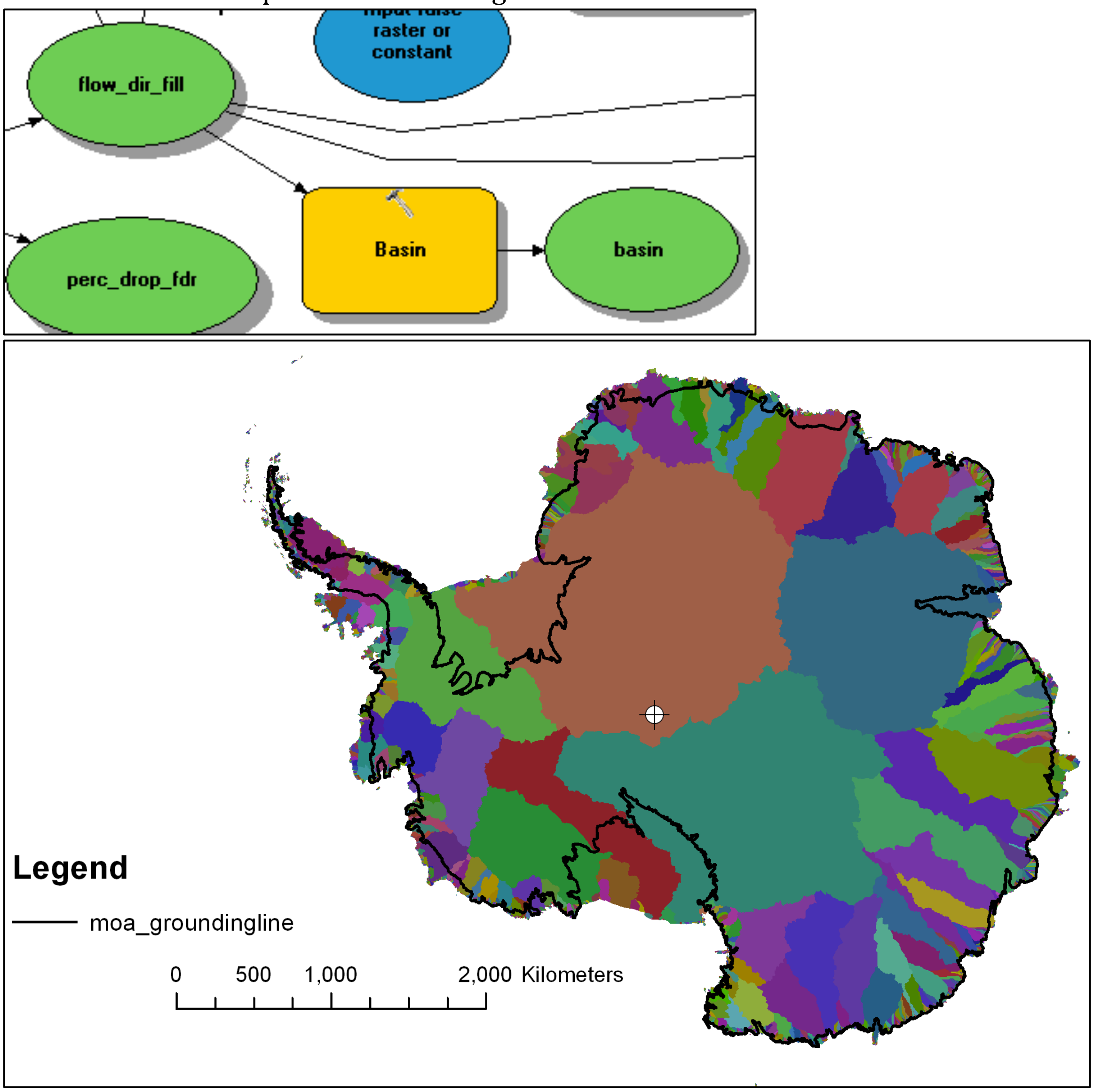


Figure 14. Water catchment basins (unique color ID per basin). NASA MODIS-derived ice sheet grounding line is shown. Modelbuilder step details are shown in box above. Location of South Pole indicated by crosshair.

