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A Glacier Runs Through It: Effects of Late Wisconsinan Glaciation on Stream Drainage Near the Terminal Moraine Boundary in North Central Pennsylvania

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Presented to the Faculties of the University of Pennsylvania in Partial Fulfillment of the Requirements for the Degree of Master of Environmental Studies 2007.

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A Glacier Runs Through It
Effects of Late Wisconsinan Glaciation on Stream Drainage Near the Terminal Moraine Boundary in North Central Pennsylvania

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May 13, 2008

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Abstract

Stream morphology in north central Pennsylvania has been influenced by the passage of multiple glaciers during the Quaternary period, and most recently by the Late Wisconsinan ice sheet which began to recede just 10,000 years ago. While glaciers can take a heavy erosive toll on the landscape, the Late Wisconsinan and previous glaciers stopped when they reached Pennsylvania, and as such were not as thick and did not cover the ground as long as in regions to the north. This paper examines current morphology in an area along the north central part of the state that contains both glaciated and non-glaciated regions. The research is intended to show the degree of impact from Wisconsinan glaciation on stream drainage, as well as the extent to which this impact can be spatially seen.

Front photo: View looking north east from central Lycoming County, Pennsylvania. The furthest ridge in the center background is Jacoby Mountain, with an elevation of just over 1800 feet. The Late Wisconsinan ice sheet came to a stop on the other side of the ridge.
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Introduction

The northern tier of Pennsylvania has spent the last 2 million years under the influence of a relatively cool climate that has brought the periodic flow of ice sheets in and out of the state since long before it was given any names or geographic boundaries. With origins in the bays of Canada near the Arctic Circle, each advance of glacial ice has tended to taper and diminish once it reaches the area of Central Pennsylvania, near the physiographic junction of the Appalachian Plateau and the Allegheny Front.

While the glaciers are but the most recent on a long list of geologic processes that have shaped the region, modern rates of stream and river erosion pale in comparison to the amount of change that glaciation brought to the landscape. The presence and pattern of ice has thus been the dominating factor in carving out the present landscape and directing the drainage that is seen there today. This study takes a look at the extent of that impact.

In spite of the significant influence of the ice sheets, the most recent of these, the Late Wisconsinan that receded about 10,000 years ago, perhaps had much less influence on area drainage than those which flowed across the landscape before it. This ice sheet essentially followed the same path as the ones that preceded it, and reached its maximum across the northeast corner of Pennsylvania. Here at the end of the glacial line, as it were, the ice was not as voluminous, and its choice of where to go was driven primarily by the existing regional topography.

In looking at a study area within north central Pennsylvania that includes area covered by Late Wisconsinan ice and areas left ice free beyond the terminus boundary, an examination of the stream patterns, geology, elevation, and evidence from prior
glaciations will be used to explore the impact of the Late Wisconsinan ice sheet. Did the
glacier leave a discernable mark on stream morphology in the region, and can this be seen
both physically and spatially? Additionally, to what extent has stream morphology
adjusted to modern processes over the 10,000 years since the glaciers left? To what
degree did the longer history of glaciation determine this morphology and any
adjustments made during interglacial periods? The analyses here can also provide
evidence as to how the area drainage is reclaiming the patterns that were present before
the Late Wisconsinan ice came through.

The comparison of stream length, bifurcation ratios, elevation and slope among
specific stream orders should reveal some of the surficial differences in relative
morphology among Late Wisconsinan glaciated and non-glaciated streams. While one
would plausibly expect to find that in general, streams running over non-glaciated regions
- having not had their channels repeatedly obliterated by a plow of glacial ice – would
have had more time to establish longer runs and deeper beds along the mountains, the
study looks at how visible these outcomes may be. The data and spatial analyses that
follow also explore some of the ways that the streams within glaciated regions - running
through the valleys and mountains that repeatedly hosted the furthest outreaches of the
ice sheet pancake flowing out of Hudson Bay – divulge their relative youth.
Glaciation in Pennsylvania

The best direct evidence for glaciation indicates that the planet has experienced at least four major periods of continental ice coverage during the last 1 billion years. It has been speculated that similar ice ages occurred as long as 2.5 billion years ago. The modern Quaternary period that began 2.5 million years ago is considered part of the most recent of these ice ages, although the current Holocene epoch which began about 10,000 years ago, marked the end of the last glacial period of the current ice age, as the climate shifted into the warmer interglacial phase that it remains in today (Crowl and Sevon 1999, 225).

