UMEÅ UNIVERSITET

Geological factors affecting the channel type of Bjur River in Västerbotten County

- A study concerning the connection between surficial geology, landforms, slope and different hydrological process domains in a stream catchment above the highest shoreline.

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Abstract

Process domains categorizes sections of streams according to its local dominant processes. These processes often reflect on the local ecology and the streams appearance. But the underlying reason why these different process domains are formed are still not completely certain. In this study the distribution of the process domains: lakes, rapids and slow-flowing reaches in the Bjur River catchment were compared to the geological factors of slope, surficial geology and landforms to see if any connections could be found. The possibility of using GIS (geographic information systems) and remote data to distinguish these stream types and to connect them to the different studied geological factors were also examined. The hypothesis for this study is that the geological factors of slope, surficial geology and landforms all should have an influence over the distribution of the process domains in Bjur River. The analysis was executed through map-studies in ArcGIS and statistical analysis in Excel. All process domains showed statistical significance towards the studied geological factors. The slope was generally steeper in the rapids than in slow-flowing reaches and lakes. The surficial geology displayed more fine-grained sediment (peat) in proximity to lakes and slow-flowing reaches whilst till was more abundant close to rapids. Hilly moraine landscapes were most common around lakes, while rapids displayed a high percentage of glacio-fluvially eroded area. Slow-flowing reaches also showed to have around 44% of its studied points around glacio-fluvially eroded area, and 43% at areas without any major landforms. Even if the statistical analysis and figures display a difference between the different process domains, it is still difficult to say which of these geological factors that plays the most crucial role for their development. However, by using remote data and through studies over slope, adjacent surficial geology and landforms the different process domains can be differentiated from one another.

Keywords: Process domains, Channel type, Surficial geology, Slope, Landforms, Above highest shoreline, Northern latitudes

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1 Introduction

Sweden has an average water runoff of about 12 litres per second for each km^2 (SMHI 2007). A large portion of that water accumulates in valleys and creates streams that flow through our landscape (Bolin and Falkenmark 2004a). Streams erode, transport, and deposit sediment, and all of these are processes that affect the appearance of both the streams themselves and their nearby landscape (Davis 1899; Schumm 1985). These processes can, for example, create meander bows when the stream encounters an obstacle, like a large boulder, which can affect the course of the stream. The stream can then start eroding the outer bends and deposit its transported material in the inner bends creating these typical winding patterns (Johansson 2005, Kasvi et al. 2017, Seppälä 2005a). There are multiple models to try and define streams and distinguish its different segments and processes, and one of them is the theory of stream evolution initiated from base level changes or tectonic uplift. Davis (1899) and Schumm (1985) provides common examples of these kinds of stream evolution models. The top of the catchment is generally a zone characterized by fluvial erosion, whereas the middle is a zone of transportation, often through meanders. Deposition is common near the outlet, which promotes the formation of deltas (Cluer and Thorne 2013).

However, these models are often generalized when seen in the context of a larger catchment-scale. According to later studies, the channel seems to rather be controlled by small-scale variations, but even in a local scale there are still multiple ways to categorize streams. One example is by its bedforms, where the form of the riverbed is seen as a result of specific flow attributes, slope, sediment access and the sediments coarseness (Montgomery and Buffington 1997). Another way to categorize streams is through their process domains (Montgomery 1999). Process domains categorize streams according to their geomorphic processes (with e.g. major erosion or deposition), which then reflect upon the stream morphology, flow velocity and the resulting major ecology living within, and around the stream (Nilsson et al. 2002). To use the concept of process domains is a way to generalize an otherwise very complex variation of stream morphology. Different types of process domains used in this study are *lakes*, *slow-flowing reaches* and *rapids*. Fluvial processes have a major impact in many landscapes where it erodes, transports and deposit materials along its course (Seppälä 2005a). But the reason why river morphology and the ambient landscape change over time are still a bit uncertain. Some connections have been drawn with, for example, the changes in flood length and the length of winters and its accumulati on of snow. An increased amount of precipitation has connections to e.g. water discharge and sediment erosion (Rapp 1986). Fine sediment makes it easier for erosion and transport, whilst coarse sediments act as an obstacle, altering the streams' flow direction. The vegetation adjacent to streams could enable or restrict lateral erosion of streams (Johansson 2005, Kasvi et al. 2017, Seppälä 2005a).

At northern latitudes, including Scandinavia and Canada, there is at least one other major event that could affect the rivers morphology and its adjacent landforms and geology—the glaciations (Brardinoni and Hassan 2006, Seppälä 2005b). At times when the glaciers were frozen at their base, the underlying landscape was preserved from erosion, but during periods of warmer ice, there was larger impact on its substrate (Johansson 2005, Lundqvist and Robertsson 2002). Glaciers deposited different types of till and contributed to the formation and preservation of different landforms such as drumlins and hilly moraine landscapes. During the melting of the glaciers, large amounts of meltwater were released which provided different sized materials to be deposited as glaciofluvial sediments (Fredén 2002, Johansson 2005, Seppälä 2005b). Continuous land uplift became a secondary effect from the deglaciation and release of pressure over the earth's crust, which left the shoreline retreating in many coastal areas in Sweden even more rapidly than the sea level rise (Eronen 2005, Lundqvist 2002). This causes the river processes to continuously advance in response to the deglaciation that occurred about 16 000-9000 years ago in Sweden (Lundqvist 2002). Some of these areas in the northern latitudes that were covered by the latest glaciation displays a higher lake density as seen to a global perspective (Messager et al. 2016). This makes them interesting for further studies regarding their underlying reasons for development of different process domains. Bjur River is a well-studied catchment area situated in the northern parts of Sweden and is therefore an appropriate location to study.

This study examines if it is possible by using GIS (geographic information systems) and remote data to understand where different process domains form based upon the geological factors of slope, adjacent surficial geology and landforms. Therefore, the aim is to investigate if these geological factors have any connection to the resulting process domains in the Bjur River catchment. To acknowledge and to study these differences in process domains is important to aid understanding of the underlying reason to these hydrological changes and to help us figure out how to manage and restore these rivers (Lotsari 2015, Wohl 2018).