Create parallel set of results without dependence on ice overburden pressure

One method to analyze the effect of the overlying ice sheet's pressure is to rerun through these steps without having calculated the induced hydraulic head. This is done by skipping over the "calculation of pressure potential and hydraulic head" step and directly inputting the extracted bed topography raster into the Fill tool. The result of doing this is in Figures 15-18.

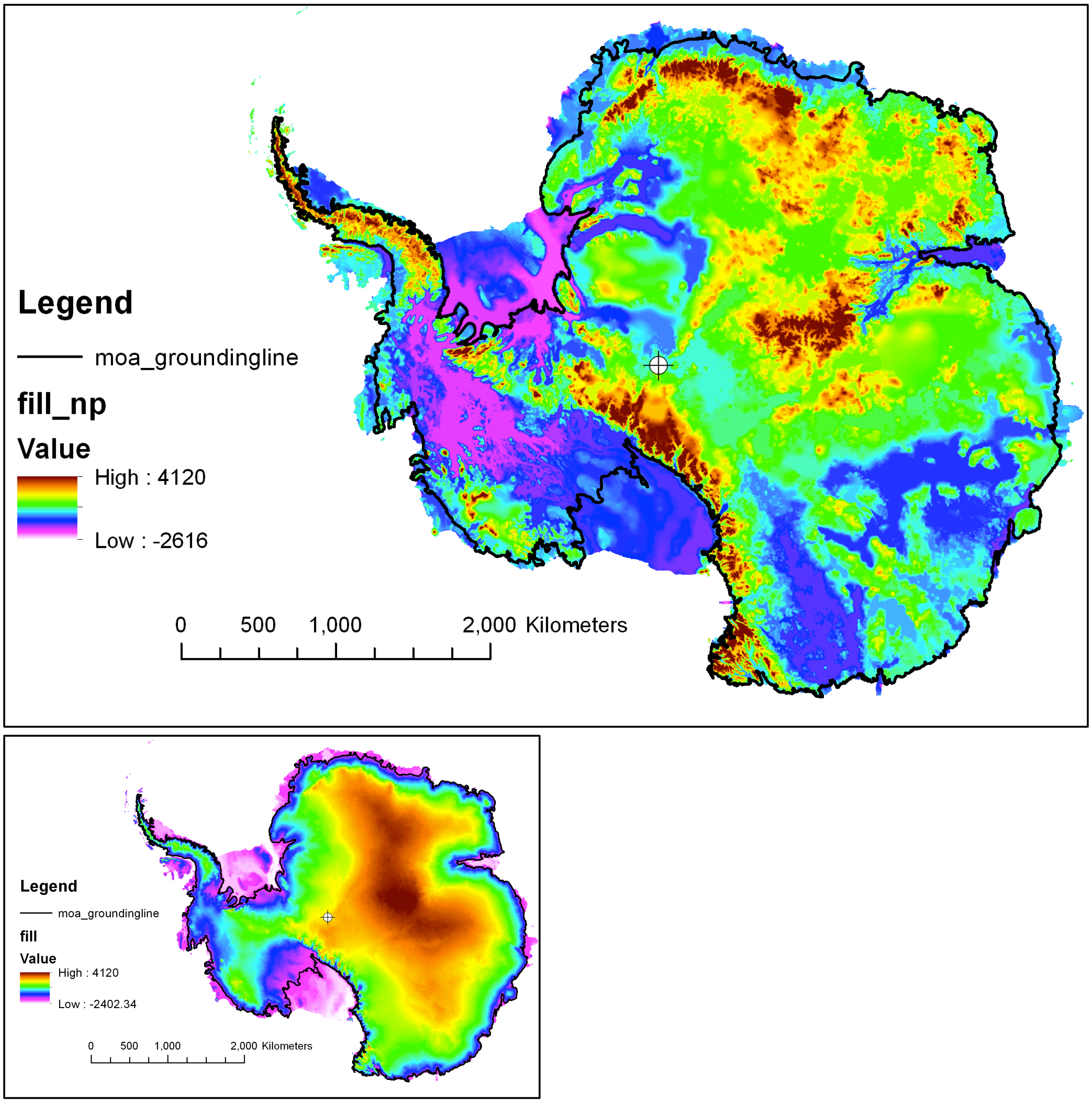


Figure 15. Filled hydraulic head (expressed in meters) based on bed topography, neglecting ice overburden pressure. Figure 9 included for comparison.NASA MODIS-derived ice sheet grounding line is shown. Location of South Pole indicated by crosshair.