The study area for this paper lies within central northeast Pennsylvania and covers approximately 8,300 square miles immediately below the border with the state of New York (Figure 1).

Figure 1: Major Rivers and counties distributed across the Late Wisconsinan glacial boundary and study area. (Data source: PASDA/DCNR 1995, PASDA/Penn State 1996, PASDA/PennDOT 2007)
This region is primarily forested and supports mostly small rural communities and working farmland. The majority of streams drain to the Susquehanna River basin; the northwest corner of Potter County and most of McKean County drain to the Ohio River Basin, and a very small area of north central Potter County drains to the Genesee River Basin in New York. During the Quaternary period, this area has experienced climates alternating between cold, glacial and peri-glacial conditions and warmer, temperate interglacial conditions (Braun 2006b, 10).

Figure 2: Positions of Illinoian and Wisconsinan glacial limits in Pennsylvania. Older, Illinoian ice sheets extended into approximately one third of the NonGlaciated section of the study area. (Data source: PASDA/DCNR 1995, USGS 2004, PASDA/PennDOT 2007)

Pennsylvania saw approximately ten shifts between these two climate types over the last 1 million years. Evidence of at least three glacial advances exists within the
northeast section of the state (see Glacial Deposits MapA and Figure 2), including pre-Illinoian (850 ka), late Illinoian (150 ka) and Late Wisconsinan (entered Pennsylvania 20 ka) (Braun 2006b, 10). Evidence of a fourth, earlier advance is present in the northwest corner of the state, and it is presumed that this advance brought ice to the northeast as well but no remnant deposits have been discovered.

During the last of these glacial periods, the Late Wisconsinan, a continental ice sheet covered parts of North America for 25,000 years (Braun 2006b, 10). The extent of glacial erosion and volume of glacial deposition indicates that toward the northern border of Pennsylvania, Late Wisconsinan ice was present for 8,000 – 10,000 years, and lasted 2,000 – 3,000 years near the glacial terminus where it stopped further to the south (Braun 2006c, 251). Ice began to recede from this terminus 10,000 years ago. The glacial features and deposits in north central PA are so subtle that many early maps of the area do not show them, and the path of glacial end moraine was difficult to follow. Occasional evidence of striations and stream deposits made it clear, however, that ice had in fact been there.

West of the Lehigh River in Pennsylvania, a well-defined terminal moraine is rarely found, and the moraine boundaries are nearly indistinguishable from nearby ground moraine and colluvium (Crowl and Sevon 1980, 3). Glaciers moved out from the Hudson Bay and across the region flowing toward the southwest. While the ice is estimated to have reached a thickness of as much as 2 miles deep at its northern source, by the time the outer extent reached Pennsylvania, the thickness of ice along the margin was closer to about 3,000 feet (Sevon and Fleeger 1999, 11).

The thin ice presumably melted fairly quickly at the margin, where ice retreat was relatively rapid (Crowl and Sevon 1980, 10). End moraine can be seen on some north-facing slopes where topography was enough to block ice flow. In other areas it was able
to flow over, or around, the mountains and placed end moraine on south-facing slopes (Crowl and Sevon 1980, 12).

Earlier advances across the region would have caused notable erosion, removing much of the remnants that previous glaciers left behind. Deposits from these earlier glaciers are really only seen in places where these advances extended beyond the limits of the Late Wisconsinan ice. These prior glaciations followed very similar paths and patterns to the Late Wisconsinan, including ice flow direction and deposition patterns (Braun 2006b, 11)

Older glacial limits are primarily parallel to that of the Late Wisconsinan, and ice flowed over the region in the same general southwesterly direction each time. Glacier ice and meltwater erosion features that were initiated during the first glaciations generally became enlarged and/or deepened by subsequent glacial advances, particularly this close to the terminus (Braun 2006c, 249).

Spatially speaking, glacial advances in Pennsylvania covering the northeast corner of the state, moving toward the southwest, appear to have stopped roughly at the structural front that lies between the Appalachian Plateau and Ridge and Valley physiographic provinces. There is little evidence indicating that this is anything other than coincidental; by the time glacial flow reached the area it was quite thin, and would not have progressed much farther regardless of the topography.

