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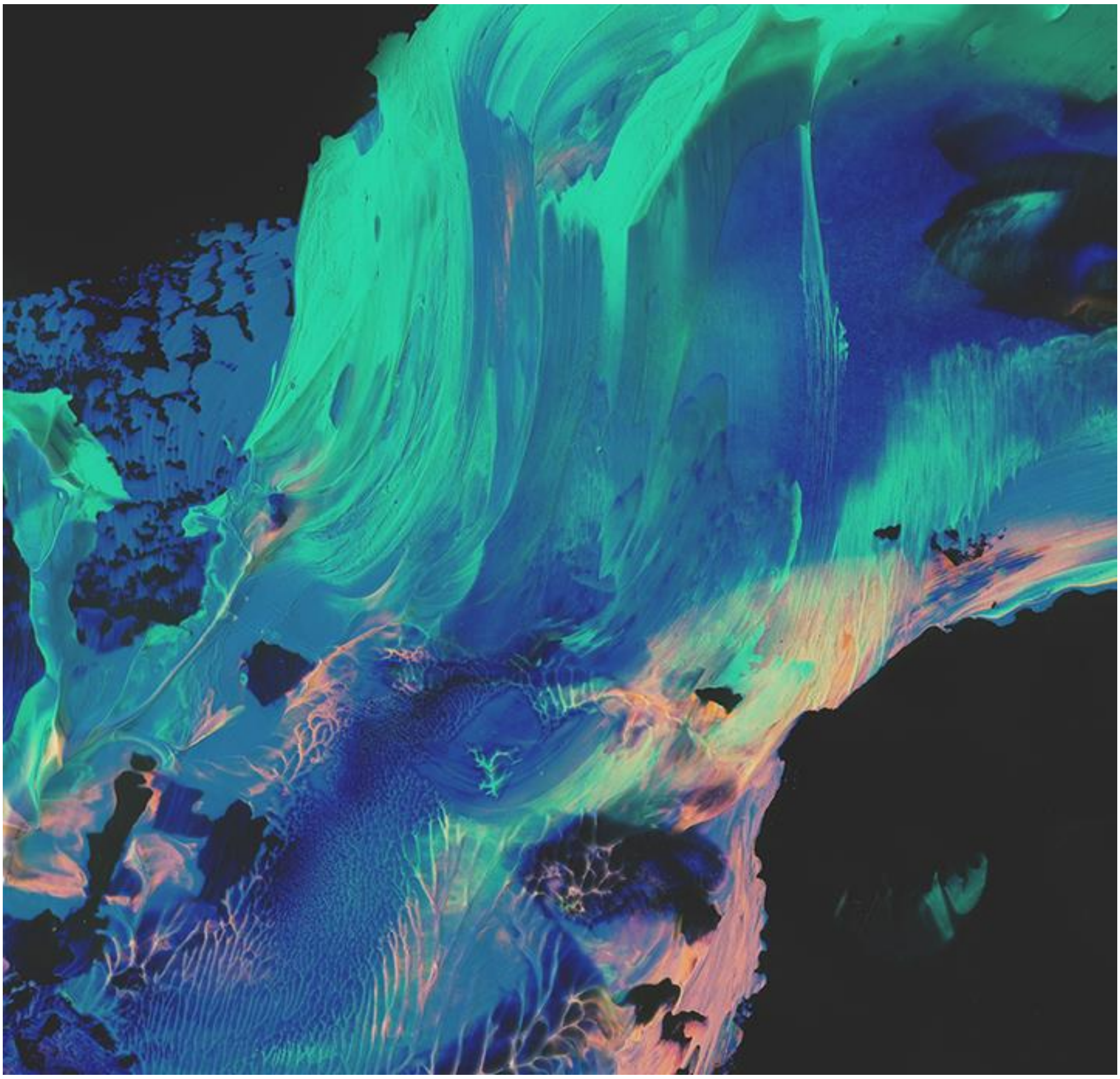

Is it possible to define different process domains in stream systems based on remote data?

Comparing surficial geology, geomorphological characteristics in the landscape and channel slope between lakes, rapids and slow-flowing reaches.

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Abstract

Restoration of stream channels have become a common way of trying to restore both the channels and the ecosystems that earlier have been channelized mainly to facilitate the movement of timber. According to previous studies a lot of the restoration has been performed without a sufficiently detailed plan and with too little focus on how the landscape interplay with the restoration, which makes the potential to learn from possible mistakes minimal. In this study, a hydrological analysis of Hjuken river was done to examine if remote data through an analysis using GIS could be used for identifying three different process domains (lake, slow-flowing reaches and rapids), and if it is possible to determine which process domain it is by examining three different variables: channel slope, surficial geology and the geomorphologic characteristics in the landscape. Based on the statistical treatment and the analysis of the data, the result shows a significant difference between every process domain and variable except for the channel slope when it comes to slow-flowing reaches and rapids. This tells us that all the variables that has been analysed could be a crucial factor in most of the cases. However, the result does not seem reliable compared to previous studies. The conclusion of the study is that the error from the identification of the process domains is from the orthophotos. Remote data is too weak to use as the only source for this kind of analysis. However, the definition of process domains is probably more diffuse than today's description. There needs to be more studies on each process domain, it is probably not enough with three different types, either there should be subclasses for each process domain or even more process domains.