1.1 Hypothesis

In this study the geological factors of slope, surficial geology and landforms are predicted to have an influence over the distribution of the process domains (lakes, slow-flowing reaches and rapids) in Bjur River. Slopes are predicted to have a connection towards the resulting process domains where higher slopes should lead to higher flow velocity and therefore be more abundant in rapids, whilst the lowest slopes are assumed to be found in lakes. The surficial geology is expected to be more coarse-grained in rapids where the fine sediments have been eroded and transported (Lotsari et al. 2015, Nilsson et al. 2002, Palucis and Lamb 2017). The large grains could also promote turbulence which is more common in rapids. Fine-grained sediment tends to deposit at low flow velocities and is therefore assumed to be more common around lakes. Most process domains should be found – to some extent, close to till-connected landforms (e.g. moraine landscapes) according to its frequency in this area. Lakes and slow-flowing reaches have relatively low flow velocities and should therefore be more uncommon connected to landforms of high relief. Rapids and slow-flowing reaches are predicted to some extent be over layering its own fluvial deposits through e.g. occasional alterations in the channel path or episodic flooding's of fluvial sediments.

2 Methods

2.1 Study site

The study was carried out in northern Sweden in a stream called Bjur River (Figure 1). Bjur River is a tributary of the Vindel River, one of Sweden's few national rivers and a river of great national interest (Alatalo 2017). The national rivers are according to the Swedish environmental code rivers protected against any expansion of hydroelectric power (miljöbalken 1998:808, ch. 4, 6 §). The Vindel river originates from the mountain region between Norway and Sweden. It flows towards the eastern coast where it, in Vännäsby merges with the Ume River, which has its outlet in the Baltic Sea (Johansson 2005). The Vindel and Ume Rivers can be described as an "inland and mountain river to the low hilly coast of the Bothnian sea in Sweden" (Johansson 2005) based on its morphology, location, historical evolution and predicted development.

Bjur River has a catchment area of 381 km^2, and an entire stream length of 67km, whereas a stream length of 59 km was studied in this report (Figure 1). Between the years 1981-2010, the daily average water discharge at the outlet of Bjur River reached 4,90 m^3 per second. The average precipitation in Bjur River catchment is about 690 mm per year and the river has an outflow of approximately 392 mm per year (SMHI and Havs och vattenmyndigheten n.d.). The winters are often snowy, and the summers tempered to warm (Bolin and Falkenmark 2004b). The elevation of Bjur River outlet are about 300 meters above sea-level, whilst the highest shoreline is at about 220 meters, ~13 km east from Bjur River, towards the coast (Lidmar-Bergström 2002, Lundqvist 2002). Gneiss and granite dominate the local bedrock (Norling 2002, Persson 2002), making boulder-rich areas common in proximity to the granite bedrocks (Persson 2002). The surficial geology is characterized by till, with glaciofluvial deposits located around some of the river channels (Fredén 2002, Persson 2002).

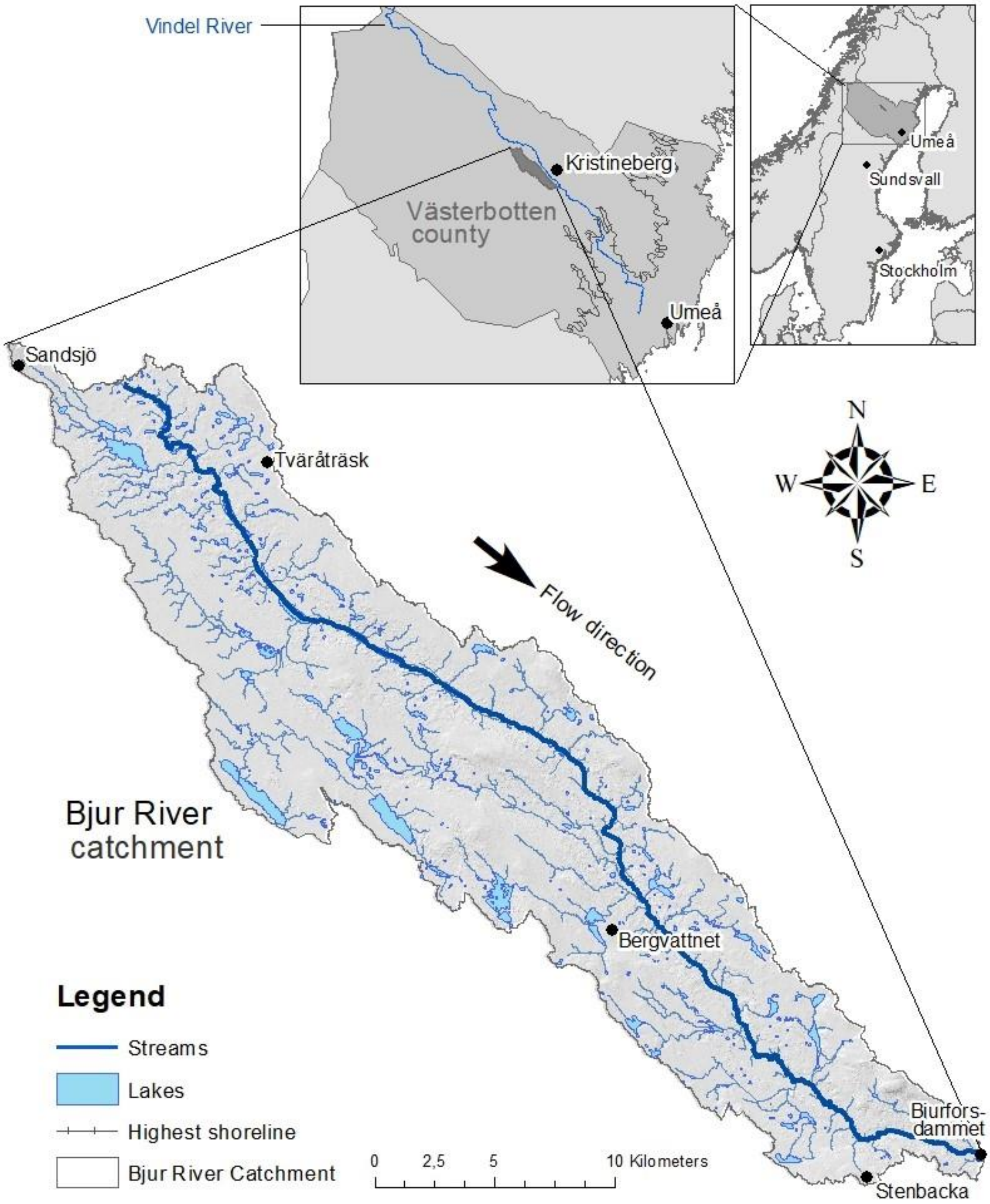

Figure 1. Location of Bjur River and its catchment. The small-scale inset map describes the catchments location in Sweden and its relation to the highest shoreline. The lighter, slender streamlines display streams with a minimum catchment area of 0,35km^2. The darker, broader stream indicates on the main stream, the one focused on in this study. The stream flows into the Vindel river at Bjurforsdammet. The hillshade is shown with an azimuth of 315 and altitude of 35 to highlight the differences. The coordinate system used is SWEREF99 TM and the data is collected from ©Lantmäteriet and ©SGU, national boundaries, counties, large rivers and the highest shoreline is collected from ©Natural Earth.