The study area in this paper lies within the Appalachian Plateaus province of the state, and in fact comprises much of the mountainous high plateau section of the state (Glaciated High Plateau and Deep Valley Sections, Figure 3). This area is between the high and low plateau sections and is more deeply dissected than both. Only in this section is there a prevalence of dissection creating relief of 800 feet or more (Briggs 1999, 365).
Valleys present prior to glaciation that were parallel to ice flow would have been more prone to scour than those valleys perpendicular, which sometimes became buried with back-fill upon glacial retreat (Braun 2006b, 11). Approaching the terminus, the ice was thinner and shows a much wider range of flow directions as it became more driven by existing topography. The area is comprised of bedrock ridges with valleys between that are filled with up to 30 – 150 feet of glacial till (Braun 2006b, 12). The original dendritic to trellis drainage patterns were little modified by glacial erosion, but some local drainage has been modified by glacial deposits (Braun, 2006b, 13).

West of Lycoming Creek, till has a restricted distribution and is generally rather abundant only in valley bottoms and on adjacent side slopes. This gives evidence to the decreasing thickness of the ice as it reached the margin, and the occurrence of intense frost action, here where elevations are higher than they are to the east and a colder
climate would have prevailed during deglaciation. This resulted in the widespread deposit of colluvium and removal of glacial till from hilltops and slopes (Crowl and Sevon 1980, 13).

Very small kames exist west of Loyalsock Creek to Oswayo Creek (near the New York border) in valleys draining the glaciated area. Some kames and lake deposits appear to be related to a proglacial lake in the valleys of Pine Creek and its West Branch which drain toward the glacial border (Crowl and Sevon 1980, 13).

Elements of glacial scour within northeast Pennsylvania are similar to those that occurred farther to the north in the Finger Lakes region of NY. These depressions are notably smaller due to the fact that they are closer to southern limit of the glacier, and occur primarily on sandstone which is more resistant than the shale in New York (Braun 2006c, 248). The implication here is that glacial erosion was significant though not as marked, and enough to justify the designation of the Small Lakes Section of the Appalachian Plateaus province.

Estimated rates of glacial and periglacial erosion overall in the Appalachians exceed modern fluvial erosion rates (Braun 1989, 233). For this reason, the presence of the glaciers is recognized as the process dominating the shape of that landscape as it appears today.

**Drainage in North Central Pennsylvania**

Drainage throughout Pennsylvania was primarily to the north and west across the state towards Hudson Bay until about 250 million years ago. Not until tectonic action began opening up the Atlantic Ocean did new stream gradients toward the east start heavily eroding the region and allow the rivers of Pennsylvania to shift their flow into the newly created sea. This drainage arrangement was pretty much set until glaciation swept through and made some last minute modifications (Briggs 1999, 377).
The Glaciated Low Plateau section divides its drainage primarily to the Delaware River in the east and the North Branch of the Susquehanna River in the west, where local relief tends to be stronger. Glaciation in this section resulted in a “modified rectangular to dendric pattern of drainage” (Briggs 1999, 367) that trends primarily north-south. The presence of numerous small lakes, ponds and swamps in the area are also remnants of a glaciated past.

Moving westward into the Mountainous High Plateau section (MHPS), drainage is still somewhat rectangular with local trellis patterns. Eventually, streams achieve steepened gradients as they flow off of the plateau to tributaries of the North and West Branches of the Susquehanna. In the center of the MHPS the drainage has a stronger and larger-scale trellis pattern, and headward erosion of the West Branch Susquehanna has contributed to the deepening of valleys and dissection in the area that allude to its name (Briggs 1999, 367).

It is this section of the province that contains the Pine Creek Gorge – or Grand Canyon of Pennsylvania - stretching 55 miles through Tioga and Lycoming counties, and reaching a maximum depth of 1450 feet (Briggs 1999, 368). This gorge lies within the study area along the upper reaches of Pine Creek, just inside the glacial boundary, and owes its beginnings to damming caused by Late Wisconsinan glacial debris. Pre-glacially, Pine Creek flowed to the northeast. The build-up of deposits left by the advancing and then retreating ice blocked the Creek and created a lake. Glacial meltwaters then overflowed the lake to the south, causing the Creek to reverse its flow which now leads to the West Branch Susquehanna (Thompson and Wilshusen 1999, 818).