Keywords: Process domains, Lakes, Slow-flowing reaches, Rapids, GIS, Slope, Surficial geology, Geomorphological characteristics in the landscape.

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1 Introduction

1.1 Background

A stream channel can be defined by its process of bringing freshwater from a higher location to a lower one down the landscape. In Sweden there are about 27,663 watercourses, with a total length of 192,000 km (Eklund 2010). The appearance of streams in northern Sweden differ a lot from other places, because the characteristics of the channels were formed during deglaciation, which occurred about 10 000 years ago. The deglaciation brought a lot of meltwater, which in turn carried a lot of fine and coarse sediment that were deposited in the channels. The characteristics of the deposited sediment led to erosion in the bed load, which made the channels deeper. The glacier pushed down the earth crust due to the heavy weight it carried which contributed to an uplift of the landscape during the deglaciation. The uplift in combination with the erosion, contributed to formation of terraces located above the current watercourses. These terrace landscapes are common in the northern part of Sweden (Eklund 2010).

Over 50 years ago a lot of streams were channelized in Sweden and other places around the world. The main reason for the channelization were to facilitate the movement of timber, but other anthropogenic influences have also remodelled the streams which in its turn has degraded the ecosystems (Törlund & Östlund 2002, Kuglerová et al. 2016). Today, restoration by both redistribution of sediment from the edges of the streams and by placing larger boulders and dead trees in the channel has become a common way of trying to restore the channels and the ecosystems (Kuglerová et al. 2016, Gardeström et al. 2013, Nilsson et al. 2015).

To complete the restoration and reach the original levels of large wood and large boulders in the channels, this material needs to be positioned in the water. However, boulders and wood are not always available in the neighbouring areas to the extent that they are needed, which makes the restauration more difficult to achieve. A solution to this problem may be to transport this material to where it is needed (Gardeström et al. 2013).

According to precious studies, information on how the original channels looked like before it was affected by channelization does not always exist. A lot of the restoration has also been performed without a sufficiently detailed plan and with too little focus on how the landscape interplay with restoration. Because of this lack of preparatory work, the potential to learn from their possible mistakes and then improve the restoration is unfortunately minimal (Brudvig 2011, Gardeström et al. 2013, Nilsson et al. 2015).

To understand if, and if so, which factors of the landscape that affect the success of the recovery after the restoration, we first must understand how stream networks are structured. "Process domains" is a concept produced as a suggestion for an alternative of variants of stream channels. The hypothesis says that spatial variation in geomorphic processes regulates temporal patterns and organization in the channel, which in its turn affect the ecosystem and the dynamic in the channel (Montgomery 1999). At a coarse scale, there are different factors controlling the suite of the geomorphic process, such as the regional climate, the vegetation and the topography. Through this controlling the stream channels can be classified, which in turn can identify parts of a stream network with similar characteristics (Montgomery 1999).

In some tributary catchments in northern Sweden, stream channels are classified into three different types: rapids, slow-flowing reaches and lakes. Rapids are defined by coarse sediment (from gravel to larger boulders) on the channel bed, by its high channel slope and by its high flow velocities. Slow-flowing reaches can be both straight or meandering and contains fine sediments or peat due to the low slope and low flow velocities which favours deposition of fine material (Su et al. 2019). A lake is defined by permanent water in a sink that is naturally been formed in the surficial geology (Havs och vattenmyndigheten 2019).

Figure 1. Orthophoto showing examples of the three process domains. A – Rapids, B – Slow-flowing reaches and C – Lakes.

1.2 Aim

In this study, a hydrological analysis of Hjuken river is conducted to find out if remote data can be used to identify the three different process domains, and if three different variables (channel slope, geomorphological characteristics in the landscape and surficial geology) correlates with where the different process domains were found (figure 1). The hypothesis for this study is that remotely-obtained data will be enough to identify the process domains.

2 Material and Method

2.1 Study area

Hjuks river catchment is a smaller catchment in Northern Sweden, Västerbotten County, just above the small village Hjuken in Vindeln municipality (figure 2). The catchment is places below the high coast line and outlets in Vindeln River which is a tributary to Ume River catchment. The area of the catchment is 394 km² and includes 74 lakes. The main river (Hjuks river) is around 51 km long and consists of multiple different process domains (calculated in GIS) (SLU 2018).

