<u>Mapping Wayne County Esker Network:</u>

Spatiotemporal Analysis Of Glacial Recession Rates During The Glacial Maximum

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<u>Abstract</u>

In this paper, several soil samples taken from an esker formation at Gerald Eddy are used to produce a rough image of a typical esker formation, characterizing how it is distributed from crest to slope. This is used to inform the mapping of the greater esker network for the region for the purposes of attempting a spatiotemporal analysis of the short term cycles of accelerating and decelerating melting throughout the long-term glacial recession from Michigan. The introduction will provide background on the glacial history of Michigan and the relevant processes necessary to understand for the purposes of this analysis.

The methods will elaborate on how both (1) a soil profile of a typical esker for this region will be established based on the qualitative and quantitative data from Gerald Eddy; and (2) how a map of Michigan's esker network will be qualitatively estimated using various datasets. The results will first illustrate the trends in soil profiles from the lowest slope of an esker towards the elevated crest of the esker, then they will show the local and regional estimated course of an esker compared with multiple rasters representing relevant datasets that characterize an esker. Discussion will elaborate on what the parent material of the esker soil appears to be, and why the hypothesis was ultimately unsuccessful. The conclusion will reflect on post glacial depositional processes realized during the mapping process, and how this can provide the basis of alternate methods of spatiotemporal analysis.

Introduction/Background

Michigan is highly shaped by glacial activity and recession that dominated the region during the late pleistocene epoch, beginning around 2.5Ma and receding only 12,000 years ago[6]. As glaciers melted, the meltwater fed into enormous networks of subglacial rivers. These rivers picked up vast amounts of coarse sands and gravels generated by glacial movements which crushed up parent material and transported them large distances. As glaciers faded they left behind eskers - distinct elevated mounds of the gravels and coarse material transported by these subglacial rivers.

Eskers in South-Western (distal) boundaries of ice sheets during the glacial maximum were uncovered first. Conversely, eskers in North-Eastern (proximate) regions were the last to be uncovered as the ice sheets fully receded. This means that northern eskers existed for a longer period, giving them more time to develop vast deposits of materials, forming larger eskers. This determines the size of an esker: eskers increase in size the longer that they are covered by glaciers. Therefore as an extension, relative elevation can be used to trace the path of a glacial recession on a macro-scale.

In addition to their larger periods of development time, more proximate regions experienced greater discharge energy than distal regions. The rates of glacier recession were not uniform across all regions. Glaciers generally retreated at increasing rates, which increased the volume of meltwater flowing through subglacial rivers at a given time. This consequently increased the discharge in subglacial rivers as time went on. Proximate eskers were the last to be uncovered by ice sheets, therefore they not only had more time to develop, but they also experienced far greater discharge than distal eskers.

In summary, more northern proximate eskers correspond to increased discharge and development time. This implies that there would be observable compositional variation across Michigan eskers based on their geographic positions relative to the ice sheets. Besides size would produce two other key characteristic differences:

1.) The overall grain size would be relatively smaller in distal regions, and relatively larger in proximate regions.

2.) The parent material of distal regions would be more representative of the local geology than proximal regions.

The further upstream of an esker's path, I hypothesize that the soils will become increasingly less correlated with the local geologic bedrock. I expect that the eskers may become increasingly composed of foreign parent material transported from other regions. I speculate that temporal information may be gathered about the small-scale timeline of glacier recession rates during different periods of fluctuating climatological warming/cooling. If my hypothesis is correct, this will assist in creating more accurate time-transgressive[7] models of Michigan's glacial recessions.

Methods

The spatial relationship of the esker relative to any foreign source of the parent material will provide critical information towards establishing the localized pathway of the esker compared to time. I believe that temporal information may be gathered about the small-scale timeline of glacier recession rates during different periods of fluctuating climatological warming/cooling. This lends insight into the discharge of the meltwater that was flowing through the esker, and therefore the rates of melting.

The first step is to identify key characteristics of the soil profiles found at Gerald Eddy. This will be determined by quantitatively using R-squared analysis to determine the strength of correlations in the distribution of soil grains and composition versus elevation. This has two uses. First, it identifies correlated features of the esker's soil order like productivity, vegetation type, etc. that can be cross referenced with elevation data in the mapping process. This eliminates the possibility of confusing an esker for some other geologic formation with steeply elevated terrain. Second, it provides critical quantitative data on the soil profile composition that can be used to determine if the esker soil is likely derived from the local bedrock or bedrock transported from some other region, which is critical for analysis.

I will then proceed to the second phase of my procedure. I will use GIS to trace the course of the esker's path using elevation mapping data as well as any other helpful diagnostic data patterns emerging from the microtopographic analysis of Gerald Eddy. Once I construct a map of the estimated shape of the esker, I will determine if the relationship between the esker's parent material and the local geologic bedrock becomes weaker as it moves further North. Assuming my assumption is correct, I will evaluate where the original parent material likely was transported from based on the soil data from Gerald Eddy. I will use my findings to estimate the regional spatial course of glacial recession. I will speculate on the rates of melting, assuming there is a strong emergent trend in the difference between local bedrock and soil class that reveals information about the melting/discharge rates in different stages of the glacial recession. Finally, I will cross reference my results with the known patterns of glacial recessions to see if my analysis was accurate.

Results

An esker's profile is highly variable across the slope from crest to the bottom of the slope. The profile is composed of much more fine materials towards the crest of the esker, with the soil increasingly composed of oxidized iron.