While stream segments in this area have patterns more like the Appalachian Mountain section of the Ridge and Valley Province, the broad ridge tops of mountains in
the section are at elevations that place them firmly in the Appalachian Plateaus province, as more of the relative area is covered by said ridges than by valleys, while in the Appalachian Mountain section the reverse is true (Briggs 1999, 368).

Pennsylvania tends to be a surface water rich state, with a high-density stream drainage system. Additionally, the largest areas of natural wetlands in the state occur in the northern regions where glaciations have occurred (Click 1999, 680). Evidence that this drainage system in the north central part of the state was only mildly, or mostly locally, affected by Late Wisconsinan glaciation exists in the form of remnants of the stream channels that preceded current ones.

The majority of smaller stream tributaries flowing down the slopes in this highly dissected region tend to run closely parallel to their “interglacial consequents” (Von Englen 1945). These former stream channels reveal the course of drainage prior to the most recent ice advance, and which were subsequently covered by till (. That they remain means that the erosive effects of the glacier were not intense enough to completely remove them, and the current drainage has largely followed in their footsteps.

This phenomenon is seen not just in this part of Pennsylvania where the ice was relatively thin, but also exists within similar topographies that lie further to the north which would have been under greater volumes if ice. Not until north of the Finger Lakes region in New York do these former stream channels disappear, entirely removed through glacial erosion.

**Glacial Processes With Respect to Landscape Evolution and Stream Morphology**

The advance and retreat of glacier ice, whether in the form of a continental ice sheet or a local mountain valley glacier, leaves a very distinctive trademark on the ground that it reaches, and in most cases, even on ground that it doesn’t. Glaciers become powerful erosive forces that scrape, break, remove, and deposit rock along the landscape.
The ice can serve to dam existing drainage ways, creating lakes and diverting the flow of stream channels. As the ice melts, it can send substantial amounts of debris and meltwater down river. It also leaves behind large blocks of ice that create ponds, kettles and wetlands that can still be seen in the modern topography.

Evidence of the extent of glacial scour in north central Pennsylvania can be seen along the North Branch of the Susquehanna River near Wilkes-Barre, where as much as 100 meters have of scour exist before you reach bedrock beneath the current river channel. Subsequent glacial activity has filled, or buried, this river valley with deposits that raise it to the current level (Braun 2006c, 250).

One of the abundant glacial characteristics in the region is the series of “till knobs” created from till moraines formed as the glaciers retreated, and that have since been eroded and modified. These are on average 30 meters thick or more, and several hundred of them, alternating between lakes and wetlands, can be seen in the namesake Small Lakes Section of the Appalachian Plateau (Braun 2006c, 253.).

In valleys positioned transverse, or perpendicular, to the direction of glacial flow, glacial till was deposited more thickly on the north facing mountain slopes, forming “till shadows”. In these valleys, “one-sided” post-glacial bedrock gorges with bedrock on the southside and till on the north side are common, forming as the drainage finds its way through by creating incisions along the contact between bedrock and till. (Braun 2006c, 261). Most of these till deposits do not show any evidence of older pre-Wisconsinan till underneath.

A stunning example of the consequences of a till shadow feature occurs in the study area about 2 miles north of the glacial terminus along the West Branch of Wallis Run. Here, in a section that was almost completely buried by till, the eastern side of the valley is comprised of glacial till with sandstone ledges exposed on the west side, and the
stream falls over a series of rock ledges to create a waterfall for 80 feet (Braun 2006a, 12). The location sits, not surprisingly, in what is now called Cascade Township.

Till shadowing also impacted drainage patterns further north of the glacial terminus near Worlds End State Park, where Loyalsock Creek experiences a 180 degree bend before it continues through a small gorge. A pair of incised meander loops existed at the location prior to glaciation. The north end of the meander was buried by a thick till shadow (Braun 2005, 10). When the glacier was gone, the Loyalsock made its way through the valley center, and at the bend the stream channel is presently cutting back into the till that covered the meander, exposing an outcrop of till nearly 200 meters high.