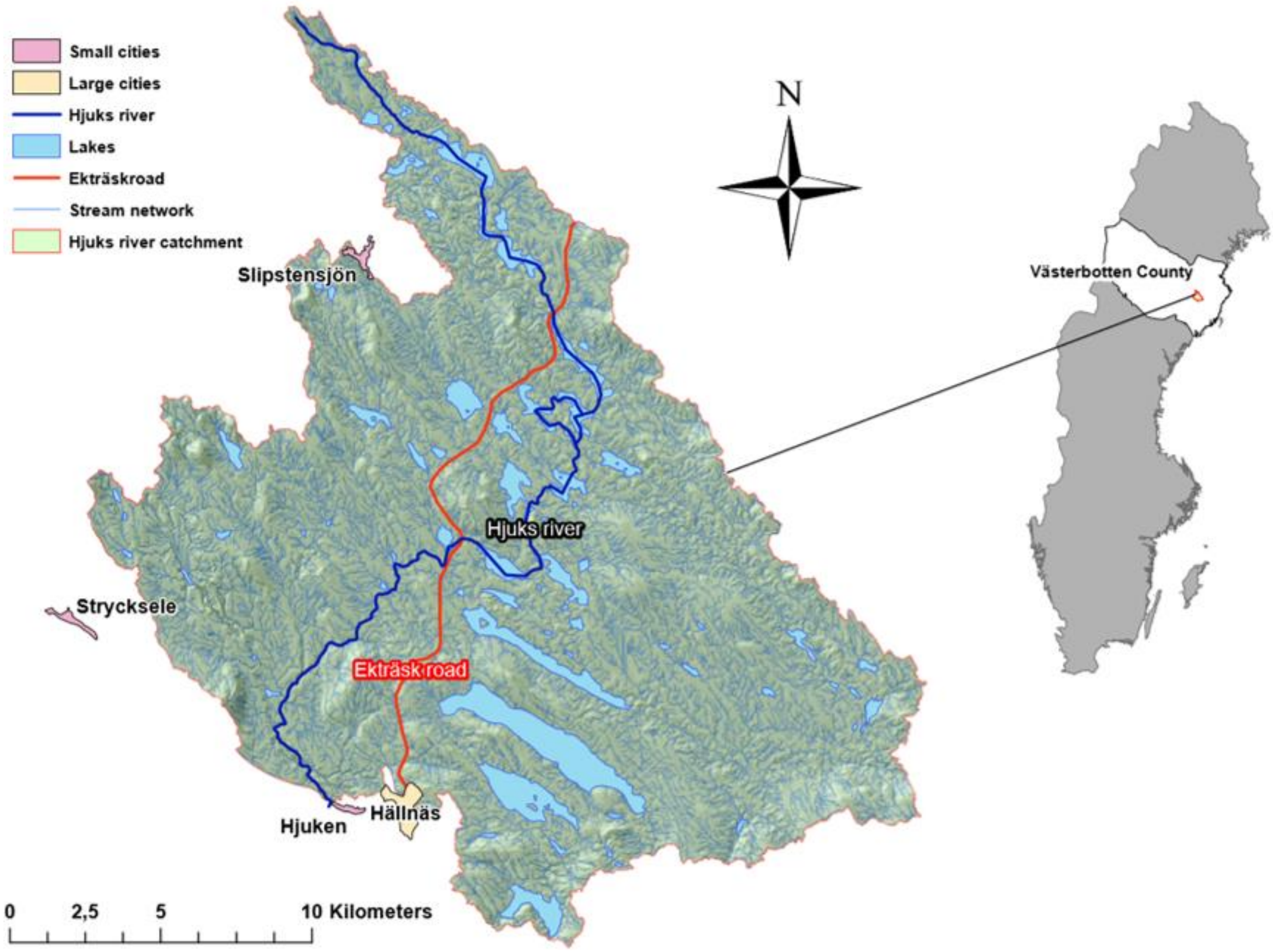

Figure 2. A map over Hjuks River catchment. The insert map shows where in Sweden the catchment is located, in Västerbotten County northern Sweden, close to the town of Hällnäs (Lantmäteriet n. d). The coordinate system used is SWEREFF99TM.

2.2 Files

For the analysis, Esris program ArcMap (which is one of the main components of ArcGIS) was used. Files were downloaded though Geodata extraction tool, a download service from several different authorities in Sweden (Table 1).

Table 1. Metadata over the files that has been used for the analyses over the process domains.

Files	Coordinate System	Description of file	Source	Tool/ method
jordarter_25-100k_jg2	SWEREFF 99 TM	Vector file over surficial geology	SGU	Download
jordarter_25-100k_lf	SWEREFF 99 TM	Vector file over geomorphologic characteristics in the landscape	SGU	Download
ortoRast3006_7140470_737844.tif	SWEREFF 99 TM	Orthophoto over hjuksriver	Lantmäteriet	Download
ortoRast3006_7140470_707844.tif	SWEREFF 99 TM	Orthophoto over hjuksriver	Lantmäteriet	Download
ortoRast3006_7125549_737844.tif	SWEREFF 99 TM	Orthophoto over hjuksriver	Lantmäteriet	Download
ortoRast3006_7125549_707844.tif	SWEREFF 99 TM	Orthophoto over hjuksriver	Lantmäteriet	Download
hojd2m3006_7129494_698430.tif	SWEREFF 99 TM	3D representation of a terrains surface over the area around Hjuken catchment [2x2 meters]	Lantmäteriet	Download
Rivers_streams_swe	SWEREFF99 TM	Vector file over rivers and streams in Sweden	Lantmäteriet	Download
Lakes_VB	SWEREFF 99 TM	Vector file over lakes in Västerbotten county	Lantmäteriet	Download
S02010_sR99TM_region	SWEREFF 99 TM	Small cities in Sweden	SCB	Download
T02010_SR99TM_region	SWEREFF 99 TM	Large cities in Sweden	SCB	Download

2.3 Variables

The channel slope was calculated over a DEM (2x2 meter) in ArcMap with the tool “slope”, which explains the steepness in the channel [%]. Both the geomorphological characteristics in the landscape and the surficial geology was analysed through two vector files (table 1). The geomorphological characteristics in the landscape over the study area were: moraine ridges, drumlin or similar and moraine landscape/hilly moraines. The different surficial geology in the study area were: postglacial coarse silt/fine sand, glaciofluvial sediment, clay/silt, peat, till, outcrop and postglacial sand.