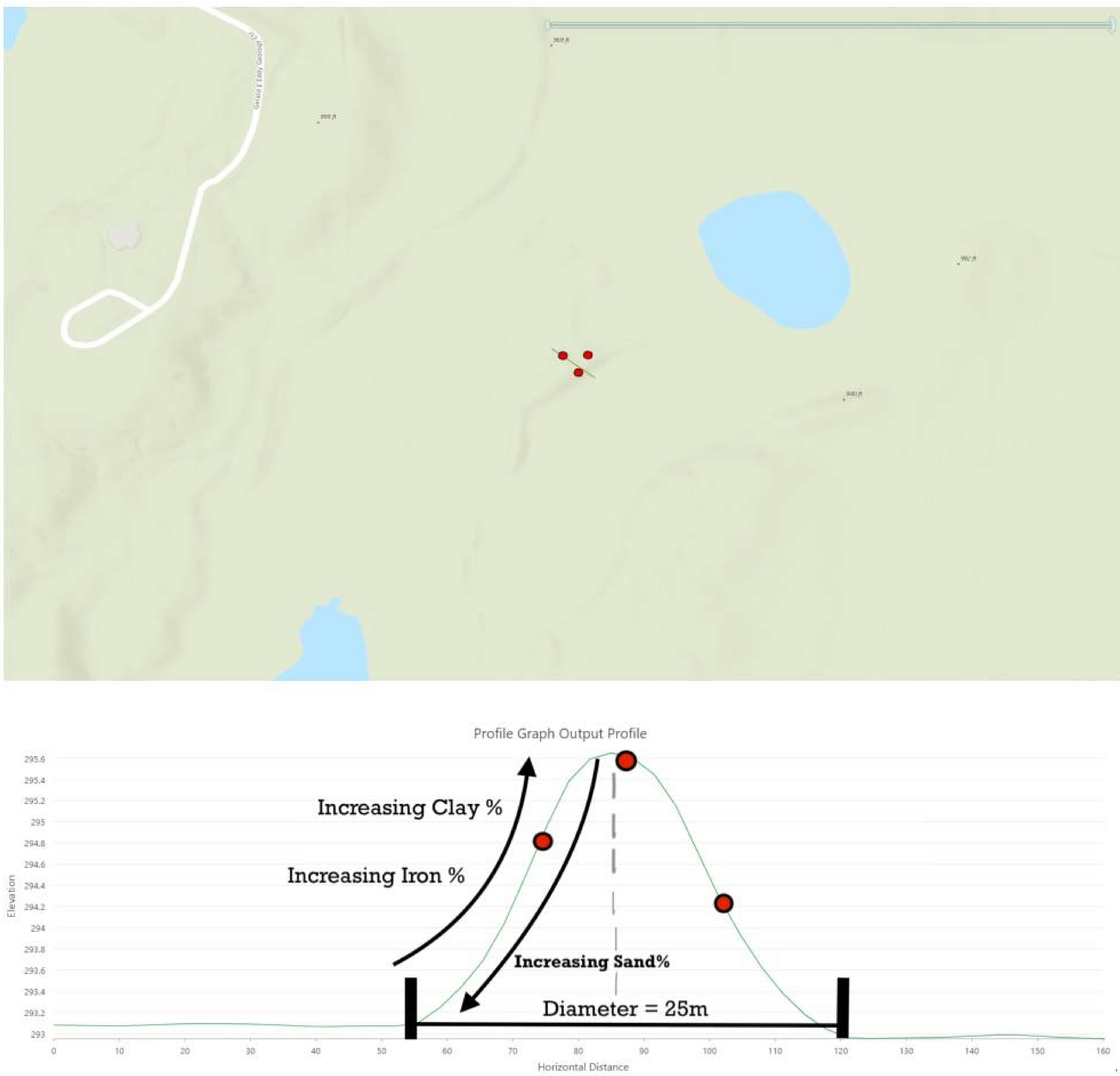
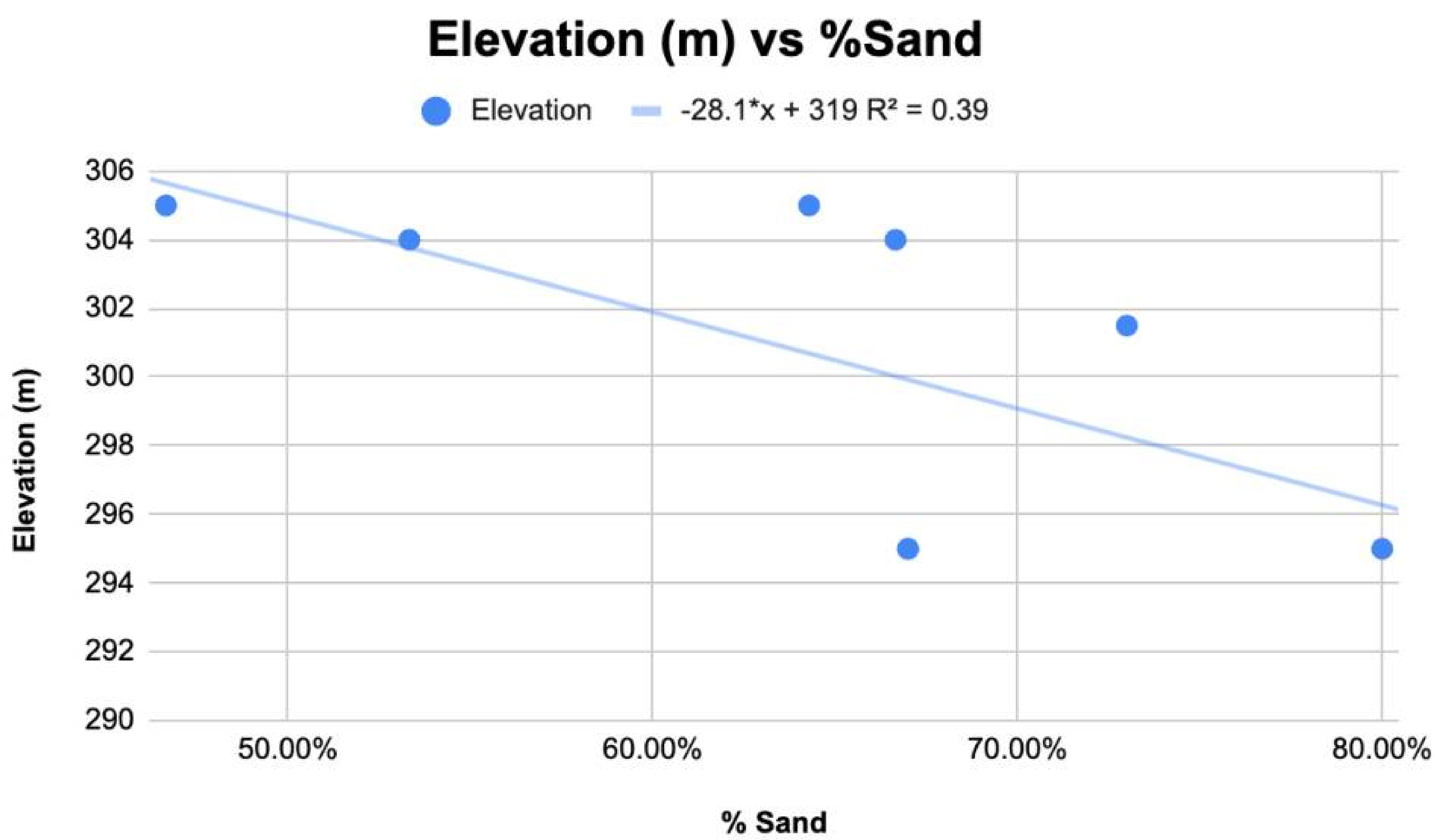
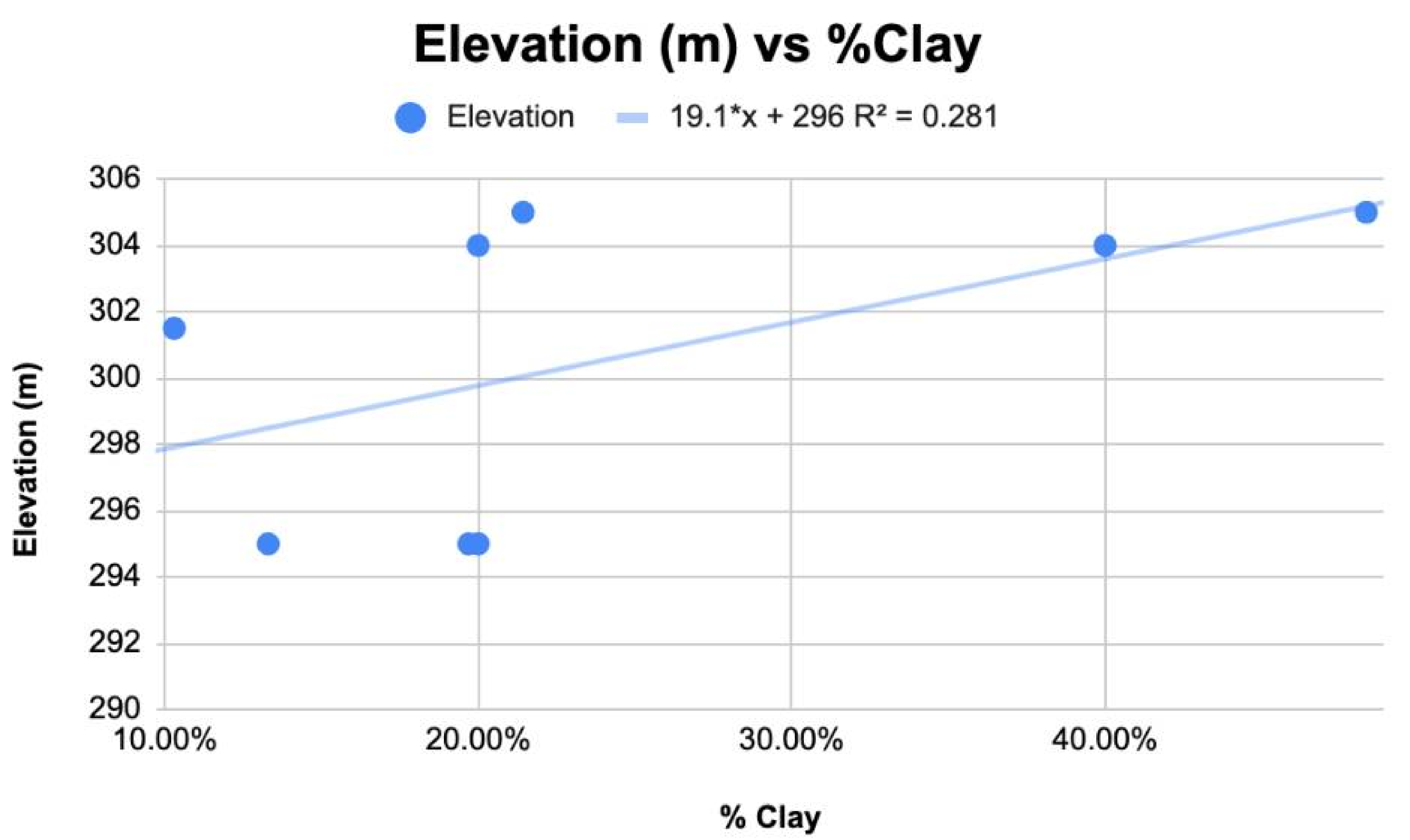