2.2 Data collection

A 2-meter DEM-file (digital elevation model), general map and orthophotos were obtained from Lantmäteriet (The Swedish National Land Survey). A file containing both surficial geology and landforms at the scale of 1:25 000 and 1:1 million was obtained from SGU (The Swedish Geological Survey) to work with as map layers in the computer program ArcGIS (Environmental Systems Research Institute (ESRI). 2016). The surficial geology contained polygons over e.g. peat, till and glaciofluvial sediments, whilst the landforms included more formations, like hilly moraine landscapes or glaciofluvial eroded areas.

2.3 Data handling

The coordinate systems of the different map layers were checked in ArcCatalog, a file manager so that they all were uniform with each other. The "Fill" tool was used for the 2-meter DEM file to smooth out irregularities that could affect the analyses. The "flow direction" tool was then used; this tool tells you in which direction all the cells in the DEM file slopes. Flow accumulation was then calculated on the DEM file to determine where the larger streams was formed based on the direction of the cells, and how much was calculated to have been accumulated into each cell. Raster calculator was used to convert the flow accumulation to a convenient cell size of 1m^2 by multiplying the flow accumulation raster by 4. Raster calculator was then also used to set conditional statements over how small minimum catchment area these streams need to have to be displayed on the map, for example: to only show streams with a smallest minimum catchment area of 0,25km^2, the conditional statement of equation 1 was stated (Eq. 1).

Eq. 1: **(Con (*Flow accumulation raster in m^2*>250000, 1, 0))**

The resulting stream raster was then converted into a polyline using the "raster to polyline" tool. Different minimum catchment areas for streams were tested to determine the one most suitable for the presentation and upcoming analysis. A new shapefile was created, and a point was set using the editor toolbar to mark the Bjur River outlet where the stream met the Vindel River by the Bjurforsdammet (Figure 1). The "watershed" tool was used to delineate the Bjur River catchment area, which later was converted into a polygon using the "raster to polygon" tool. To restrict shapefiles to this catchment, the "clip" feature was used. The file containing the catchment was also used to calculate the catchment area. First a new field was added into the shapefiles attribute table before a tool called "calculate geometry" was used to extract the area of the catchment. The catchment-file and the different files containing streams of various minimum catchment areas was extracted to a KML file and checked on top of a map in ©Google Earth Pro to see which minimum catchment area for streams that matched the satellite images best.

The 2m DEM file was restricted to the catchment area by using the tool "Extract by mask". To highlight elevational differences, a hillshade with an azimuth of 315 and altitude of 35, as well as contour lines was created. The DEM file was also used to create a layer containing information about the slope percent for each cell in the catchment area using the "*slope*" tool. The files containing landforms and surficial geology was clipped, and the orthophotos was extracted by mask to fit the extent of the Bjur River catchment.

A new shapefile was then created in ArcCatalog and by using the editor toolbar in ArcGIS a polyline could be constructed to that file. To mark out to main stream, I drew a line from the Bjur River outlet and continued upstream following the route with the largest stream accumulation. To ensure the route of the main stream I checked the attributes of the cells upstream in every stream branch where two visually same-sized streams collided. I tried to follow the centre of the stream according to the underlying orthophotos. After the entire main stream was mapped out, points were constructed at every 50 meters of the stream using the “Construct points” tool in editor toolbar (figure 1). Further upstream it got more difficult to distinguish the stream and its appearance in the orthophotos, therefore all points upstream from the point where the stream started narrowing down below 5 meters were removed in this study. For the remaining points I added an additional field into the attribute table containing the title “Process domains”, where I added information about each point’s specific process domain. Different process domains were decided through visual observation of the map at each point and a subjective opinion based on the channel geometry and appearance. Narrow, white shimmering sections where defined as rapids, narrow reaches without any white shimmering or major widenings were defined as slow-flowing reaches, and where major widening occurred were defined as lakes (figure 2a). The different process domains were checked at each point and a number connected to each type of domain where then entered to the attribute table of each point.

The lakepoints as I interpreted them, were later checked with the already mapped out lakes in the general map over the area and through the layer containing water in the surficial geology shapefile. My lakepoints generally agreed with SGU: s map over surficial geology but partly due to the SGU: s surficial geology map being modelled in the scale of 1:25 000 and that I worked at a much larger scale, the borders where not always consistent to each other.

Because I wanted to collect data adjacent to streams to each point, I had to enlarge the area from which the information was collected. I therefore created buffer zones for each point so that they extended out of the stream and covered adjacent landforms and surficial geology. The width of the buffer zones differed for each process domain, the width for rapids and slow-flowing reaches was decided through the widest point in each process domain to make sure that all buffer zones would extend past the stream itself. The lakes had much larger variation in width than the other process domains. So, in order to avoid the risk of covering a too large an area outside of the closest landforms and surficial geology, the lake points were categorized according to the width of the lake at each point. The calculation used is shown in equation 2, where “*the maximum value in each width category*“ refers to the different lake width categories shown in Appendix 1.

Eq. 2: ***[The maximum value in each width category]*/2+20**

This equation (eq. 2) together with the 50-meter differences between the lake width categories (shown in Appendix 1) restricted the minimum distance out from the shore to 20 meters, and the maximum to 45 meters (figure 2b, c). The slope was extracted directly through the points with the “extract multi values to points” tool, whilst the dominating surficial geology and landform within each buffer zone was collected using the “spatial join” tool. The different geological factors (slope, dominant surficial geology and landforms) could now be found in the attribute table, as well as the information over process domain and width of buffer zones, to each specific point.

The information stored in the attribute table was then exported as a database file (.dbf) to Excel where all data were sorted and calculated through statistical analysis.

Data was obtained for a total of 1180 study points, where 277 were collected from lakes, 824 from slow-flowing reaches and 79 from rapids. The results for slope sometimes showed odd values of -9999 percent in the dataset; these was treated as false values and where therefore replaced by adjacent locations’ percentual mean slope value. The results from the surficial geology in the scale of 1:25 000 showed a large number of unidentified points (288 out of 1180 points, 24%). Therefore, I downloaded another layer displaying surficial geology at a coarser scale of 1:1 million from SGU (Appendix 2). This layer’s information was also extracted to each point using the same buffer zones as the one for 1:25 000 (Appendix 1) and the same “spatial join” tool in ArcGIS to be able to get a more representative picture by replacing the unidentified points in the scale of 1:25000 with the ones from 1:1million (Appendix 2 and 3).