2.4 Creating stream network

A stream network was created in ArcMap. First, a DEM over the area were filled using the tool “fill” to exclude any artificial sinks; then, new raster files were created showing both the flow direction and flow accumulation. Then a stream raster was created; In order to create a stream raster, the flow accumulation raster needed to change from showing how many cells that flow into all downstream cells to show the size of the upstream area (m^2). This calculation was done using raster calculator. A raster file showing whether each cell was a stream (number 1) or not (number 0) was also calculated using a conditional statement in raster calculator. The minimum size of the catchment area was based on a review by Wohl (2018), where the catchment characteristics of north-central Colorado were used as a reference for the Hjuks river catchment based on its similar characteristics, such as the vegetation, precipitation, and the crystalline lithologies. The minimum catchment size ranges from 10 000 – 600 000 m^2, where the smallest area (10 000 m^2) was chosen to ensure that no stream channels was excluded. A conditional statement in raster calculator were used to give the flow accumulation file values>0,01km^2. This file together with a digitized point at the outlet at the Vindeln River was used to create the catchment area using the watershed tool.

2.5 Digitizing lakes, slow-flowing reaches and rapids

The Stream network raster did neither follow the Hjuks river in the orthophoto or the surficial geology file as precise as was wanted, therefore the Hjuks river was digitized (converted geographic data from a scanned image into vector data) as a polyline based on a visual analysis of those three different files, first over the orthophoto with the stream network raster on top, followed by an analysis over a file with surficial geology with the stream network on top to make the polyline as correct as possible. Points were plotted out through the digitized polyline with a distance of 50 meters using the editor tool "construct points". All points were analysed to figure out what kind of process domain they were in. To write down all the identified process domains based on numbers (1 – lake, 2 – slow-flowing reaches and 3 – rapids), a new field was added in the attribute table, which is a table that is connected to the shapefile that contains information of each point. All points upstream where the river got narrower than 5 meters was considered too narrow to do a correct analysis and were excluded.

2.6 Creating a buffer (zone) around each process domain

The file over the surficial geology included a water-layer over Hjuks river, this layer was narrower than Hjuks river in the orthophoto, and because the buffers were made to connect the dominated surficial geology and geomorphological characteristics in the landscape around every single point of the process domains it made more sense to use the file over the surficial geology to decide the distance of the buffer, Otherwise the distance would have been larger which could have included surficial geology that did not occur around the specific point. Two buffers around both the slow-flowing points and the rapid points were made using the tool "buffer" in ArcMap, where a smaller buffer was made for the surficial geology and the largest for the geomorphologic characteristics in the landscape. For slow-flowing reaches, a surficial geology buffer of 25 meters (except the points that were located where the channel was wider than 100 meters, here 45 meters were chosen as the distance - point 125, 126, 127 and 205) and a buffer for the geomorphological characteristics in the landscape of 50 meters was created. For rapids a buffer for the surficial geology were made with the distance of 15 meters, and for geomorphological characteristics in the landscape a buffer of 50 meters. For the lake points, four different sizes of the buffer zones were needed due to the variation in the width: >50 with a buffer of 50, >50, <100 with a buffer of 100, >100, <200 with a buffer of 200 and >200 with a buffer of 320 (widest point was around 315), same buffer zone were used for both the soil type and the geomorphological characteristics in the landscape (figure 3).