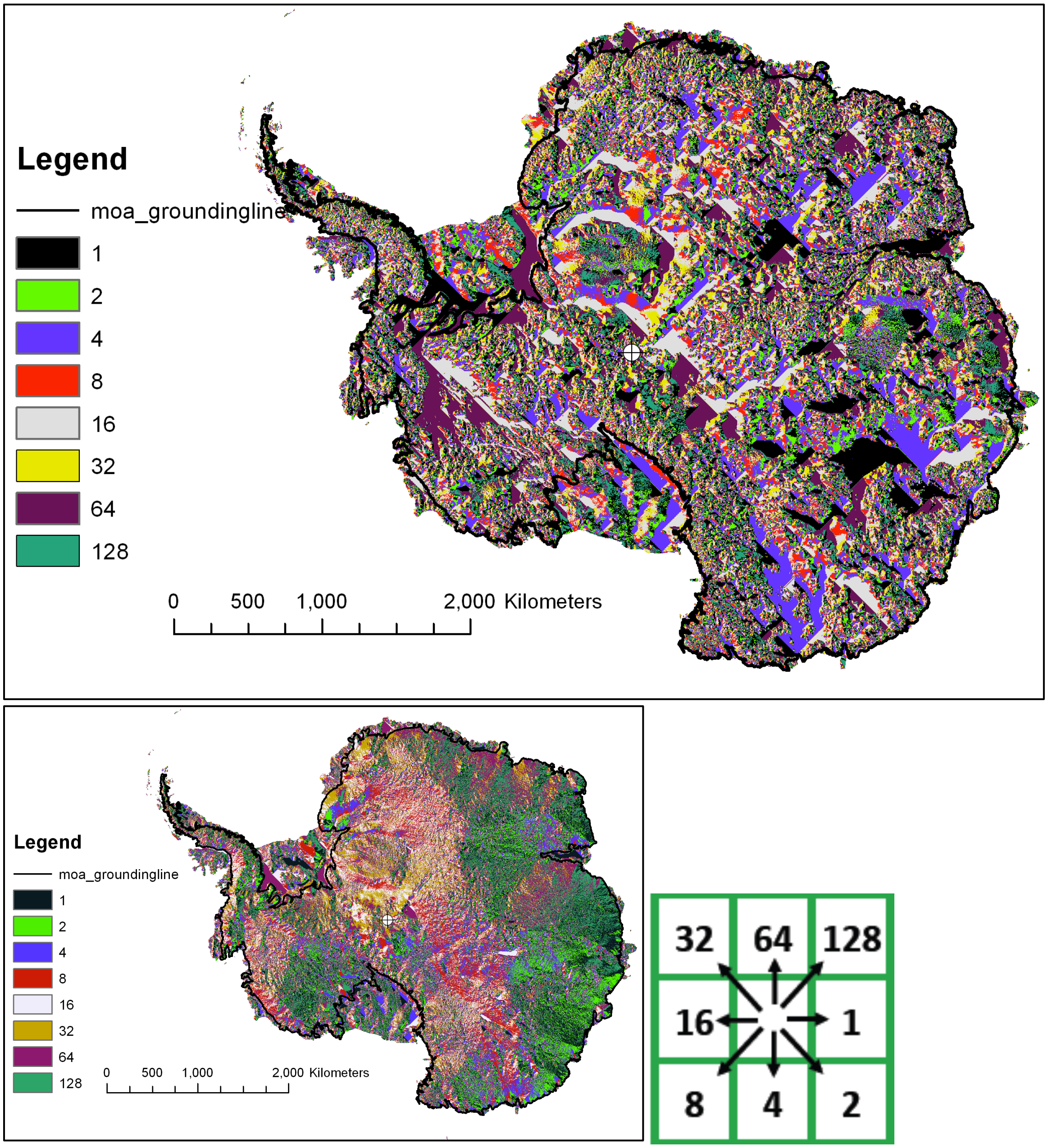