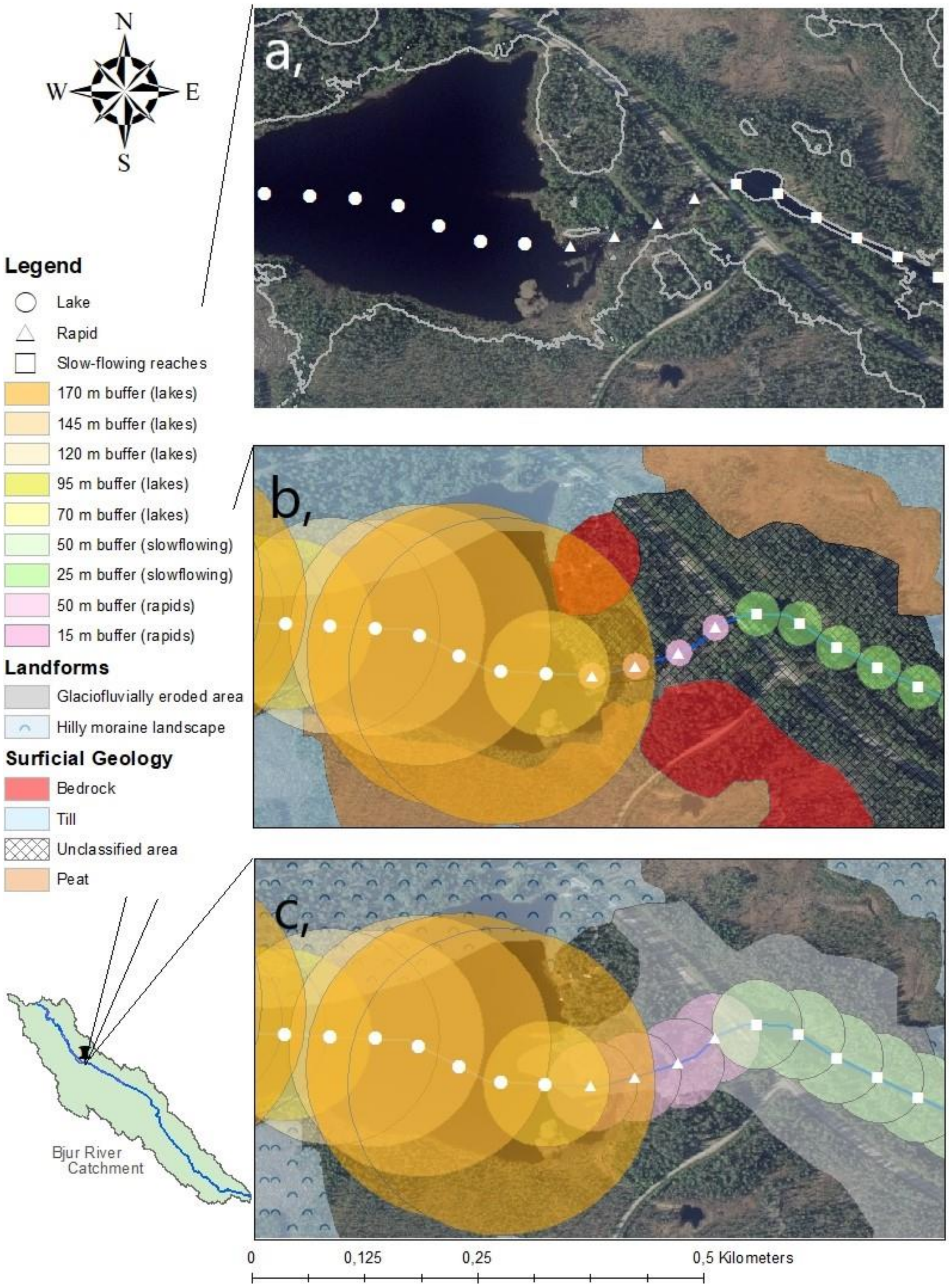

Figure 2. Schematic picture of the process domains. Inset map *a* show a delineation of process domains and underlaying contour lines every 5 meters elevational difference. Map *b* show buffer zones used to include adjacent surficial geology, and *c* displays buffer zones to include adjacent landforms, all in a representative part of the Bjur River catchment. The coordinate system used is SWEREF99 TM and the data is collected from ©Lantmäteriet and ©SGU.

2.4 Statistics

2.4.1 Numerical

I wanted to test if the channel slope (measured in percent) had any connection to the variation in process domains. Normal distribution was tested on the dataset, but the results turned out negative, but with that in mind a One-way ANOVA and a Tuckey-Kramers post hoc test was still executed. The significance level was set to 0,05 and the results were calculated and presented in figures using the Excel Office 360 program.

2.4.2 Categorical

Surficial geology and landforms were collected as a non-continuous dataset with categories instead of numerical data. This resulted in a Chi- squared test, testing if any significant difference could be found between different landforms or surficial geology and the different process domains. The test was calculated and presented in figures using the Excel Office 360 program where the significance level was set to 0,05. Percentual values were rounded before they were presented in figures.

3 Results

3.1 Slope

The different process domains had a quite large variation in maximum slope, from 1% in lakes to a maximum value of almost 50% in rapids. All domains still showed low median values of 0% in lakes and slow-flowing reaches, and 1% in rapids (Figure 3).

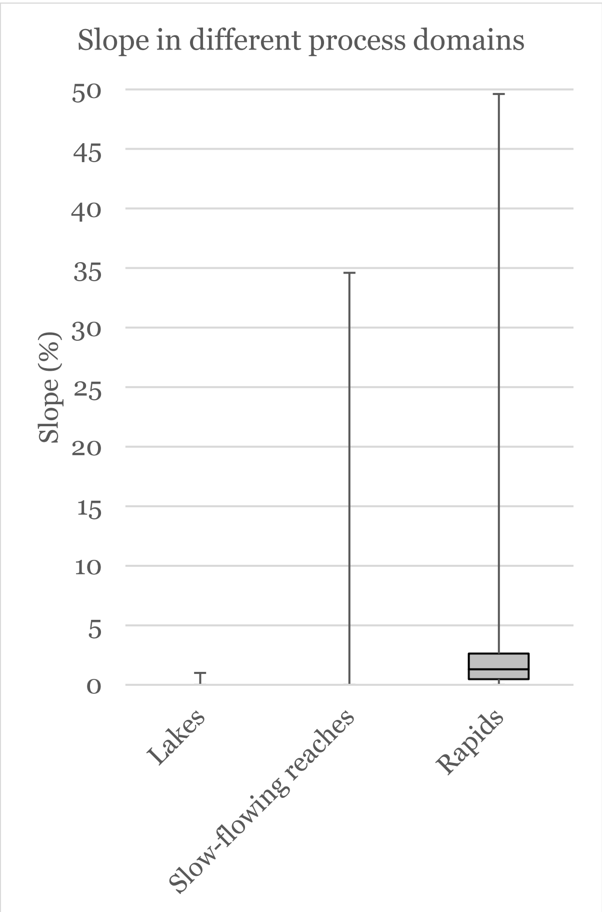

Figure 3. A boxplot of the slopes in different process domains in the Bjur River. Median values in both lakes and slow-flowing reaches is 0, leaving only the highest 25% visible as whiskers.