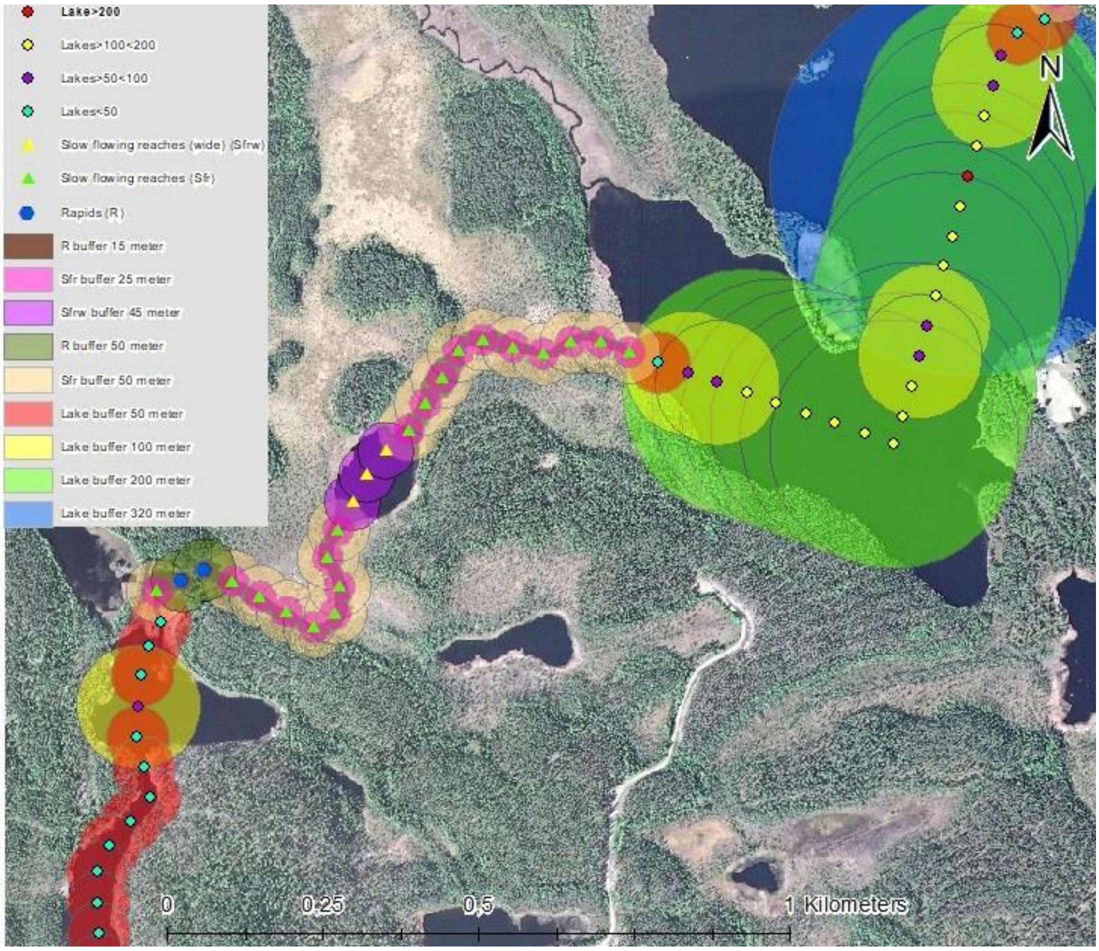

Figure 3. A map over three process domains (Lakes, Rapids and Slow-flowing reaches) and their buffer zones. (SLU n.d). The coordinate system that have been used is SWEREFF 99 TM.

To join the categorical factors (surficial geology and geomorphological characteristics in the landscape) the tool "spatial join tool" was used, and for the quantitative factor (slope) which was calculated based on the DEM, the tool "extract multi values to point" was used.

2.7 Statistical analysis

Six standard databases files (.dbf) with information of dominated surficial geology, dominated geomorphological characteristics in the landscape and channel slope for all three different process domains were exported to Excel to easily sort the data. For the categorical variables (geomorphological characteristics in the landscape and surficial geology), all the different process domains were plotted to each variable and a bar graph was made to visualize differences. A chi-squared test was done to determine whether there is a significant difference between observed and expected frequencies in the three categories, where a p-value < 0.05 rejects the null hypothesis which says that two categorical variables are independent in some population.

For the quantitative variable (slope), a one-way ANOVA was used to analyse the variance between the three process domains. A Tukey's post-hoc test was used to determine between which process domains there are a significant differences. A p-value <0.05 and Q-value above the critical value (3.31) were considered significant based on 14 degrees of freedom for surficial geology and 5 degrees of freedom for geomorphological characteristics in the landscape.

3 Result

For the slope in the different process domains rapids have the highest value of 4,08% followed by slow-flowing reaches on 3,75% and lakes with the lowest on 0,09%. The standard deviation also varies, lowest number for lakes at 0,67, followed by rapids at 4,74 and finally slow-flowing reaches with a quite high number at 9,80 (table 2).

Table 2. Average values and standard deviation for slope in the different process domains [%].

	Average [%]	Standard deviation [%]
Lakes	0,08	0,67
Rapids	4,08	4,74
Slow-flowing reaches	3,75	9,80

For slope, a one-way ANOVA analysis showed that there is a significant difference between some of the process domains based on the p-value (<0.0001). Tukey's post-hoc test showed a critical value of 3.31 which tells us that there is a significant difference between both lakes and rapids (Q-value over the critical value: 3,31 < 7,739) and between slow-flowing reaches and lakes (Q-value over the critical value: 3,31 < 11,162). Based on the Q-values (> critical value), slope could be a crucial factor for where both slow-flowing reaches and lakes are formed and for where lakes and rapids are formed (table 3).

Table 3. Tukey's post-hoc test based on slopes.

		Difference	N group 1	N group 2	SE	Q-value
Lake	**Rapids**	3,99	424	97	0,52	7,74
Rapids	**Slow-flowing reaches**	0,33	97	362	0,52	0,63
Slow-flowing reaches	**Lake**	3,66	362	424	0,33	11,16
					Critical value: 3,31	

The chi-squared test for the geomorphological characteristics in the landscape showed a p-value of 0 which rejects the null hypothesis which says that two categorical variables are independent in some population, this means that some of the process domains are not independent in some population when it comes to the geomorphologic characteristics in the landscape.

All three process domains were dominated by moraine ridges, followed by moraine landscapes/hilly moraines. For both lakes and rapids, the moraine landscape/hilly moraines were about half as abundant as the moraine ridge. Drumlin or similar did only occur within the lakes (figure 4, appendix 1).