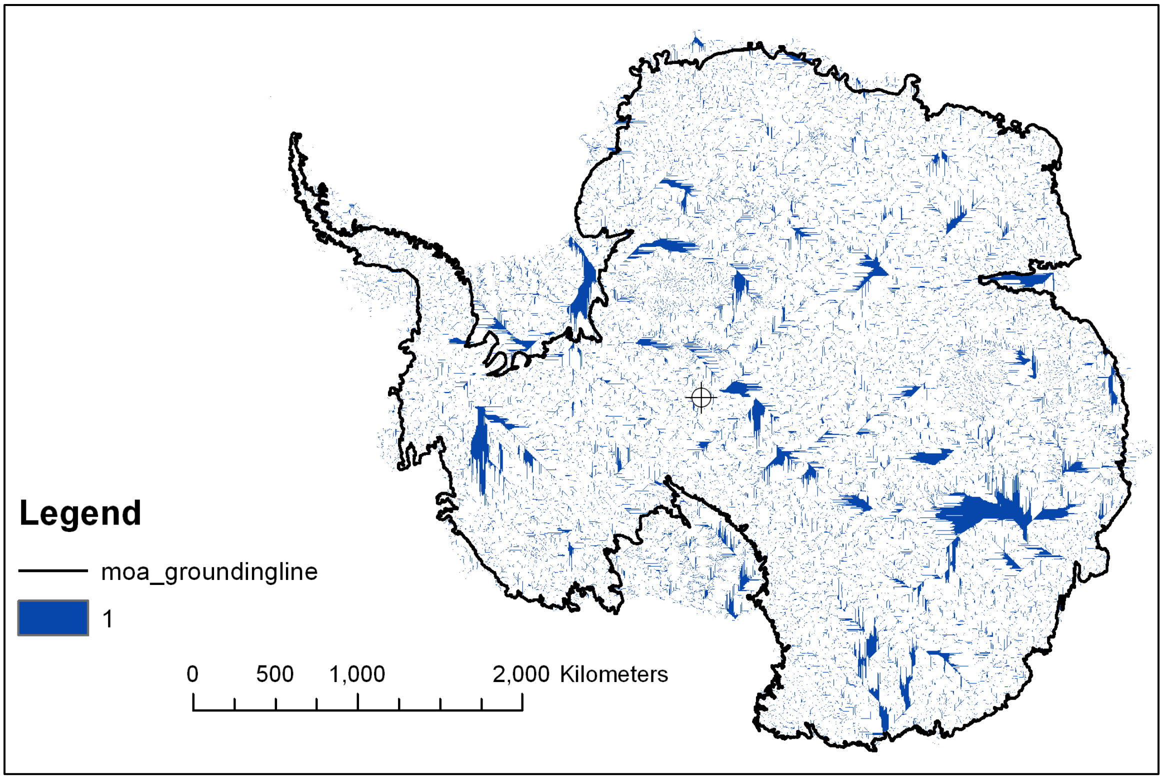