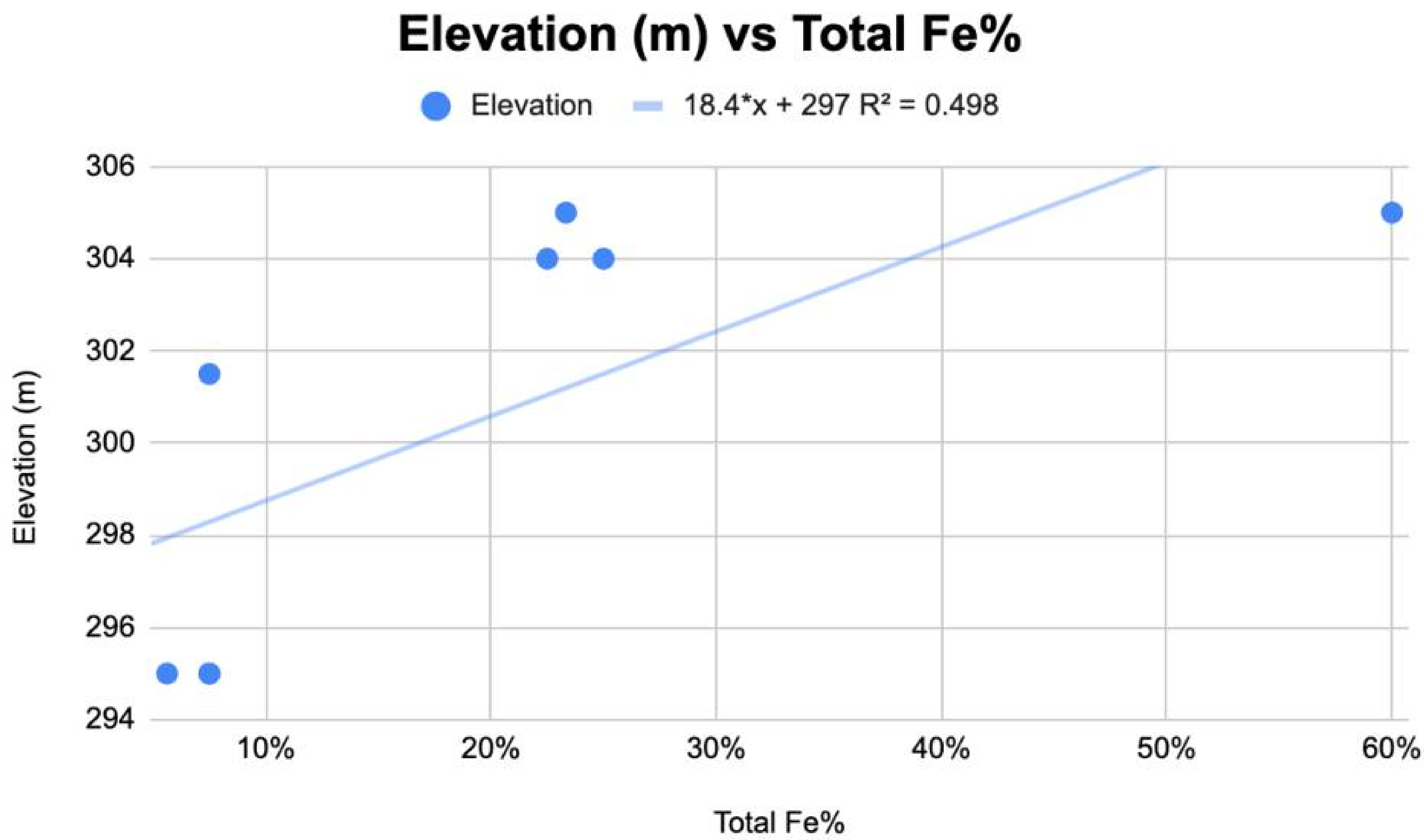
Figure 1: Map and annotated cross section of Gerald Eddy esker formation. Notable trends from data illustrated. Locations of sites from 2024 teams represented via red dots. Note: elevation derived from DEM is offset from on-site elevation recordings by ~10m.