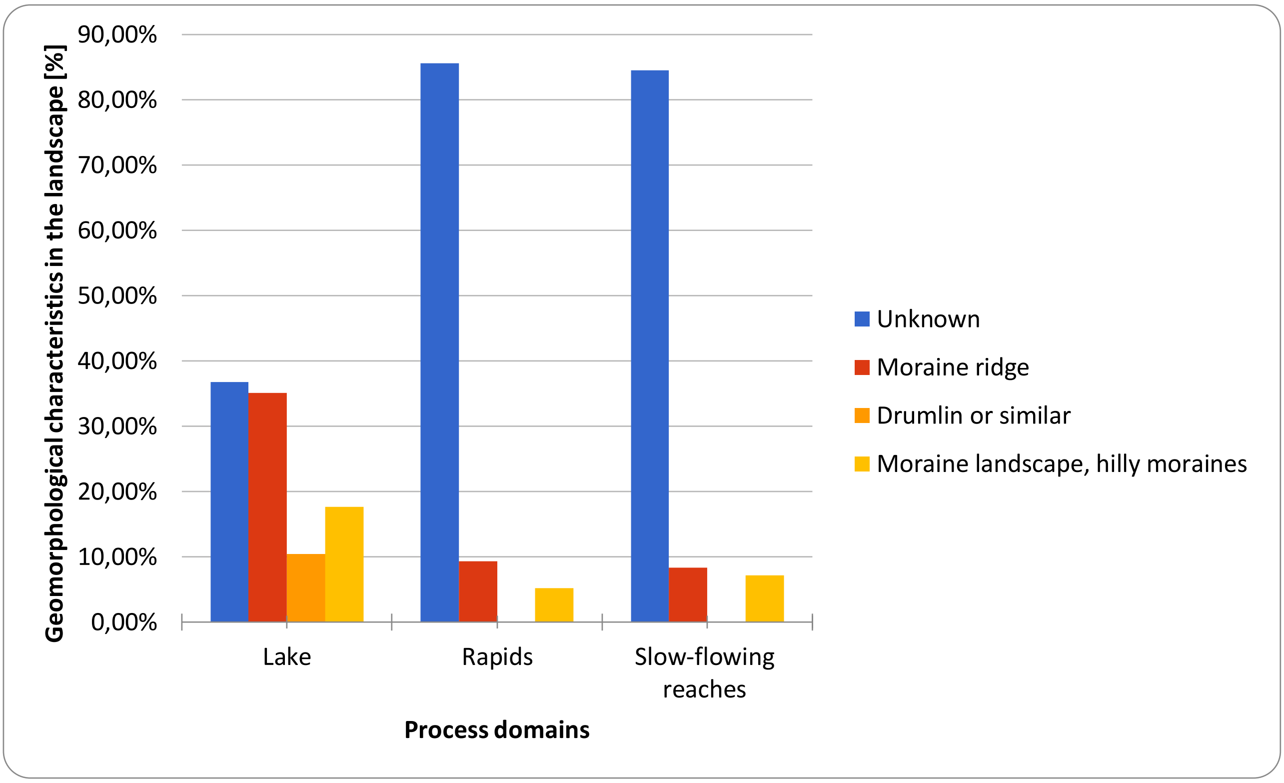

Figure 4. Geomorphological characteristics in the landscape [%] in the different process domains.

In the same way as for the geomorphological characteristics in the landscape the chi-squared test for the surficial geology shows a p-value of 0, which tells us that there is a significant difference between some of the process domains when it comes to the surficial geology.

The dominated surficial geology in the lakes were till at 48,1% followed by peat at 44,8%, this means that the remaining surficial geology types were very rare (postglacial coarse silt/fine sand at 1,6%, glacifluvial sediment at 2,3%, outcrop at 0,2% and postglacial sand at 0,9%), clay/silt did not even occur in any of the lakes. Till were the most common surficial geology in the rapids at a percent of 73,2, followed by clay/silt at a percent of 22,6, the two other surficial geology that occurred were outcrop at a percent of 1,0 and peat at a percent of 3,0. In the slow-flowing reaches peat was the most common surficial geology at a percent of 32,41 followed by till at a percent of 30,4, both clay/silt and glacifluvial sediment were also quite common at a percent of 15,7 respective 14,68. Postglacial coarse silt/fine sand and outcrop did occur in a small amount at a percent of 4,4 and 2,2 (figure 5, appendix 2).

