Mine Closure 2025 – S Knutsson, AB Fourie & M Tibbett (eds)

doi:10.36487/ACG_repo/2515_80

Understanding the landforms and landscapes of northern Sweden to inspire geomorphic landform design in mine rehabilitation and closure

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Abstract

Geomorphic-based solutions for land rehabilitation in areas transformed by human activities such as mining, civil engineering, or urbanisation focus on designing and constructing landforms and landscapes that replicate the morphology and dynamics of natural systems.

The GeoFluv method is the most widely used approach for geomorphic landform design, combining the design of stream channels and upland hillslope areas into stable landforms. Its widespread application in various climatic environments has led users to consider how it could be better adapted to replicate the geomorphic features and dynamics found in these different climate regions.

The objective of this study is to assess the characteristics of drainage networks in the Norrbotten region (northern Sweden) and provide recommendations applicable to geomorphic landform design projects in mine sites within such climatic environments. Using a combination of remote sensing tools and fieldwork, 67 first-order channels and four drainage networks developed on quaternary moraine and glacial till deposits were identified around Kiruna, Abisko and Svappavaara. The identified channels had low-flow to moderate-flow, with varying degrees of sinuosity and a clearly identifiable stream bed. Channel morphometric parameters such as the width/depth ratio, channel reach length, drainage density, distance from ridgeline to channel's head, and sinuosity were measured using remote sensing tools and mobile Global Positioning System (GPS) stations.

A compilation of morphometric characteristics of the measured channels is presented in this study. The results show that glacial legacy landforms and materials strongly influence channel geometry by constraining fluvial processes. Morphometric characteristics of the channels such as the width/depth ratio and overland flow path length show a clear deviation compared with the same characteristics in channels dominated by fluvial processes. Suggestions that can be incorporated in geomorphic landform design software are presented according to the observed results in order to adapt design outcomes for the northern Sweden climate and achieve more stable landforms.

Keywords: *geomorphic restoration, geomorphic landform design, GeoFluv, cold environments, mine closure*

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1 Introduction

The reconstruction of new landforms and landscapes is necessary in areas that have been affected by human activities involving 'earth-movements'. These activities often lead to transformations that impact all components of ecosystems and landscapes, including vegetation, soil, topography, substrate, hydrography, and hydrogeology.

Geomorphologic-based restoration solutions emerged to address erosion-induced instability issues occurring on mine waste storage facilities in the United States during the 1990s, associated with conventional topographic reconstruction methods. Since then, these restoration methods have seen an extraordinary growth, especially since the early 2000s, with multiple works published, such as Bugosh & Eckels (2024), Bugosh & Epp (2019), DePriest et al. (2015), Hancock et al. (2019), Martín Duque et al. (2010, 2020, 2021), Nicolau (2003), Sawatsky et al. (2000, 2008), Toy & Black (2000), Toy & Chuse (2005) and Zapico et al. (2018, 2020, 2021).

Currently, there are only a few restoration methods with a well-established, systematic procedure based on geomorphologic science to replicate natural, three-dimensional landforms at a landscape scale. All of these methods are based on fluvial geomorphology and revolve around replicating watersheds and drainage. Of all the truly geomorphic methods currently available, the GeoFluv method is the most widely applied worldwide, with dozens of restoration projects globally. The GeoFluv method was the first geomorphic landform design method to combine the design of stream channels with upland slope areas into a stable landform. It was also the first method associated with a commercial software (*Natural Regrade*), which helped users create GeoFluv designs in a computer-aided design environment. Designed landscapes include 3D scalloped concave–convex hillslopes that break long slopes into smaller ridges and swales, preventing the formation of rills and gullies commonly associated with the rectilinear structures of traditional engineering methods (Bugosh & Eckels 2024). The swales on valley slopes convey water to the designed channels in a non-erosive manner.

The GeoFluv method was originally developed to address erosion problems in mines located in environments where fluvial processes dominate the landscape configuration. However, there are regions where these processes play a secondary role. An example of this can be found in high-latitude environments, such as Canada or Scandinavia, where the landscapes have been predominantly shaped by glacial or fluvioglacial processes and infiltration and groundwater flow play an important role in channel dynamics. The application of the GeoFluv method is not excluded in such environments, in fact, there are successful examples of geomorphic restoration projects in high-latitude areas such as the Healy mine in Alaska.