Elevation (m) vs %Sand
Elevation
-28.1*x + 319 R² = 0.39
Elevation (m)
306
304
302
300
298
296
294
292
290
50.00%
60.00%
70.00%
80.00%
% Sand



Elevation (m) vs %Clay
Elevation
19.1*x + 296 R² = 0.281
Elevation (m)
306
304
302
300
298
296
294
292
290
10.00%
20.00%
30.00%
40.00%
% Clay



The relationship between sand versus elevation yielded an R-squared value of 0.39. The relationship of clay versus elevation yielded a R-squared value of 0.28. They are both moderately correlated with elevation, with sand having the stronger relationship. However, though the strength of the relationship is similar, the relationship to elevation is inverted for sand and clay. Sand has a negative correlation with elevation, and clay has a positive correlation with elevation. In other words, grains become increasingly coarse further away from the crest of the slope towards the bottom. This makes intuitive sense, because an increase in the proportions of coarser grains would logically imply a decrease in the proportions of smaller grains.

Total Iron percentage yielded the strongest result, with an R squared value of 0.50 (when rounded up to two significant figures). This value demonstrates a strong positive relationship. Iron content dramatically increased from a minimum of less than 10% at the lowest portions of the esker to a maximum of up to 60% at the crest of the esker. This visibly changes the Munsell color of the soil, and gives soils at this site a characteristic light or yellowish hue.

Figure 2: Images of soil profile taken from crest site of esker. Horizon A (left) and Horizon E (right).

	Average Percentage of Coarse Fragments
Esker	**38.33%**
Lowland Forest	28.33%
Hardwood Swamp	2.67%
Bog	2.67%

Table 1: Average Percentage of coarse fragments recorded in each biome at Gerald Eddy.

There are several other diagnostic features to note from this site. Namely, every site reported large clastic gravels from this site below the surface. Each group reported the esker as having the highest percentage of coarse fragments than any other area surveyed at Gerald Eddy. In Image 1, you can see large clasts of variable size ranging up to 4cm in length. There is even more of such material in the E horizon. These gravels are angular in shape. They represent relatively immature quartz clasts from parent material broken up and deposited in this esker via subglacial rivers.

Multiple different variables were cross compared in order to map this esker's trajectory. The primary feature used to map this esker's trajectory was the sharp increase in slope, because it characterizes the esker topographically. The yellow below represents a slope of 5.1 - 47.2 degrees. This is done by taking the first derivative of a USGS surface DEM map.

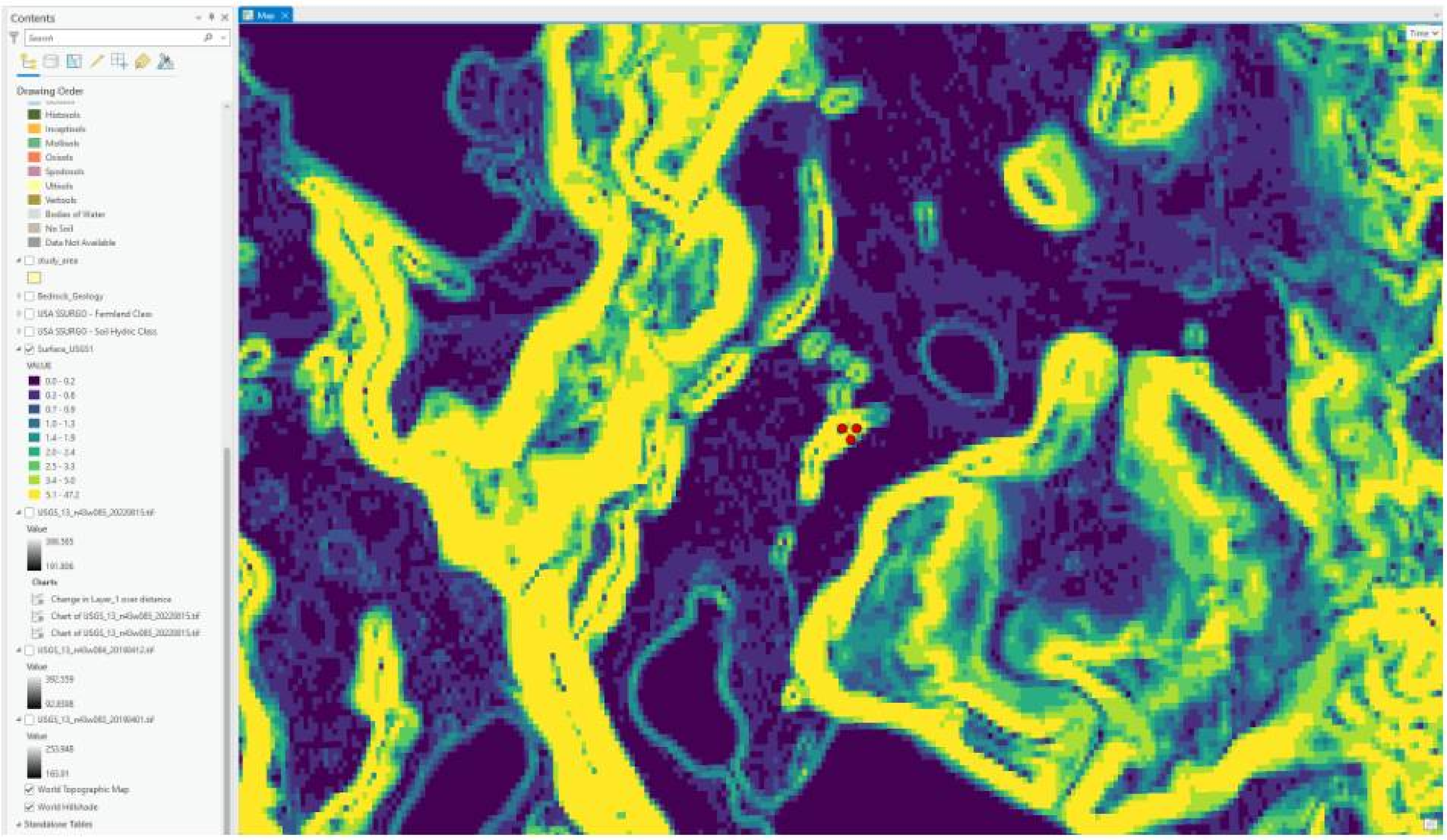


Figure 3a: Surface Elevation Slope - Local Area

On a local scale, two further variables were identified that strongly corresponded with the areas of steep elevation that marked the seeker's path: soil order and hydric class. The esker soil differed in order compared to the other soils in the immediate area. The esker soil is classified as an alfisol of the boyer series order. The soil order surrounding it at lower elevations were mollisols. Additionally, the esker soil strongly differs from its surrounding soil when compared by hydric class. While esker soils are classified as "not hydric", surrounding soils are classified as "all hydric". These are opposite classifications within this variable. Soil order and hydric class distinguished the esker from the surrounding environment, and therefore provided viable additional sources of data to supplement the reconstruction of the esker's original path and increase the confidence of the results.