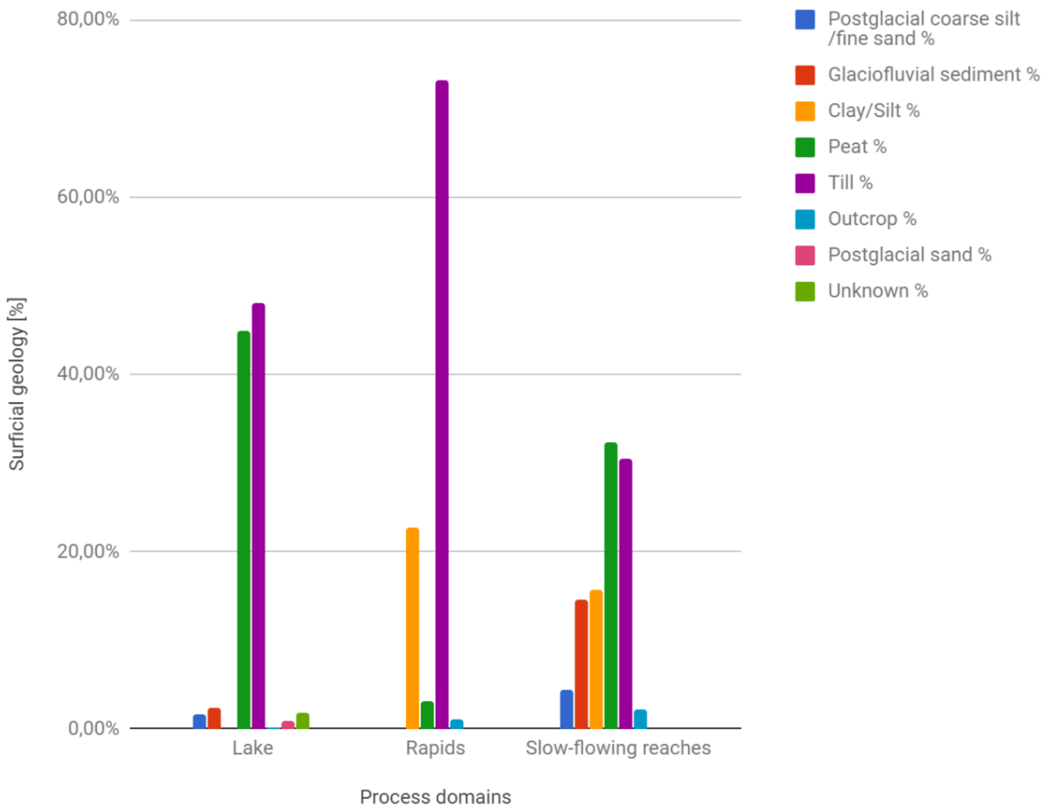

Figure 5. Surficial geology in the different process domains [%].

4 Discussion

According to the statistical analysis of the remotely-obtained data, slope is not a crucial factor for where a rapid or a slow-flowing reach is formed because there is no significant difference between those two process domains and the channel slope. Equivalent average values for the two process domains also strengthen this result, 4,0% for rapids and 3,7% for slow-flowing reaches. The high standard deviation number for both rapids and slow-flowing reaches which explains how the observed values differs from the average value, could on the other hand explain the average values as an uncertain result (table 2).

Based on the study in Fennoscandia they categorise rapids with high channel slopes and slow-flowing reaches with low channel slopes, the result in this study does not match that definition due to the high average values in channel slopes for slow-flowing reaches at 3,75% (Su et al. 2019). Lake and rapids on the other hand shows a result which matches with previous studies, low channel slope in lakes, high channel slope in rapids (Su et al. 2019, Drakare 2014).

Talking about the visualization of the process domains through the orthophoto in GIS, one reason that can make it more difficult to identify the slow-flowing reaches is that they can be classed as a type in-between lakes and rapids by its similar look. An incorrect identification of some of the rapids where they were identified as slow-flowing reaches may therefore be a reason why the channel slope in the slow-flowing reaches shows such a high average value as 3,75%.

The channel slopes were calculated over a DEM which represent the terrain surface with a resolution of 2x2 meters, which in this case was the highest resolution available. Depending on how the pixels are placed regarding to the stream channel, this could explain that it does not provides an accurate representation of the channel slope. The result also depends on the quality and the generalization of the digital elevation model (DEM), which might therefore conduce to incorrect results, like measuring the lateral channel slope instead of the longitudinal channel slope (Tang & Pilesjö 2011).

In a report about lakes by Swedish University of Agricultural science, the definition of lakes regarding channel slopes are <0,1% (Drakare 2014). The average channel slope in lakes in this study matches the definition of Drakare (2014) with an average value of 0,08% (<0,01%). The well-matched result of this studies compared to the definition of Drakare (2014) can be explained by the certainty that the lakes that were pointed out really were lakes. I think the remotely-obtained data contained more information where the lakes were located than for the locations of the rapids and the slow-flowing reaches, mainly based on the vector file over all the lakes in Västerbotten (table 1).

The chi-squared test showed that there is a significant difference between some of the process domains and the surficial geology (p<alpha 0,05), which tells that surficial geology could be a crucial factor for where each process domain is formed. In slow-flowing reaches the most common surficial geology vary between four different types: till 30,4%, peat 32,4, clay/silt 15,7% and glacifluvial sediments 14,6%. In lake and rapids, the most common surficial geology varies between two types, till at 48,1% and peat at 44,8% in lakes and till at 73,2% and clay/silt at 22,6% in rapids. Combining the analyse of the amount of the most common surficial geology in each process domain with a visualization of figure 5 tells us that a significant difference between each process domain regarding the surficial geology are very likely.