Glaciofluvial features, resulting from the flows of meltwater, are notably absent in this region (Photo 1). These types of deposits are much more common in areas with similar topographies to the north and to the east, particularly in valleys parallel to glacial flow. However, valley bottoms of some of the larger rivers in Pennsylvania that remained ice free, including the Susquehanna and Pine Creek, contain several feet of Late Wisconsinan outwash sediments, deposited by meltwater streams. Smaller streams such as Lycoming Creek and Loyalsock Creek (both of these are included in the study area) contain similar outwash deposits (Crowl and Sevon 1999, 229).
In updating the glacial terminus for his 2006 map, Braun locates it along Wallis Run about a mile and a half north of its confluence with Loyalsock Creek, noting the presence of the head of outwash and the presence of up to 100 feet of glaciofluvial deposits flanking the stream valley (Photo 2).
Along the terminus, several stream hollows that sit just within the glacial boundary have been “choked” with glacial deposits, over which present streams still run. Conversely, stream hollows that sit just outside the boundary do not contain such glacial deposits, and many of the present stream channels flow directly over bedrock (Braun 2007, 16).

Along Lycoming Creek just outside of the glacial terminus, abandoned stream channels can be seen at the mouth of the Glendenen Run tributary where outwash sediments were abundant enough to dam the stream, forcing the drainage around them to the north. These gravel deposits were at the same time sparse enough that they were eventually removed with the help of action from the larger Creek, and the Run returned to its pre-glacial channel.

Throughout periods of glacial advance during the Quaternary, the non-glaciated portions of Pennsylvania experienced extensive periglacial activity (Crowl and Sevon 1999, 228). The Late Wisconsinan stages would have likely supported a tundra environment in the area, including some continuous permafrost. This environment, which was probably seen during prior glaciations as well, facilitated a great deal of freeze-thaw cycling along the bedding planes and fractures within the sandstones along many of the Appalachian Mountain section ridges (Crowl and Sevon 1999, 228).

The break up and subsequent downslope movement of the broken rock debris over thousands of years is believed to have lowered mountain elevations as much as several tens of feet (Photo 3). These processes along with post-glacial erosion would have also helped to remove glacial deposits. Additionally, areas outside of the Late Wisconsinan glacial boundary that contain remnants from older glacial advances reveal that some of the colluvium there has come from till that was once sitting upslope.
Methodology

In order to assess variations between streams affected by Late Wisconsinan glaciation and those outside of the glacial boundary, as well as any apparent effects on drainage pattern development, an 8,303 square mile study area was identified in north central Pennsylvania (see Pennsylvania Stream Drainage Map B). The study area encompasses six counties in their entirety and portions of 12 additional counties. It also covers seven physiographic sections in the state, including all of the Glaciated High Plateau section of the Appalachian Plateaus Province (Figure 4). Notably, the Late Wisconsinan ice sheet boundary runs diagonally through the study area dividing it almost directly in half. The northeastern section was under glacial ice as recently as 10,000 years ago; portions of the south central section, extending beyond the Late Wisconsinan terminus, were also under ice during Illinoian advances 150,000 years ago.
The area receives regionally common temperate climate seasons and rainfall amounts. It also supports highly analogous types of vegetation cover. This part of Pennsylvania was heavily timbered at the end of the 19th century, and now sustains secondary growth forest over a large percentage of the area.

Data and digital GIS files encompassing the location were collected from the Pennsylvania Spatial Data Access (PASDA) website, including vector files for streams, lithology, and Late Wisconsinan glacial terminus boundaries. Stream line files were converted to raster format for use with elevation grid files. Digital Elevation Model (DEM) 30-meter resolution data and topographical quadrangle maps were obtained from the USGS. Elevation files were collected for the 18 counties included in the study area and mosaic-ed into a single grid file *(See Pennsylvania Elevation in Relief Map C).*
data was also used to calculate downstream slope values. Considerations for and known complications with using DEM data is discussed in the results section. All GIS was performed using ESRI ArcView software.

The stream line files for Pennsylvania include metadata information identifying the Strahler stream order number for each stream segment within the map file, allowing for the classification and segregation of these for analysis (Figure 5). These same files contain data on each stream segment length, which was ultimately used to calculate mean stream lengths and bifurcation ratios for all stream orders.