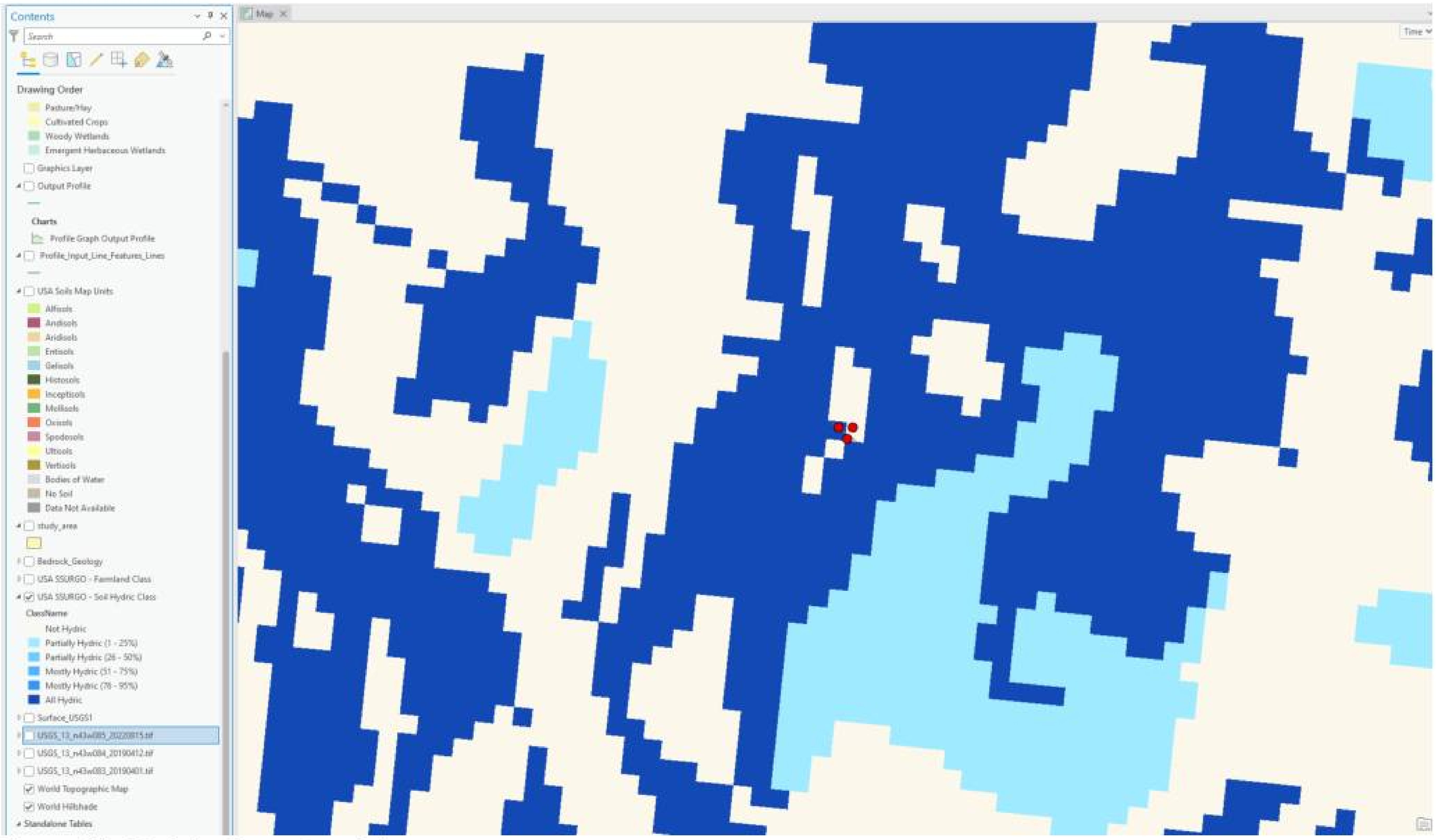


Figure 3b: Hydric class - Local Area

Figure 3c: Soil Order - Local Area

The following figures show the estimated trajectory of the original esker's path compared with multiple different sources of data. Zooming out to the greater regional area, there appears to be a complex network of eskers oriented Northeast to Southwest. The size of the line tracing the esker is proportional to the estimated strength and size of its river - with the exception of the NE origin portion, which was likely larger than its thin line implies. Thicker lines represent regional subglacial rivers of greater size, smaller portions represent the smaller rivers that branched off from larger ones. The Gerald Eddy sites are marked at the small SE branch. On a regional level, two additional criteria emerge that closely correspond to an esker's trajectory: farmland class and vegetation type. The esker is mostly classified in these two categories as "not prime farmland" and "deciduous forest", respectively. Figure 4f compares this path to the local bedrock geology.