Figure 16. Flow direction raster (index square above) based on bed topography, neglecting ice overburden pressure. Figure 10 included for comparison. NASA MODIS-derived ice sheet grounding line is shown. Location of South Pole indicated by crosshair.



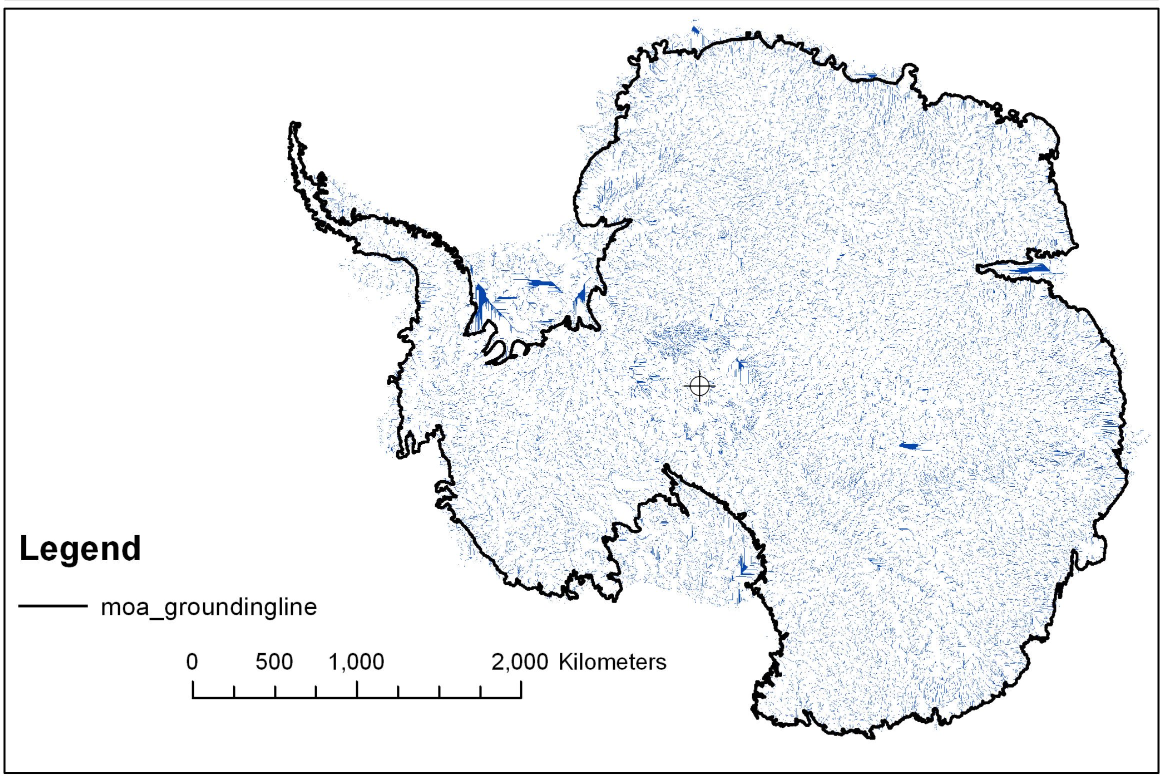
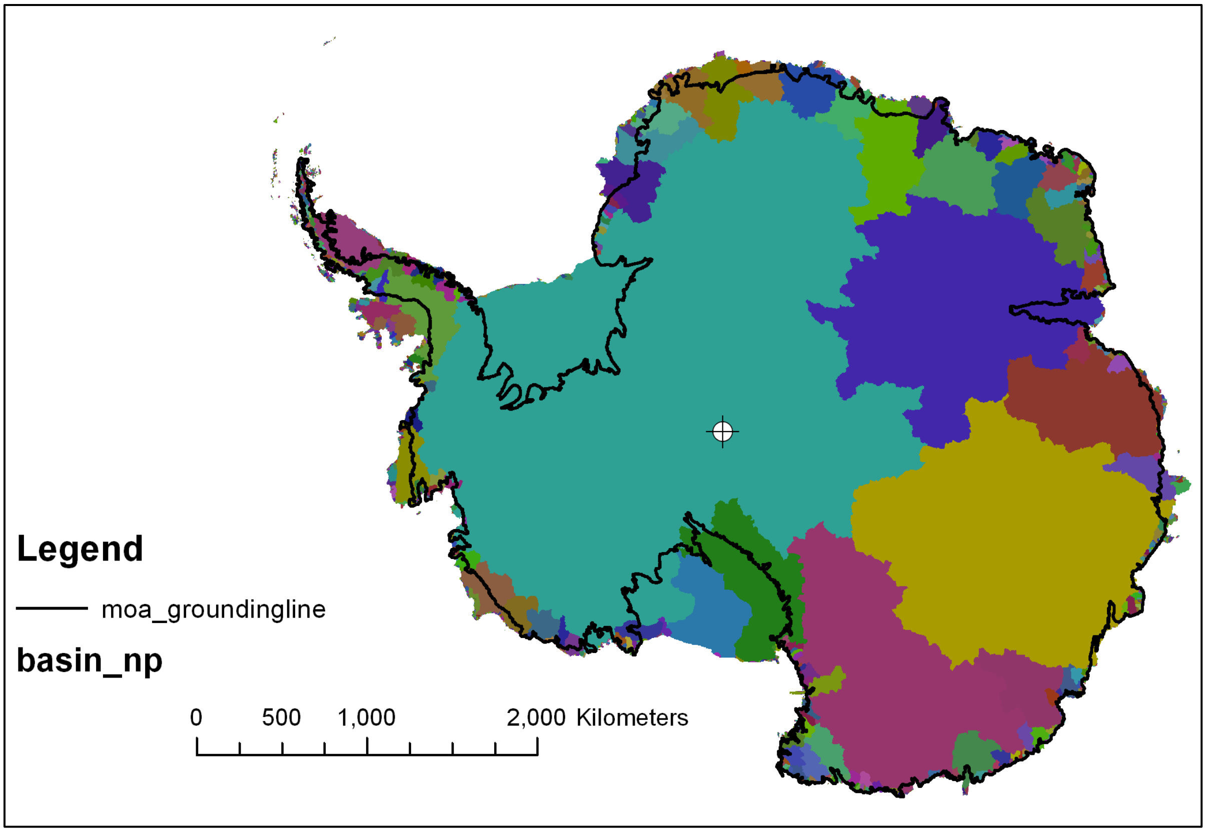