Figure 5: Strahler stream order distribution within study area. The West Branch of the Susquehanna River is the only 7th order stream in the area, and runs only through the non-glaciated section. (Data source: PASDA/DCNR 1995, PASDA/Penn State 1998)
Using the Strahler order designations to view stream distribution, for example, 2\textsuperscript{nd} and 6\textsuperscript{th} order streams would appear like this (Figure 6 A and B):

Figure 6A: Distribution of 2\textsuperscript{nd} order streams within study area, compared to distribution of 6\textsuperscript{th} order streams shown in Figure 7 below. (Data source: PASDA/DCNR 1995, PASDA/Penn State 1998)

Figure 6B: Distribution of 6\textsuperscript{th} order streams. (Data source: PASDA/DCNR 1995, PASDA/Penn State 1998)
Digital lithology data was then used to determine the primary geology underlying each stream segment, revealing that the majority of all streams in the study area flow over sandstone rock (see Bedrock Lithologies, Appendix A). Other area geology, in order of decreasing prevalence, includes mudstone, siltstone, and shale, with nominal amounts of calcareous shale, limestone, dolomite and quartzite (Figure 8).

Figure 8: Primary bedrock lithology of study area (Data source: PASDA/DCNR 1995, 2001)
As such, streams of all orders, 1st through 7th, flowing over sandstone were separated. This provided a way to compare drainage in Wisconsinan glaciated and non-glaciated areas using sandstone as the control for geologic substrate. This created a sample of just over 13,000 stream segments for analysis within the study area: 6,189 in the glaciated section, 6,991 in the area not covered by Late Wisconsinan ice (Figure 10. See Table 1, Appendix C).
This set of stream segments was then used to calculate stream frequency among all orders, for both glaciated and non-glaciated sections. In both sections, first order streams are easily predominant, present in numbers equaling the number for all remaining orders combined (see Frequency Charts, Appendix B). This pattern is consistent with the dendridic drainage of the area.

Results

Among 1st order streams, where the mean length for glacial streams is 1224 feet and that for non-glacial streams is 1301 feet. Additionally, greater numbers of non-glaciated streams occur at or near mean length than do glaciated streams. Very short and very long glaciated streams are more rare than their non-glaciated counterparts.
This trend reverses among 2\textsuperscript{nd} order streams, where more of the glaciated streams have lengths near the mean. Second order non-glaciated streams have a broader range of lengths. This in spite of the fact that the longest stream segment in the entire study area, the glaciated Little Mahoopany Creek at more than 12,600 ft., is a second order stream. Fifth order streams have the shortest mean length in both areas; in fact there were no 5\textsuperscript{th} order streams segments with a length of more than 3,700 ft.

The respective mean lengths of streams in both Late Wisconsinan glaciated (WG) and non-glaciated (NWG) areas are very similar among stream orders until 6\textsuperscript{th} order, when the mean length of glaciated streams exceeds the mean length of non-glaciated by more than 200 ft (Chart 1A). In general, the mean length of both WG and NWG streams decreases slightly from 1\textsuperscript{st} order on down through 5\textsuperscript{th}. The mean length then spikes up by more than 300 ft for 6\textsuperscript{th} order streams.

![Mean Stream Length - Sandstone](chart1a.png)

\textit{Chart 1A: Mean lengths of stream orders for streams flowing over sandstone.}

The mean stream coefficient (COE) indicates the amount of variation in length within each stream order, and was calculated by dividing the standard deviation of length by the mean length for each stream order. The resulting COE graph (Chart 1B) for both
WG and NWG stream orders essentially follows the same curve as their respective Mean Length graphs. However the graph indicates that 1\textsuperscript{st} and 2\textsuperscript{nd} order WG streams have greater variation in length than NWG streams.

![Chart 1B: Coefficient of variation for stream orders among streams on sandstone.](chart1b.png)

Additionally, using the individual stream order data, bifurcation ratios were measured to assess the relative evolution of any given order into the next higher stream order. This rate essentially determines, for example, the average number of 1\textsuperscript{st} order streams that are present before forming a 2\textsuperscript{nd} order stream, and so on.