Mining deposits in these climatic zones are also subject to fluvial erosion processes, particularly during their initial stages, when there is no vegetation cover to protect the mining materials. Nevertheless, the climatic characteristics of these regions and glacial influence on channel regimes require geomorphic designs to be adjusted to mimic, as accurately as possible, the functionality and appearance of the landscapes and drainage networks of those regions.

The objective of this paper is to assess the characteristics of landforms and drainage networks in the Norrbotten region of northern Sweden and provide suggestions for adapting the current geomorphic restoration methods, specifically the GeoFluv method, to mine rehabilitation and closure within such climatic environments.

2 Study area and regional setting

The channels and drainage networks measured in this study are located around the Kiruna municipality, in the Norrbotten region of Sweden. The study region comprises an area of approximately 32,600 km^2, extending from the northern section of the Scandes mountains to the erosion surfaces and plains of the Fennoscandian Shield (Figure 1). The rivers and channels in this region have a general flow direction from northwest to southeast, mostly flowing from in the Scandes mountains, along the Swedish–Norwegian border – towards the Gulf of Bothnia in the Baltic Sea. The study region is covered by an extensive taiga and birch forest and the valleys and lowland areas are generally comprised of quaternary till and glaciofluvial deposits (Fredén 1994).

The present landscape in northern Sweden is a product of numerous glaciations, directly through erosional and depositional landforms and indirectly through post-glacial isostatic rebound (Polvi et al. 2014). The quaternary sediments in the study region were deposited during different stages of the Weichselian glaciation (120,000 to 12,000 years before present), and are composed by different layers of glacially drifted till covering older glaciofluvial sediments (Polvi et al. 2014; Smith 2018). The extreme cold conditions present during the Weischelian glaciation favoured the preservation of landforms and sediments beneath thin till sheets. The Kiruna area lies within a region of well-preserved glacial landscapes (Smith 2018), and contains a plethora of glacial origin landforms, including drumlin fields, ribbed, Veiki and Rogen moraines, eskers, glacial erratics, and boulder fields (Ivarsson 2007; Fredén 1994; Seppälä 2005).

In the study region, the configuration of the drainage networks appears to be largely driven by the glacial legacy landforms and sediments (Alexanderson et al. 2022; Hauer & Pulg 2018; Mason & Polvi 2023; Stroeven et al. 2016). Drainage networks in northern Sweden are characterised by low slopes and present many boulder-bed semi-alluvial channels (Polvi 2021; Rosenfeld et al. 2011), that is, channels that follow some alluvial patterns but are constrained by other processes (Ashmore & Church 2001). This kind of channel contains abundant cohesive or coarse sediment, called lag or glacial legacy deposits, which are fixed immobile points in the channel deposited by previous glaciation regimes and are not influenced by the current fluvial hydrological regime (Gran et al. 2013; Pike et al. 2018).

Fennoscandian rivers are strongly influenced by modern-day ice processes for much of the year (Lotsari et al. 2015; Polvi et al. 2020). It is unclear if rivers influenced by glacial legacy sediments follow similar patterns and geomorphic processes to their alluvial counterparts (Bergman et al. 2022; Hauer & Pulg 2021). Mason & Polvi (2023) concluded that semi-alluvial channels in Fennoscandia are predominantly controlled by inherited glacial sediments, as glacial legacy materials have a strong influence on channel geometry by constraining alluvial processes. At the catchment scale, the lack of association between drainage area and channel width or depth indicates that channels are not fully alluvial as they cannot modify their bed and banks to achieve equilibrium alluvial forms.

3 Methodology

This study utilised both fieldwork and remote sensing techniques (Geographic Information System; GIS) to collect data on first-order channels and their morphological parameters. This was done over several campaigns conducted from 2019 to 2024 in Abisko, Kiruna, Nikkaluokta and Svappavaara (Norbotten region, northern Sweden).

Table 1 provides a summary of the methods used and the morphological parameters measured during each campaign.