The Tukey-Kramer Post Hoc test had q-values exceeding the critical value of 3,31 for a test with a significance level of 0,05, and degrees of freedom exceeding 120 (df=1177) within groups. This means that the null hypothesis was rejected and that all the process domains were significantly different from one another regarding slope (Table 1).

Table 1. The results of Tukey-Kramers Post Hoc test for slope. 'Difference' refers to the difference between the average values of the two compared groups, 'n' is the number of points in each group, and 'SE' is the standard error, q stands for q-statistic and tells us the p-value where the false discovery rate is taken into account.

Tuckey-Kramer Post Hoc Test		Difference	n (group1)	n (group2)	SE	q
LAKE	RAPIDS	3,3	277	79	0,3	12,8
RAPIDS	SLOW-FLOWING REACHES	2,7	79	824	0,2	11,4
SLOW-FLOWING REACHES	LAKE	0,6	824	277	0,1	4,1

3.2 Surficial geology

A Chi-squared test was executed on the dataset for surficial geology at a scale of 1:25 000, complemented by points from the scale of 1: 1 million for the points that were unclassified (figure 4, appendix 2). The result showed a p-value below 0.0001 with 18 degrees of freedom when all process domains were tested, showing that a significant difference was found between the domains regarding surficial geology. The results for surficial geology displayed in figure 4 shows that both lakes and slow-flowing reaches has a high percentage of close-by peat and about one quarter of till. However, the rapids show almost half of its sampled points adjacent to till whilst glacial, and glaciofluvial sediments has the second highest percentage (figure 4). The surface geology shown in appendix 3 are less detailed than those in figure 4 and appendix 2. Appendix 2 in the scale of 1:25 000 shows a majority of peat in both lakes and slow-flowing reaches whilst the one in 1:1 million (appendix 3) shows almost no peat and seems instead to be dominated by till in all process domains.

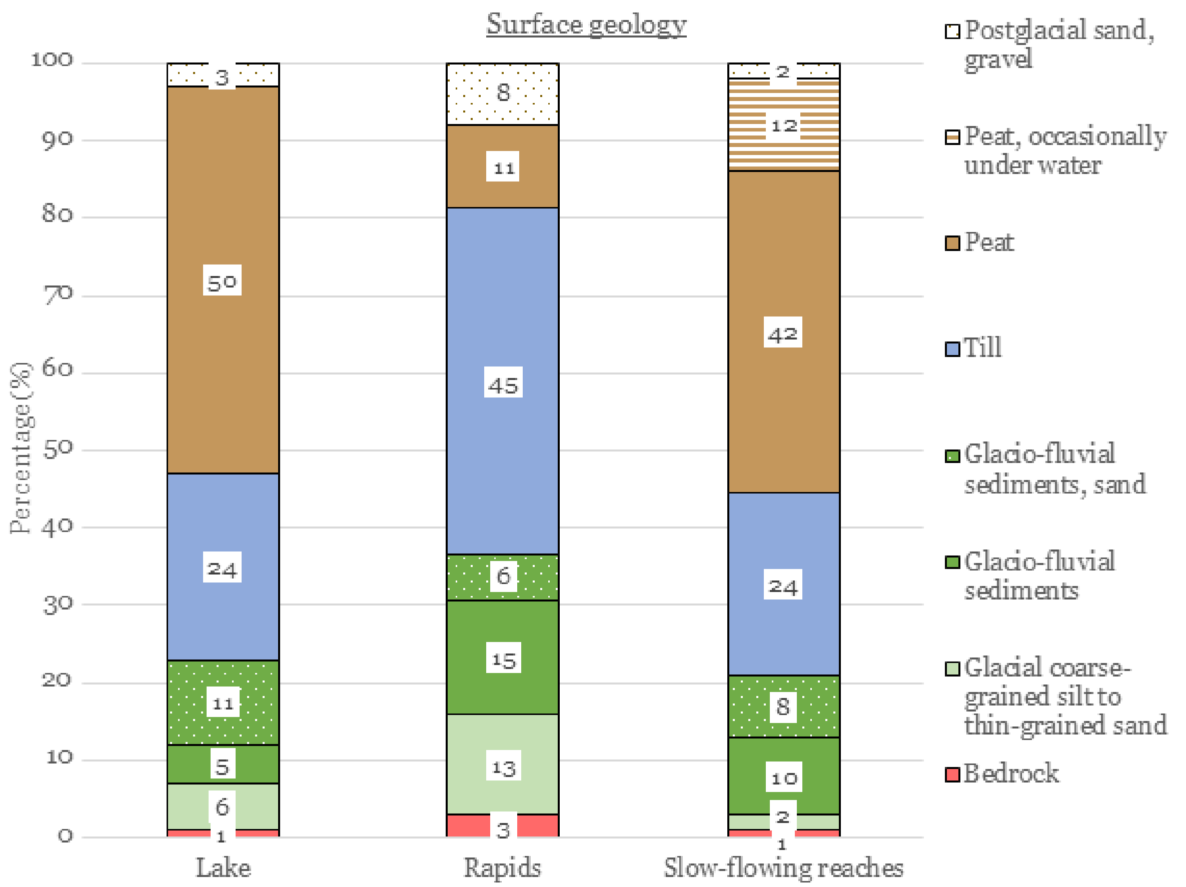

Figure 4. Distribution of surficial geology in different process domains from SGU maps at scale of 1:25 000, with complementary points from the scale 1:1 million added (where surficial geology was unidentified at larger scale) (see Appendix 2).

3.3 Landforms

The landforms were shown to have a strong significant relationship between the different process domains with a p-value below 0.0001 and 6 degrees of freedom in the Chi-squared test. Both rapids and slow-flowing reaches show a high percent of glacio-fluvial eroded area whilst lakes show a majority of nearby moraine landscapes and hilly moraines (Figure 5).