By calculating the ratio of observed order streams to those of the next highest order within the study area, lower order streams tend to be “branching” at equal rates. However at the higher orders, for example, there are slightly lower bifurcation ratios for non-glaciated 4\textsuperscript{th} and 5\textsuperscript{th} order streams flowing into 5\textsuperscript{th} and 6\textsuperscript{th} order streams, respectively (Chart 1C). This may be a subtle indication of the level to which the non-glaciated section of the study area is a more mature drainage area.
Using the Digital Elevation Model (DEM) file for the study area from the U.S. Geological Survey and rasterized files for the stream data, mean elevation was calculated for each stream order. In order to achieve the most accurate elevation values from this file, calculations were made using only those elevation values directly corresponding (i.e., sitting directly under) the relevant streams.

Not surprisingly, the mean elevation for WG and NWG streams decreases at a fairly even rate from 1<sup>st</sup> order through 5<sup>th</sup> (Chart 2A). The only notable difference is that the mean elevation for 6<sup>th</sup> order WG streams is lower than that for 6<sup>th</sup> order NWG streams. This may indicate instances where glaciated 6<sup>th</sup> order streams, possessing higher rates of discharge than lower order streams, have eroded through deposits of more easily incised glacial till to reclaim former (and lower) channels.
Potentially more interesting, the calculation of elevation majority, or mode (the elevation that occurs most frequently within any given stream order), is notably higher.
among lower order NWG streams (Chart 2C). This trend may simply be a consequence of the higher elevations prevalent in the northwest part of the non-glaciated section of the study area.

![Chart 2C: Mode of stream elevation, indicating the elevation that is seen most often among stream orders.](image)

Elevation data was also used to calculate mean slope for each stream order. The degree of slope among NWG streams is steeper than WG streams across all orders except 5th (Chart 3A), again potentially indicating greater maturity of drainage in non-glaciated areas, in the absence of the scouring and therefore leveling effect of glacial ice. Notably, slope values in both areas and for all orders appear to be quite low, in spite of the resulting overall trend. Possible reasoning for this is discussed below. For the purposes of this study, it is in fact the big picture trend, instead of actual ground values, that are useful for topographic comparison.
An important notation for the use of DEM data in this study is the acknowledgement of their inherent uncertainty. Data derived from these elevation grids, including slope calculations, are subject to accuracy errors resulting from their creation methods. Although used as representations of topography for much of the GIS work...
involved in environmental analysis, they are not in fact “true” representations of the 
ground surface (Wechsler and Kroll, 1081). DEMs are traditionally created using 
interpolations from surface contour lines and point heights. More accurate files can be 
created – where not cost prohibitive – using photogrammetry and satellite data (Ziadat, 
68). The result creates a file of predicted instead of absolute elevation values for the 
given surface. Having said that, DEMs are also the most commonly used source for 
elevation data when performing GIS analyses, in the absence of any higher accuracy 
format.

Another important consideration is the even further decrease in accuracy that can 
result from the level of resolution used for a given DEM file. The resolution correlates to 
the grid cell size of any DEM raster, e.g., where a 10 meter grid cell has interpolated 
elevation values from a ground area of 10 square meters, and a 100 m grid from 100 
square meters, and so on. The accuracy of derived values decreases progressively as grid 
cell sizes get larger. DEMs of 30m were used as the finest resolution practically 
available for this study. Ten meter resolution DEM files are available for the more than 
150 USGS quadrangles that lie within the study area, and would certainly be a valuable 
implementation for further and more precise analysis.

Discussion

Even as early as 1945, interpretations of glacial drainage diversion noted that the 
Late Wisconsinan “found the way prepared for it, the country had been modeled by the 
earlier ice advances to accommodate a glacial flood,” or more specifically, the overflow 
channels previously created by more massive ice damming. Additionally, “the last ice 
apparently was of less volume than that of advances which preceded it…it was incapable 
of enhancing, or even modifying greatly, the forms from erosion created by the earlier 
glacierizations (sic).” (Von Englen, 1945).
While this generalization is large, and there are clearly examples of this most recent and relevant ice age throughout north central Pennsylvania, it does in fact bear out that overall impact on drainage from the Late Wisconsinan glacier was modest by comparison. This is especially true of an area so close to the glacial margins.

The drainage patterns that have taken shape in the area since glacial recession remain typical of those that this area maintained during interglacial periods. Although the glaciated section displays more of a “flattened” terrain, and the non-glaciated section shows deeper dissection (See Slope Gradient Map D), measurements of drainage do not overwhelmingly attest to this. They do, however, infer the presence of localized drainage impacts that play a role in this picture.