Table 1 Summary of morphological parameters measured and methods used during each of the campaigns conducted

Year	Morphological parameter	Methodology used	Number of measurements
2019	A-Channel reach length	Remote sensing	28
	Sinuosity	Remote sensing	5
2020	A-Channel reach length	Field work	4
	Sinuosity	Remote sensing	4
	Drainage density	Remote sensing	2
2021	A-Channel reach length	Remote sensing	72
	Sinuosity	Remote sensing	14
	Drainage density	Remote sensing	2
2023	A-Channel reach length	Field work	1
	Width/depth ratio	Field work	35

Year	Morphological parameter	Methodology used	Number of measurements
2024	A-Channel reach length	Field work	4
	Sinuosity	Remote sensing	38
	Drainage density	Remote sensing	27
	Width/depth ratio	Field work	192
	Distance from ridgeline to channel's head	Remote sensing	34

3.1 Identification of channels

Channels were identified by overlaying multiple data layers, including thematic geological maps, orthophotography, digital elevation models (DEMs), and hydrology data (e.g. Minkarta application). This approach was essential due to dense vegetation, which hindered channel identification with orthophotography alone.

In this study, we searched for drainage networks and first-order or second-order channels with sinuous or zigzag morphologies and with a clearly identifiable stream bed. Channels and drainage networks selected for the study were preferably those developed on moraine or glacial till deposits, due to their greater similarity to the mining waste rock materials present in the region.

3.2 Morphometric parameters

Several morphometric parameters were measured, aligning with the key inputs used in the GeoFluv method for channel and hillslope morphology. These included:

- **Channel reach length**: in GeoFluv, the channel reach length refers to the length of straight reaches in A-type channels, as defined by Rosgen (1994), i.e. channels with a slope greater than 4% and a zigzag morphology. In this study, this parameter was also measured in channels with slopes less than 4%, provided they exhibited a noticeable zigzag morphology. This parameter was measured using GIS. Longitudinal profile was taken by using Global Navigation Satellite System (GNSS), and reach length was extracted from the data in the GIS.

- **Distance from ridgeline to channel's head**: GeoFluv-Natural Regrade refers to the (maximum) distance from ridgeline to channel's head, which the geomorphic literature commonly refers to as overland flow path length. This is the straight-line distance from the origin point of a first-order channel to the watershed divide encompassing that channel. This parameter is particularly relevant in environments where fluvial erosion processes play a key role in shaping the landscape and configuring drainage networks. Although this was not expected to be case in the northern Swedish landscape, it was measured as part of this study and will be discussed in the results section. The distance was measured using 2 m-resolution Digital Elevation Model (DEM) following the shortest straight-line path between the channel head and the divisor line.

- **Sinuosity**: is defined as the ratio between the channel length and the valley length related to that channel. Channels with a very straight trajectory will have sinuosity values close to 1, while channels with a very meandering course will have higher sinuosity value between 2.7 and 3.5. Sinuosity values were classified in two separate groups: channels with slopes greater than 4%, and channels with slopes less than 4%. This distinction follows the same classification used by the GeoFluv – Natural Regrade software to differentiate between Rosgen type A-channels (zigzag morphology, slope >4%) and type B/C channels (meandering morphology, slope <4%) (Rosgen 1994). Sinuosity values were determined using GIS (ArcGIS Pro) by measuring the length of the channel in a given section and dividing that distance by the length of the valley related to that channel section.

- **Drainage density**: is defined as a measure of the length of all stream channels within a drainage basin, divided by the area of that basin. Two methods were used to obtain the total length of the drainage network using ArcGIS Pro:

a. For each channel head, a basin was created with a pour point 350 metres downstream of the channel head. Using the flow accumulation, a stream network with a minimum contributing area according to the contributing area of the channel head was created.

b. For the created basin, streams were created using the channel head's average contributing area of the surrounding area. The total length was divided by total drainage area, previously obtained automatically in ArcGIS Pro.

- **Width/depth ratio**: represents the ratio between a channel's bankfull width and depth at a specific point along the channel. The width/depth ratio was measured through fieldwork. Measurements of the bankfull and the talweg (lower point in the channel) were taken at several points along their course using GNSS. The data was then processed to obtain the width and depth, and calculate the ratio using the statistical computing software R.