Figure 17. Above; Stream network raster based on bed topography, neglecting ice overburden pressure. Below; Figure 12 for comparison. NASA MODIS-derived ice sheet grounding line is shown in both. Location of South Pole indicated by crosshair in both.



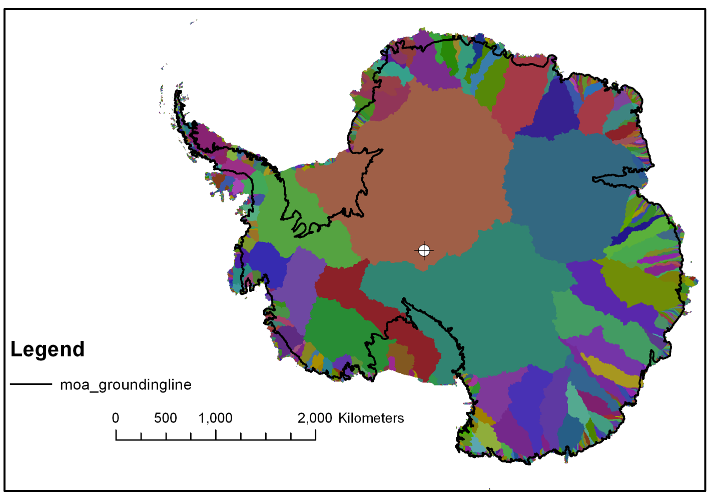


Figure 18. Water catchment basins (unique color ID per basin) based on bed topography, neglecting ice overburden pressure. Figure 14 included for comparison. NASA MODIS-derived ice sheet grounding line is shown. Location of South Pole indicated by crosshair.