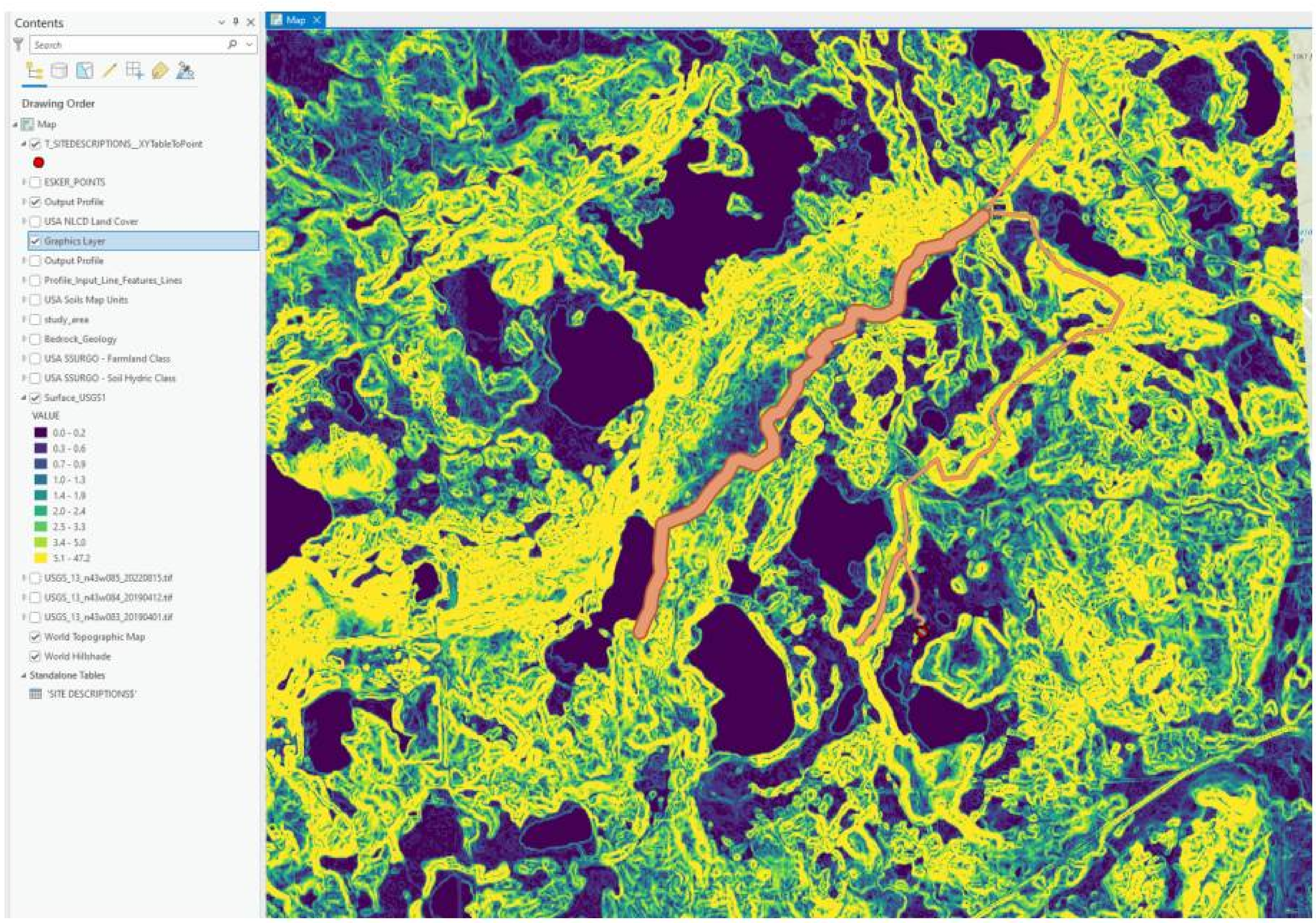


Figure 4a: Surface Elevation Slope - Regional Area

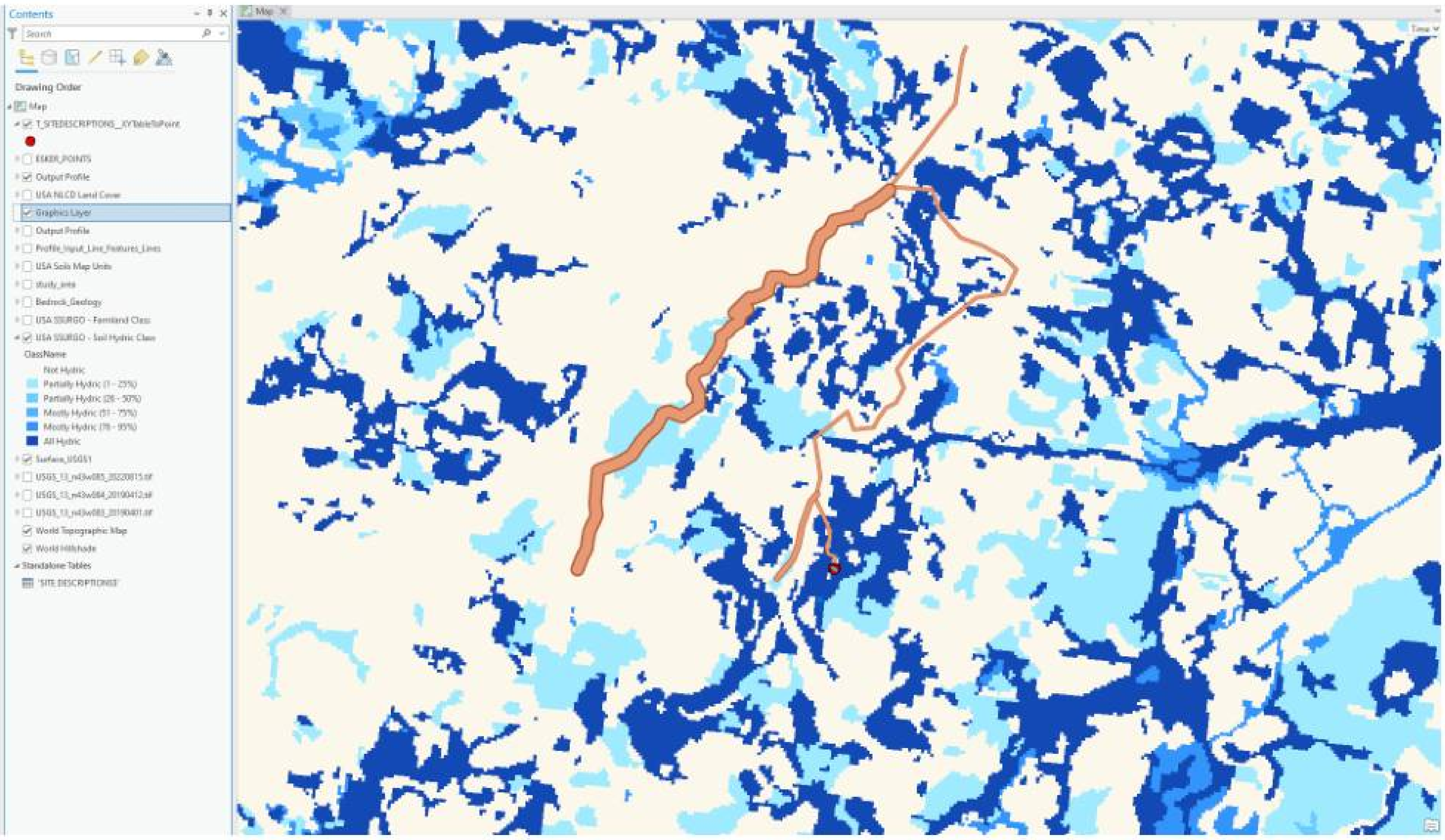


Figure 4b: Hydric Class - Regional Area

Figure 4c: Soil Order Classification - Regional Area

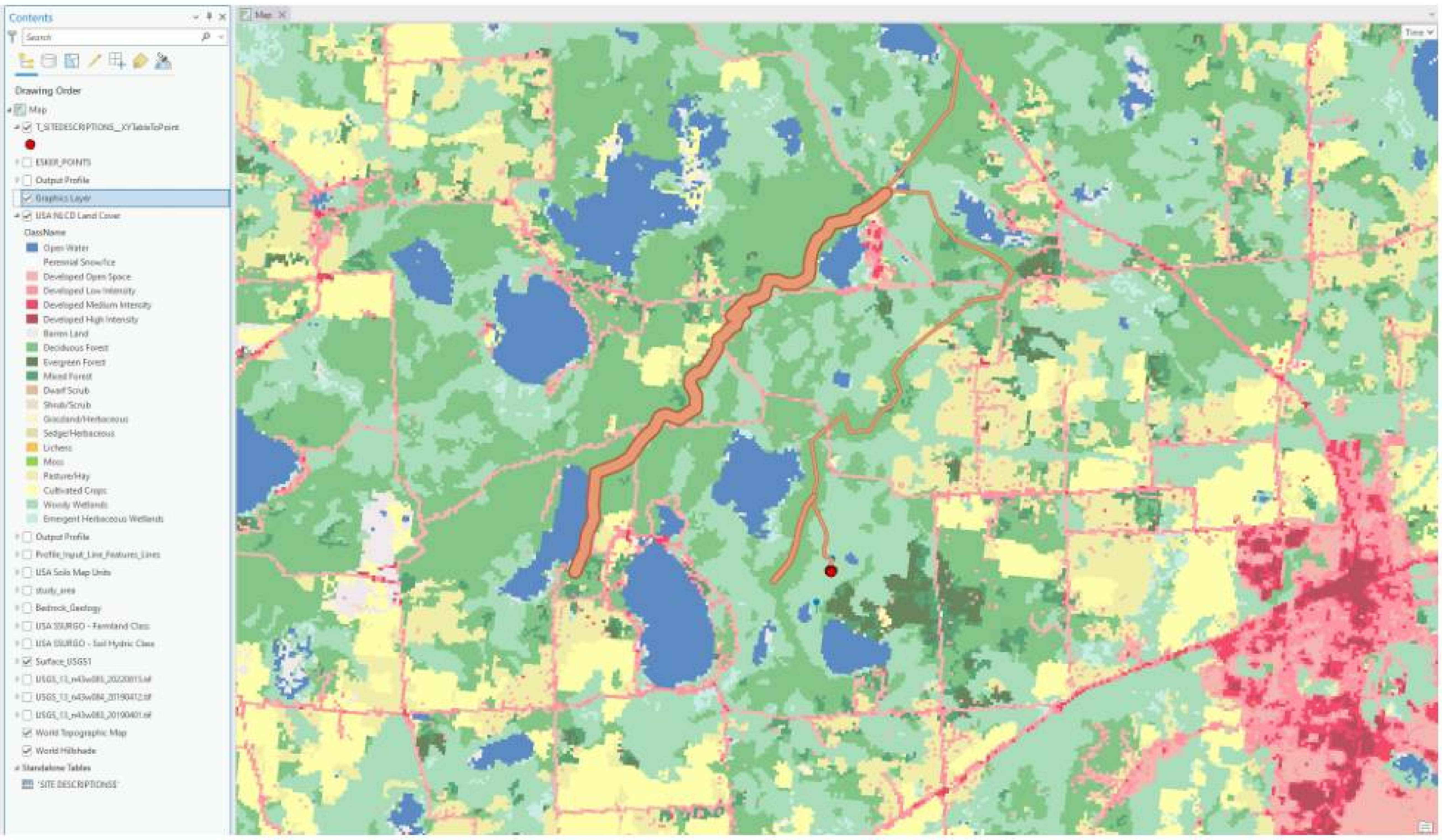


Figure 4d: Dominant Vegetation Classification - Regional Area

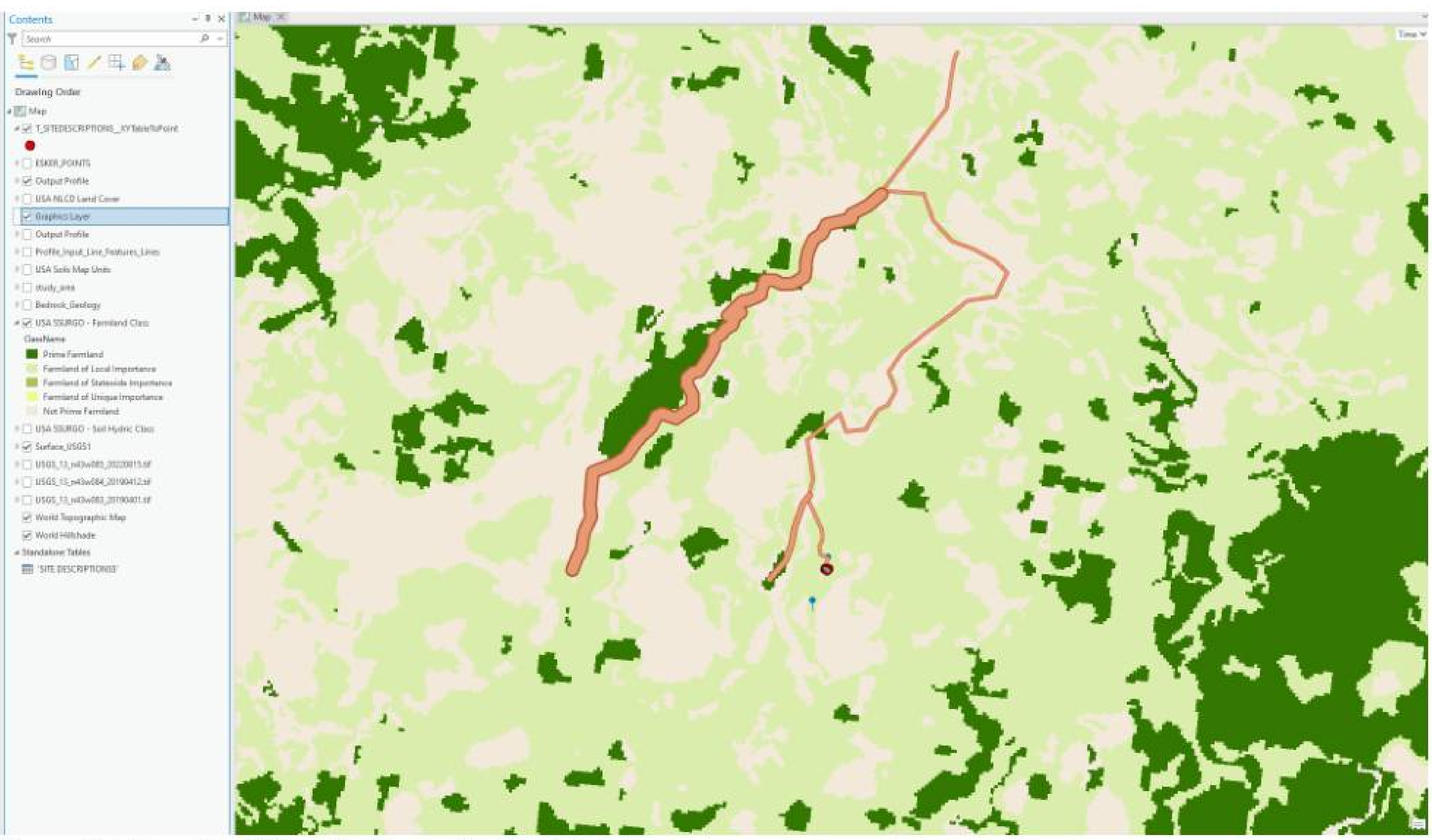


Figure 4e: Farmland Classification - Regional Area

Figure 4f: Bedrock Geology - Regional Area

Discussion

The hypothesis has not been successful due to limitations in the assumptions built into the methodology. It assumed that there would be variation in either the local bedrock or variation in the soil series type that would produce a quantifiable difference between the esker's soil characteristics and the local bedrock over the course of the esker. The soil for the entire length of the esker is the same Boyer series found at Gerald Eddy or closely associated series with no strong deviation (figure 4c). The samples analyzed from the Gerald Eddy Site are therefore likely representative of the entirety of the esker soil in the region. The local Marshall formation also completely comprises the area that the esker moves through (figure 4f). Therefore, across the entire course of the esker there is no variable deviation in the composition of the esker compared to the local bedrock. This implies that either 100% of the esker's parent material is the local bedrock, or none of it is - potentially instead being 100% transported foreign material.