Su et al. (2019) does not only categorized the process domains by the channel slope but also based on its bed sediment, where coarse sediment characterizes rapids and fine sediment, or peat characterizes slow-flowing reaches. In Penobscot Lowland a study over the surficial geology in rapids showed that the warm period after the deglaciation contributed that the river over time encountered the old outwash gravels, marine clay and glacial till (Hooke et al. 2017). The high percent of till and clay/silt in the rapids in this study matches the definition of Hooke et al (2017) and could therefore possibly be explained, as in Penobscot Lowland by the warm period after the deglaciation. However, the result of this paper still does not match the definition of Su et al. (2019) with its quite high percent of clay/silt in the rapids at a percent of 22,68. The high percent of peat at 32,41 in the slow-flowing reaches does on the other hand match with the definition of Su et al. (2019) (appendix 2).

Even though the most common surficial geology in slow-flowing reaches matched with the definition of Su et al. (2019) there were still a high percent of other surficial geology with larger grain sizes such as postglacial coarse silt, glaciofluvial sediment and till (appendix 2) which makes the result more unreliable compared to Su et al. (2019). The reason for the occurring surficial geology with larger grain sizes in the slow-flowing reaches as well as the high amount of clay/silt in rapid could in the same way as for the error of the channel slope be explained by an incorrect identification, because rapids and slow-flowing reaches do look similar in some of the remotely-obtained data, in this case the orthophotos. Another error connected to the remotely-obtained data could be the vector file over the surficial geology. The transition between the different surficial geology is very sharp, which makes it less credible. The transitions between two different surficial geology are probably more diffuse than that in reality.

The composition of the surficial geology in lakes is defined by peat and fine sediment according to Lambeck et al (1998), fine sediment includes sand, clay and silt which has a grain size with a diameter <2 mm (Naden 2010). In this study, clay/silt did not occur in any of the lakes which does not match the definition of Lambeck et al. (1998). Peat and till were the most common surficial geology in the lakes in this study (appendix 2), and when it comes to till, the composition varies a lot depending on how far it has been transported by the inland ice. The composition of till includes fine sediment, which normally varies between 10-20% but can in some cases be higher (Geological Survey of Sweden 2000). This could be an explanation to why till is the most common in this study compared to the definition of fine sediment in the study of Lambeck et al. (1998).

For the geomorphological characteristics in the landscape, the chi-squared test showed that there is a significant difference between some of the process domains and the types of landforms found nearby ($p < 0.05$), meaning that the landforms could be a crucial factor for where the different process domains are formed. The clearest difference regarding the percent of different landforms is between lakes and rapids, and between lakes and slow-flowing reaches, based on drumlin or similar which does only occur in the lakes (appendix 1). A problem with this result is that there is a quite high percent of unknown values for all three process domains (36,7% for lakes, 85,5% for rapids and 84,5% for slow-flowing reaches), which makes the result more unreliable. All those unknown values could be explained by the high resolution of the remote data that were used, which can make some of the points unidentified cause there are no major landforms nearby.

The study area for this analysis, Hjuks catchment, is located below the high coastline. A location below the high coastline implicate that both the landforms and the surficial geology has been affected by waves (Geological Survey of Sweden n.d). This means that the difference between a catchment above or below the high coastline may be that the landforms below the high coastline are more eroded and harder to define as well as the surficial geology are more washed and contains less fine sediment.

The statistical treatment and the analysis of the data shows a significant difference between lakes and the other two process domains regarding all the three variables (Slope, surficial geology and geomorphological characteristics in the landscape). Rapids and slow-flowing reaches did on the other hand only show a significant difference when it comes to the surficial geology. This result tells us that all the variables that has been analysed could be a crucial factor for where some of the process domains are formed when a significantly difference are shown. However, compared to previous studies (Su et al. 2019, Lambeck et al. 1998) this result does not seem reliable.

To make the study better I would have used the tool Hillshade in ArcMap which is a 3D representation of the surface, based on where the sun is shining from (altitude and azimuth) and visually analyzed the geomorphological characteristics in the landscape over the area to avoid all the unknown values for the geomorphologic characteristics in the landscape. To be sure that all the points (process domains) through Hjuks river were correctly identified, field observations could also have been done, such as sediment sampling and measurement of the channel slope.

The conclusion of the study is that the error from the identification of the process domains is from the remotely-obtained data. Remote data is too weak to use as the only source for this kind of analysis. However, I also think the definition of process domains is more diffuse than today's definition. There needs to be more studies on each process domain, I do not think it is enough with only three different types, either there should be subclasses for each process domain or even more process domains.

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Appendix

Appendix 1. Geomorphologic characteristics in the landscape [%]

	Lake	Rapids	Slow-flowing reaches
Unknown	36,79	85,57	84,53
Moraine ridge	35,14	9,28	8,29
Drumlin or similar	10,38	0,00	0,00
Moraine landscapes/hilly moraines	17,69	5,15	7,18

Appendix 2. Surficial geology [%]

	Lake	Rapids	Slow-flowing reaches
Postglacial coarse silt/fine sand	1,65	0,00	4,43
Glacifluvial sediment	2,36	0,00	14,68
Clay/Silt	0,00	22,68	15,79
Peat	44,81	3,09	32,41
Till	48,11	73,20	30,47
Outcrop	0,24	1,03	2,22
Postglacial sand	0,94	0,00	0,00
Unknown	1,89	0,00	0,00