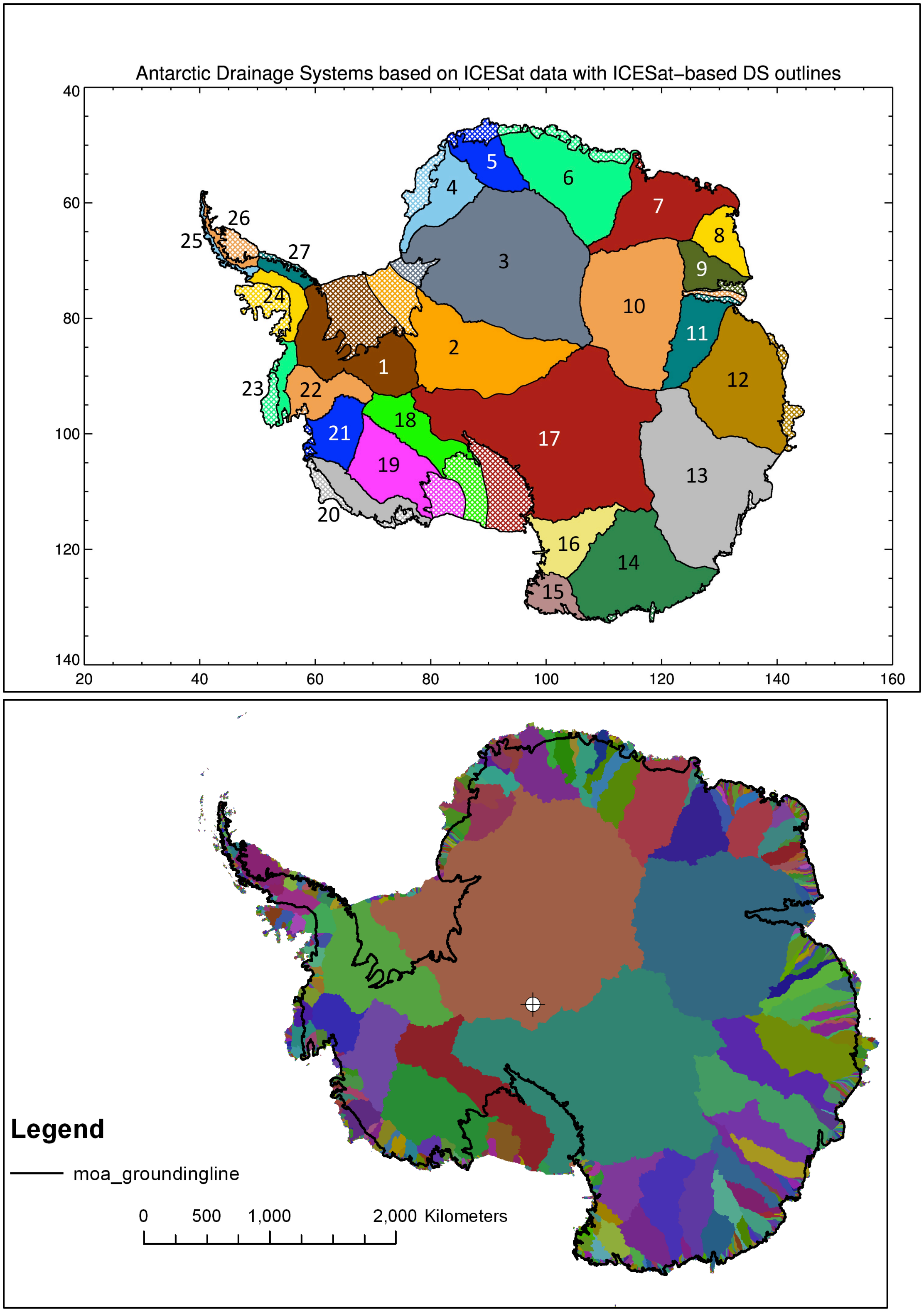


Figure 19. ICESat derived Ice catchment basins (Rignot 2011). Figure 14 included for comparison.

Discussion of Results

Overall, the results of this project worked quite well. The maps of pressure potential (Fig. 7) and hydraulic head (Fig. 8) make physical sense as the ice sheet's overburden pressure dominates the water potential; it should do so by about 11 times more than the bed topography (Roethlisberger and Lang 1987). Filling of the hydraulic head map seems to be minimal which is helpful in qualitatively assessing the validity of the approach. There are some possible patterns observable in the flow direction raster (Fig. 10), which directly leads to the map of water catchment basins (Fig. 14). Depending on the specific symbology preferences chosen, either of the stream order maps (Fig. 13) may be useful in finding which potential water flow paths could carry more flow. The water catchment basin map (Fig. 14) correlates well to the NASA ice sheet catchment map (Fig. 19). The ice sheet catchment map is a product of satellite-observed ice sheet surface velocity data collected over many years. The water catchment basin divides lineup closely with those of the ice catchment divides. The water catchment divides derived from just the bed topography (Fig. 18), neglecting the ice overburden pressure, do not match up to the ice divide catchments. This is indicative of how important the ice sheet's contribution is to subglacial water routing. The filled topographic map (Fig. 15), along with the stream network map (Fig. 17), show how erroneous the neglect of ice pressure is on the results as the water must be forced off of the continent's deep submarine basins by this methodology. This leads to large regions of raised cells to accommodate flow to the coasts.

Conclusion

While this approach could use some refinement at the smaller scales, it is overall a great start to begin answering questions about water flux underneath the Antarctic ice sheet. An improved focus is needed on deciding whether or not full ice sheet pressure should be used in all areas or just certain parts. This could be accomplished by developing an approach to determine true effective water pressure rather than just assume that water pressure equals the ice overburden pressure. Once that approach is accomplished, it would enable ArcGIS to directly feed appropriate locations of water routing to a numerical model of ice sheet dynamics coupled with subglacial hydrology, which is critically needed for estimations of sea level rise projections for the future.

References

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