The local Marshall formation is the parent material of all of the regional esker's soil. The Marshall formation is described as being "comprised of highly angular quartz grains embedded in a softer cement of mica, siderite, and clay"[7]. The esker soil precisely matches this description. Highly angular quartz grains were prevalent in the esker soil, evident by the preponderance of quartz gravels (figure 2, table 1). The iron oxides are likely due to the weathering of siderite (*FeCO3*) included in the Marshall Formation. The clays found in the esker soil are likely also common in the Marshall formation. Therefore, it is most likely that the Marshall formation is the parent material of the entire esker soil.

It is possible that if the parameters were expanded further beyond this region and the esker was traced for a greater distance, deviations between soil composition and underlying bedrock may emerge that could be practical for spatiotemporal analysis that was not possible for this experiment. This method could also theoretically be applied with greater efficacy to other regions shaped by the glacial maximum with more variable bedrock geology, like in Northern Europe[5]. Principal component analysis could also theoretically be applied through GIS software to interpret multiple input variables associated with esker features such as slope, hydric class, and vegetation type in order to generate a more comprehensive image of the extended esker network across Michigan, rather than manually cross referencing different datasets and evaluating each qualitatively.

The esker identifies it as a meandering river. It is clear that there was a complex network of subglacial rivers in this area, many of the smaller branches of such a river could not be mapped due to the vast extent of the network. The esker found in gerald eddy is a small branch of a much greater network. On a local scale, the Gerald Eddy esker path does not correspond to the NE to SW orientation expected of its movement based on the path of overall glacial retreat for this area in Michigan. The Gerald Eddy esker site moves roughly North to South, being a deviation from a larger riverbed moving NNE to SSW. This larger riverbed in itself is a smaller offshoot of an extremely large regional river oriented NE to SW, which does fit with the direction of glacial retreat in this region. It is clear that the overall orientation of the regional esker network tends to generally follow the path of glacial retreat, although zoomed in to a local scale the paths of smaller rivers were meandering and highly variable.

Conclusion

There were many things that I assumed about eskers in beginning this experiment that I determined were incorrect over the course of the experiment, causing me to reassess glacier recession as a far more complex process that involves post glacial processes to be taken into account. Namely, I assumed an esker's path and features would be relatively distinct from the surrounding environment - being almost identical to how they originally emerged from the receding ice sheets. This failed to account for the fact that as glaciers receded from an area, the shape and composition of the eskers would not necessarily be preserved because eskers were subject to alluvial processes immediately post glacial recession. This is because the meltwater pouring out from the glacier would erode its distinct shape, and produce temporary alluvial fans in the plains around the border of the glacier until it receded further[8]. This process essentially ensures the glacier would be obscuring its topographic footprints as it receded over time. Therefore the exact topographic path of the esker may not be completely accurate representations of the original subglacial river trajectory, as was originally assumed. This caused me to cross reference topographic characteristics with many other classes data to establish a more complete and accurate picture of glacial recession.

However in retrospect, this phenomenon could potentially provide an alternate method of spatiotemporal analysis: the size and extent of alluvial fans may be a measurable indicator of short term cycles of slowing/accelerating melting within the long term glacial maximum. If a glacier slowed or accelerated its rate of recession over a short time period, it would theoretically allow sufficient time for alluvial fans to develop in the area that the esker emptied into. One could assume that the longer that the glacier's border remained relatively static, a subglacial river would deposit proportionally more material into the fan beyond the glacier.

Bibliography

1. USDA Web Soil Survey
   United States Department of Agriculture, Natural Resources Conservation Service. Web Soil Survey. http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm. Accessed 1 May 2025.

2. USGS Soil and Mineral Chemistry Map
   U.S. Geological Survey. Soil and Mineral Chemistry Map. https://mrdata.usgs.gov/ds-801/map-us-plus.html. Accessed 1 May 2025.

3. Online Isotopes in Precipitation Calculator
   University of Utah. Water Isotopes in the Hydrologic Cycle. http://wateriso.utah.edu/waterisotopes/pages/data_access/form_3_1.html. Accessed 1 May 2025.

4. EPA Study of the Marshall Formation
   United States Environmental Protection Agency. Study of Marshall Formation in Michigan. https://semspub.epa.gov/work/05/84766.pdf. Accessed 1 May 2025.

5. Wersäll, Carl, Anders Bodare, and K. Rainer Massarsch
   "2005 Regional Report Europe Deep Mixing." ResearchGate, 2005, https://www.researchgate.net/publication/259481203_2005_Regional_Report_Europe_Deep_Mixing. Accessed 1 May 2025.

6. Glacial History - Michigan.gov
   Bergquist, S. G. Glacial History of Michigan. Michigan Department of Environment, Great Lakes, and Energy. https://www.michigan.gov/-/media/Project/Websites/egle/Documents/Programs/GRMD/Catalog/09/Glacial-History-Bergquist.pdf. Accessed 1 May 2025.

7. Marshall Formation Description
   Mississippian Marshall Formation of the Pointe Aux Barques Region, Eastern Michigan. Michigan Geological Survey. https://www.michigan.gov/-/media/Project/Websites/egle/Documents/Programs/GRMD/Catalog/05/GIMDL-GSA87K.PDF. Accessed 1 May 2025.

8. Ruddiman, William F
   Earth's Climate: Past and Future. 3rd ed., W.H. Freeman, 2014.

9. Glacial History of Michigan - ScienceDirect.
   Blewett, William L. "Glacial History of Michigan, U.S.A.: A Regional Perspective." Developments in Quaternary Science, vol. 1, 2004, pp. 313–325. https://www.sciencedirect.com/science/article/pii/S157108660480191X. Accessed 1 May 2025.

10. USGS Bedrock Geology Raster.
U.S. Geological Survey. Bedrock Geology of Michigan (Raster). https://ngmdb.usgs.gov/Prodesc/proddesc_59374.htm. Accessed 1 May 2025.