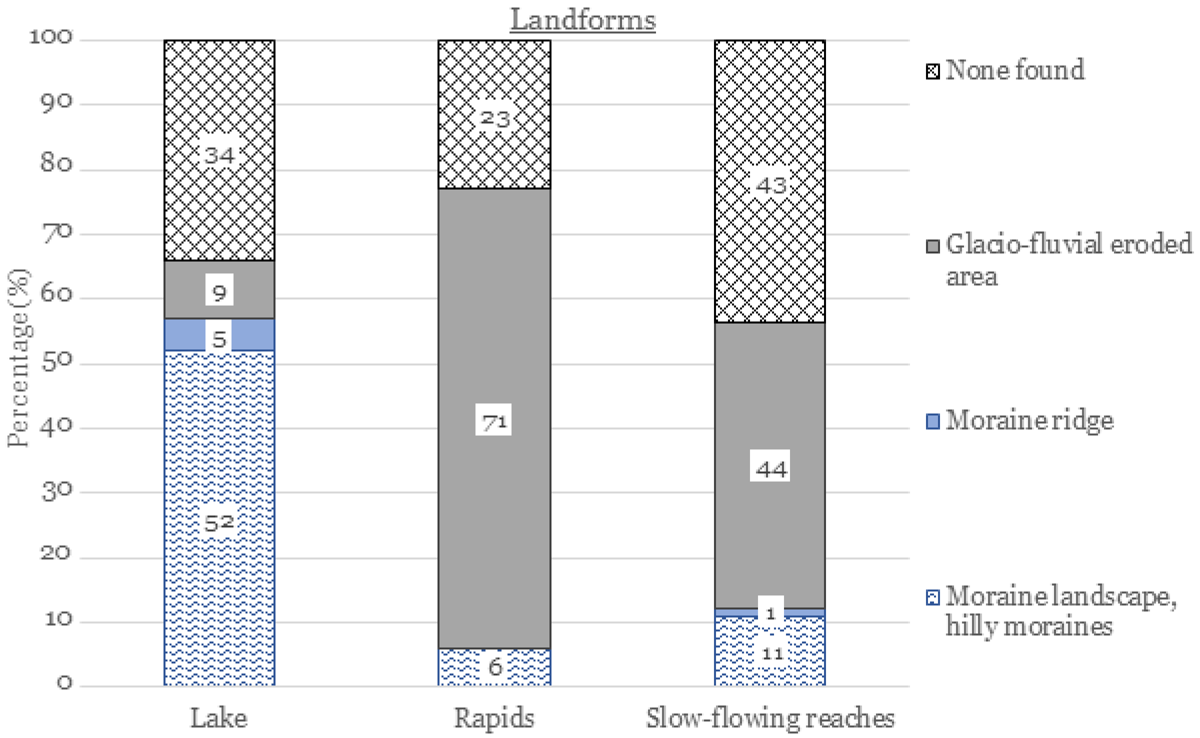

Figure 5. The distribution of landforms for each process domain. The landforms are collected from ©SGU in a map scale of 1:25 000.

4 Discussion

4.1 Slope

The largest difference in slopes found was between lakes and rapids, followed by slow-flowing reaches and rapids. The smallest difference was found between lakes and slow-flowing reaches, most likely due to the 75% lowest values within both groups was found at 0% slope. The median values showed quite similar results in all process domains studied whilst the maximum values varied widely, from~1% in lakes, to 35% in slow-flowing reaches and almost 50% in rapids. Given these numbers it would be difficult to assume a specific process domain based on a low slope when most of the points fell in the range of 0-1 percent slope (figure 3). But the higher the slope, the higher is the chance that it will form either slow-flowing reaches or rapids, and with a higher slope percentage (over ~2 percent) we can rule out lakes or in really steep slopes (over ~35 percent) even the most slow-flowing reaches.

So even if the statistics indicate a clear difference between the process domains, it is rather the maximum 25 % of the sample values in each domain that displays the difference between the three in this study. The results could also depend on the data source for slopes, which was collected from the centre of the stream channel. The value for slopes is rather showing us the slope of the waterbody's surface than the slope of the riverbed. The 2mDEM file that was collected from ©Lantmäteriet is made from LiDAR (Light detection and ranging) data. LiDAR collects data from points in the terrain and often use interpolations to estimate values in between the points (often through TIN (Triangulated Irregular Network)) to cover a larger area. Depending on the quality of the equipment, the LiDAR is more or less efficient on determining the water's surface. When the laser hits a water surface, it is poorly reflected. Therefore, the number of points in water is sparse, and larger areas of water becomes generalized through interpolations (Rönnberg 2011). This could be a contributing factor of why most of all studied point showed values of zero percent slope. The slope could also reflect the lateral slope rather than the longitudinal slope, because these calculations only takes the steepest slopes in account regardless of its direction.

The division between the different process domains with rapids displaying the highest slope percent and lakes the lowest is most likely accurate, even if the values alone might be misleading. There are possible solutions to still be able to keep this remote type of methods and get more accurate riverbed slopes. In the future, with improved techniques we might be able to use the bathymetric LiDAR data to assess the riverbeds slope as well as its form (Bailly et al. 2010). Or turn to more complicated calculations based on for example, meandering factors and assumptions based on adjacent cell slopes (Versano et al. 2012).

In general, many studies find that there is a difference in stream processes depending on the channel slope (Montgomery and Buffington 1997, Palucis and Lamb 2017, Snyder et al. 2012). For example, streams in a higher slope tend to erode and transport more materials than a stream in a flatter slope (Montgomery and Buffington 1997). We can also find trends in how the processes vary downstream when the highest slopes usually are situated in the top of the catchment (Montgomery and Buffington 1997). The Bjur River catchment seems to be more controlled by local variations than these general large-scale trends.

4.2 Surficial geology

The surficial geology adjacent to both lakes and slow-flowing reaches was dominated by peat (figure 4). Peat is a product of a long-time build up by incompletely degraded plants, a result of a relatively high growth rate and a wet local climate (Fredén 2002). The probability that it would be surrounding lakes and slow-flowing reaches seem relatively high, possibly due to the water velocity being lower than in rapids, which enables the plants to grow close to the water source. The access to water is constantly high and the stream could transport nutrients to the riparian zone during flooding (Abell et al. 2013; Triska et al. 1989) increasing the local vegetative production. Slow-flowing reaches also showed a higher concentration of points in the surficial geology category of "occasionally water- covered peat", this probably has a connection to times of high and low flows, where the water table rises during the spring floods (Seppälä 2005a).

Rapids showed almost double the amount of till than what was found at lakes and slow-flowing reaches (figure 4). Moraine is an unsorted- to partly sorted surficial geology containing multiple grain sizes that covers the majority of Sweden's surface (Fredén 2002). The high concentrations of coarse grains (like coarse gravel, cobbles or boulders) could be affecting the stream in such a way that it has difficulties eroding and transporting its materials, this could contribute to why the rapids are more fixed. Due to the higher velocities in rapids, the deposition is also lower than within most lakes and slow-flowing reaches.