The glaciated and non-glaciated streams essentially break even with respect to observed numbers and mean length, showing no significant differentiation. The variation among the range of lengths for both is very wide. The lower bifurcation ratios among higher order non-glaciated streams does imply a level of more mature drainage, as headward erosion and piracy have enabled non-glacial streams to achieve a higher efficiency.

All streams show common mean elevation trends, up until the higher orders where the glaciated streams slowly begin moving toward lower elevations than non-glaciated streams. At first this seems to argue that streams are flowing over more easily incised glacial till, especially where glacial erosion might have eroded former channels, and 6th order streams, with higher amounts of discharge, are more quickly cutting down through any till that was deposited. But this could also be an indicator of where these streams have found and reclaimed the larger channels that went before them.

The more contradictory aspect here is the mean downstream slope findings. It would be expected that non-glaciated streams would flow along flatter slopes, having had
more time to initiate headward erosion, increasing overall stream length and channel erosion, both factors which tend to decrease slope. Another trend appears to be at work here, with the implication that glaciated streams, in areas where they are flowing over “till shadows” or valleys that have been back filled by glaciation, are running over “flatter” surfaces where slopes were scoured out and then filled back up, essentially leveled out by this process.

The limitations of the digital elevation model data, which is used to calculate slope, needs to be noted at this point. Although the possible inaccuracies have been considered in the interpretation of the slope data derived for the study area, this assessment is more interested in the implications that are shown by the overall slope trends of each stream order. Using more accurate elevation data might result in “truer” values for localized slope gradients with respect to specific high and low elevation points. Here, however, it is assumed that use of this more accurate data would still produce the same trends seen with the 30-meter DEM data.

In spite of the fact that evidence is scarcer from ice sheets that flowed through the area before the Late Wisconsinan, the assertion of much of the literature is that the former tended to be larger and more impactful upon the landscape. Looking closely at this area of Pennsylvania does seem to reveal, however, that thin or not, it is the cumulative effect of this ice motion that has sculpted the particular patterns that exist there today.

All else being equal, the discernable changes in drainage brought about by the last glacier are relatively slight. But they do exist, and sometimes in glorious form, such as the Pine Creek Gorge. And in reality, more evidence from the Late Wisconsinan ice sheet remains than from any that came before it, offering invaluable clues and information about the earth moving power – literally – of these frozen geologic forces.
Moreover, these local features (sometimes morphologically defining features) are not ones that are readily seen from a broader spatial scale. The flow of streams over till versus over bedrock can be distinguished clearly at ground level, and not so easily with GIS; surficial geologic maps have been completed for very few sections within the study area, and in fact have not been completed for the majority of the state.

It also feels somewhat unfair to downgrade the immensity and reverence due any such ice sheet just by virtue of its being a late-comer to the game. Glaciation of this magnitude is like nothing that has ever been witnessed first hand, by humans, anyway. And if it had, it still left behind a landscape that would have been barely recognizable. Once the glacier was gone, the streams were left to start over from scratch. In this part of Pennsylvania, at least, enough bread crumbs remained such that they were able to successfully find their way again.
References


Appendix A

Bedrock Lithologies

Breakdown of bedrock lithology among all stream orders for both Late Wisconsinan glaciated and non-glaciated sections of the study area. Sandstone represents the primary rock type in both areas and across all stream orders.
Appendix B

Stream Order Frequencies

1st Order Stream Frequency

2nd Order Stream Frequency

3rd Order Stream Frequency
** Glaciated = streams under Late Wisconsinan ice
NonGlaciated = streams with No Late Wisconsinan ice coverage
### Appendix C Tables

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* g = Glaciated (Late Wisconsinan)
* ng = No Wisconsin Glaciation
* STD = standard deviation (length)
* COE = coefficient variable
* BR = bifurcation ratio
Map B: Late Wisconsinan glaciated and non-glaciated stream drainage across study area. (Data source: PASDA/DCNR 1995, PASDA/Penn State 1998, USGS 2001)
Map C: Elevation and relief across study area. (Data source: PASDA/DCNR 1995, USGS 2001)
Map D: Slope gradients within study area. (Data source: PASDA/DCNR 1995, USGS 2001)