The differences between the two map layers displaying surficial geology at different scales was quite large, where even the dominating surficial geology rarely coincide (figure 4 and Appendix 3). These differences could depend on for example accuracy or sampler as well as the self-evident scale differences. These scale differences could affect the results in many ways. If the scale is to coarse, there is a risk that the scattered short sections of rapids are generalized, and we might miss the real local surficial geology and the results would therefore be inaccurate. If the scale on the other hand is too large, we might get even more categories making it difficult to detect trends.

4.3 Landforms

Rapids showed the clearest connection to a specific landform compared to the other process domains. 71 percent of the rapid's points were adjacent to glacio-fluvially eroded area, and therefore the rapids seem prone to form on top of older glaciofluvial stretches. This does not correspond directly to the results in surficial geology which indicated more towards till, but the glaciofluvial eroded areas are often found above earlier till-deposits when the moraine has been washed out by the glaciofluvial streams (Sundquist and Dittrich 2015), which could be an explanation why the surficial geology indicates till deposits whilst the landforms points towards more glaciofluvial-processes.

Lakes showed a quite high percentage of moraine landscape and hilly moraines in contrast to the other process domains. Moraine landscapes and hilly moraines are primarily found in flat areas and valleys, making it more frequent in Sweden in contrast to Norway, where the landscape has higher relief. The moraine landscape can produce "a mosaic" of lakes and peat (Fredén 2002), which could explain why moraine landscapes and hilly moraines are more common among the lake points in this study. For slow-flowing reaches almost half the points (43%) consists of samples where no landforms were found. It could be that the lack of these high-relief landforms is promoting the formation of slow-flowing reaches since there is less variation in slope. This finding could also be a result of lack of details where too small buffer zones missed nearby landforms. Or it could just be that landforms are not crucial for the formation of slow-flowing reaches, and that there are other factors playing a key role deciding its formation.

4.4 Spatial and temporal context

It is important to have a temporal- as well as a spatial perspective when looking at a stream's morphology. Sometimes the resulting process domain is a product of catchment-scale controls, and sometimes it is rather local variations that makes the difference (Chappell and Brierley 2014). In this study, I focused more upon the local factors, whilst factors like sediment erosion or precipitation are not considered even if those are relevant for the stream morphology and development. Within Sweden there are large variations in altitude, vegetation, relief, precipitation, and relationship to the highest shoreline, etc., depending on the studied location (Seppälä 2005b). All these factors could affect the appearance and processes of the resulting streams. So even if we find certain trends in this study, individual streams and rivers can act differently depending on local- or catchment-scale, and even global variations (Kasvi et al. 2017).

Even if the results might vary, the method can be applied to other locations. Slopes, together with the sediment access seems to be crucial factors for the resulting process domain according to multiple studies (e.g. Palucis and Lamb 2017, Montgomery and Buffington 1997, Snyder et al. 2008 and 2012). If these crucial factors correspond in other locations, it is therefore reasonable to expect similar results. Slope often follows the same general pattern in a catchment scale, from high slopes at the top of the catchment and then decreasing towards its outlet in most locations (Montgomery and Buffington 1997). However, sediment access could vary depending on the local history (Montgomery and Buffington 1997, Snyder et al. 2008). For example, if the location is exposed to different glacial conditions resulting in other deposits or formations the major surficial geology or landforms might not agree with those in this study.

Areas below the highest shoreline are more exposed to the marine processes which e.g. sorts the materials and deposits smaller grains in the valleys while leaving more coarse-grained sediments on higher altitudes. This could affect for example the surficial geology when more fine-grained sediments tend to accumulate in valleys, where streams often are located. Resulting in an over-all higher percentage of the points in fine-grained sediments, especially for lakes and slow-flowing reaches. Different landforms could also be more prone to form below the highest shoreline, for example deltas as the base level continuously drops with the continuous land rise. The landscape itself are also generally flatter towards the coast than in the west, which should result in smaller slopes (Montgomery and Buffington 1997). But they still might follow the same general patterns regarding e.g. flat landforms contributing to the formation of slow-flowing reaches, hilly landscapes creating lakes and old channel deposits promoting the formation of rapids.

Humans also have a large impact on rivers, for example historically through logging, where any larger obstacle was removed, and the stream straightened. Today's forestry will e.g. alter the precipitation run-off, and erosion from soils and therefore also affect the sediment supply and the amount of water to streams. The Bjur River has not been affected by the development of hydroelectric power, which otherwise could have a larger impact on the river flow and appearance. Today we also have an increasing intensity of restoration projects, for example in the Vindel River, directly affecting the river morphology, through e.g. replacing obstacles as large boulders or dead wood into streams (Gardeström et al. 2013, Johansson 2005). Even today's climate is shown to have a large impact on the stream's appearance (Gardener et al. 2019).

4.4.1 Climate change

The expected future climate change is predicted to alter the river morphology (Lotsari et al. 2015). Future climate changes can come to change the predicted course of the river's development. Cold temperatures, ground freezing and precipitation as snow work as stabilizing factors and decreases erosion during the winter months (Seppälä 2005a). But in case of a warmer climate these processes might occur during a much narrower time span than before. The spring flood, which often comes as a result of snowmelt might take place earlier in the spring, decreasing the period where the ground is stabilized by freezing (Lotsari et al. 2010). The snowmelt normally causes the highest annual water discharge, but with climate change the risk for autumnal floods seems to increase (Lotsari et al. 2010), leaving the landscape exposed to multiple floods during a shorter period. This might increase the erosion and transportation of sediments from its catchment and into the stream (Chalov et al. 2015, Johansson 2005). Alterations in sediment transportation and deposition in streams are one factor that could change how the stream behaves and therefore it might also affect the formation of process domains in the longer time perspective (Snyder et al. 2008). A high flow could for example move larger obstacles downstream, preventing local meanders from forming, a higher input of sediments could also increase deposition in certain places.

According to this study it is uncertain what geological factors (slope, surficial geology and landforms) that plays the key role of different process domains location and formation, but it is clear that they have an effect, either directly or indirect. Therefore, if a large proportion of coarser sediments would move downstream as a result of e.g. increasing floods, it could hypothetically increase the chance of rapids forming further downstream.

According to climate change models, there could be large variations in climate change even across relatively small areas and you should therefore be careful when you try to generalize the climate impact to a larger area (Veijalinen et al. 2010) and it would therefore be difficult to predict exactly how different process domains will be affected, then you will need to study more in-depth upon a specific area.

4.5 Conclusions

Slope showed the general trends between process domains that was expected in the hypothesis, but the values did not show such a large difference between process domains that they could be distinguished solely from that factor. Surficial geology confirmed the stated hypothesis in each process domain with fine-grained peat in proximity to lakes and slow-flowing reaches, and (partly) coarse grained till near rapids. The landforms showed surprising results, where the differences between process domains was more obvious than expected. Till that was assumed to dominate a large part of the points in all process domains where almost absent in both rapids and slow-flowing reaches. The rapids and slow-flowing reaches that were predicted to have over layered its own deposits had rather eroded through glacio-fluvial deposits. Lakes showed to be common near hilly moraine landscapes, in contrast to the assumed flat surroundings. The peaks might help delineate the lakes catchment, but it does not seem to be the peaks themselves that promotes the formation of the lakes, but rather the valleys in-between them (figure 2a).

The results from this study's statistical analysis indeed display a difference in all studied factors (slope, surficial geology and landforms) between the different process domains. But it is difficult to know exactly which of the studied geological factors sub-categories that truly affects the outcome through these statistical analyses. The factors often influence each other, for example the moraine landscape with hilly moraines tend to be deposited in places with low slope, the slope is therefore influencing the formation of the landforms and then it is hard to rule out if it is the landform or the slope itself that is the critical factor, or if it is a cooperation between multiple variables. The moraine landscape is also a landform built up by till, and thus influencing the resulting surficial geology.

New technology with the ability to measure depth and slope at the riverbeds would have made the results from slopes more accurate. But by using remote data and GIS it is possible to identify the different process domains and differentiate them according to the variations in the studied geological factors even if all numbers are not completely certain. Through these relatively simple methods you will be able to distinguish variations in large-scale process domains which could aid future management or restoration planning for streams.

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Appendix

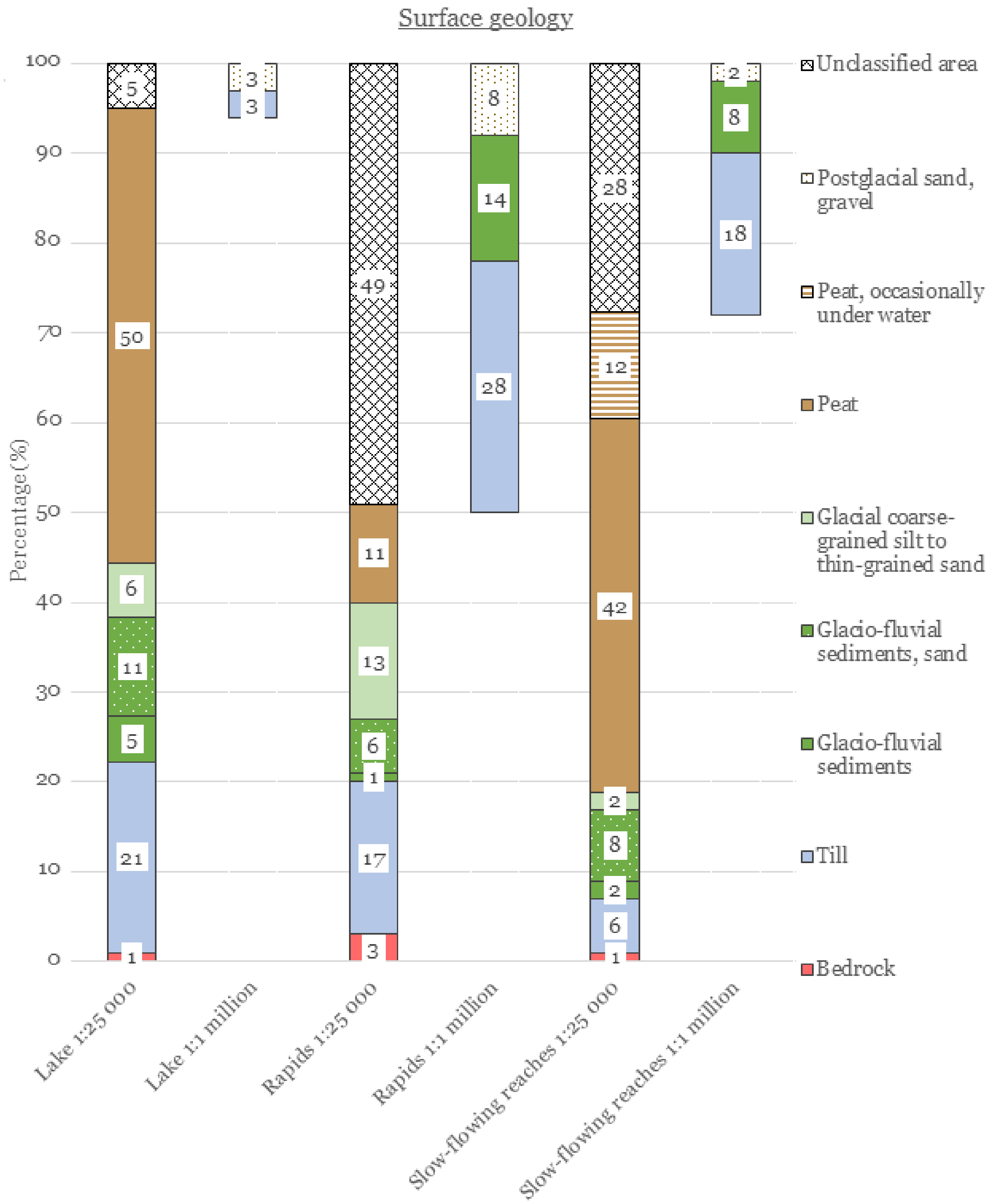
Appendix 1. Buffer zones

Buffer zones used for collecting data around points from underlying map layers in the ArcGIS computer program.

Lakes	
Factor	Buffer zone radius (m)
Slopes	0
Lake width (m)	Buffer zone radius (m)
0–50	45
50–100	70
100–150	95
150–200	120
200–250	145
250-300	170
300-350	195
350-400	220
400-450	245
Slow-flowing reaches	
Factor	Buffer zone radius (m)
Slopes	0
Surficial geology	25
Landforms	50
Rapids	
Factor	Buffer zone radius (m)
Slopes	0
Surficial geology	15
Landforms	50

Appendix 2. Schematic image over the unclassified and complementary points in surface geology

Percentual distribution of surficial geology in different process domains in the scale of 1:25 000 with complementary samples of the unclassified areas in the scale of 1:1 million. All values are rounded and therefore the percentage do not always match.



Appendix 3. Surface geology 1:1 million

Percentual distribution of points over surficial geology in different process domains in the scale of 1:1 million.