4 Results and discussion

Figure 1 shows the general location of the areas where the channels and drainage networks were identified. Figure 2 presents detailed views of selected channels and drainage networks. In total, 67 first-order and second-order channels and four drainage networks were analysed in this study.

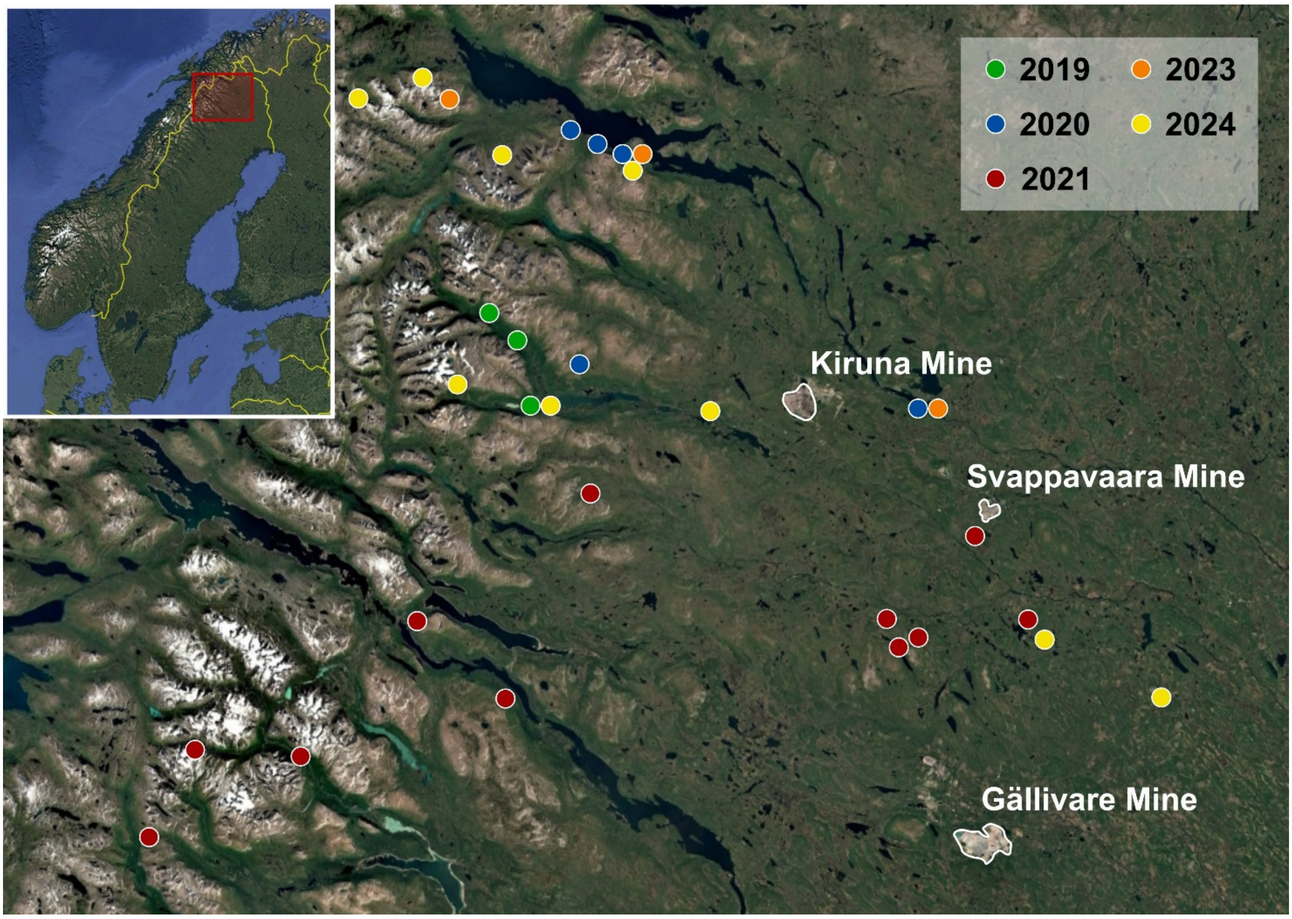

Figure 1 General location of channels and drainage networks identified and measured in this study. Points in the Figure may represent more than one channel or drainage network identified, as in most cases, several channels were identified in a single location

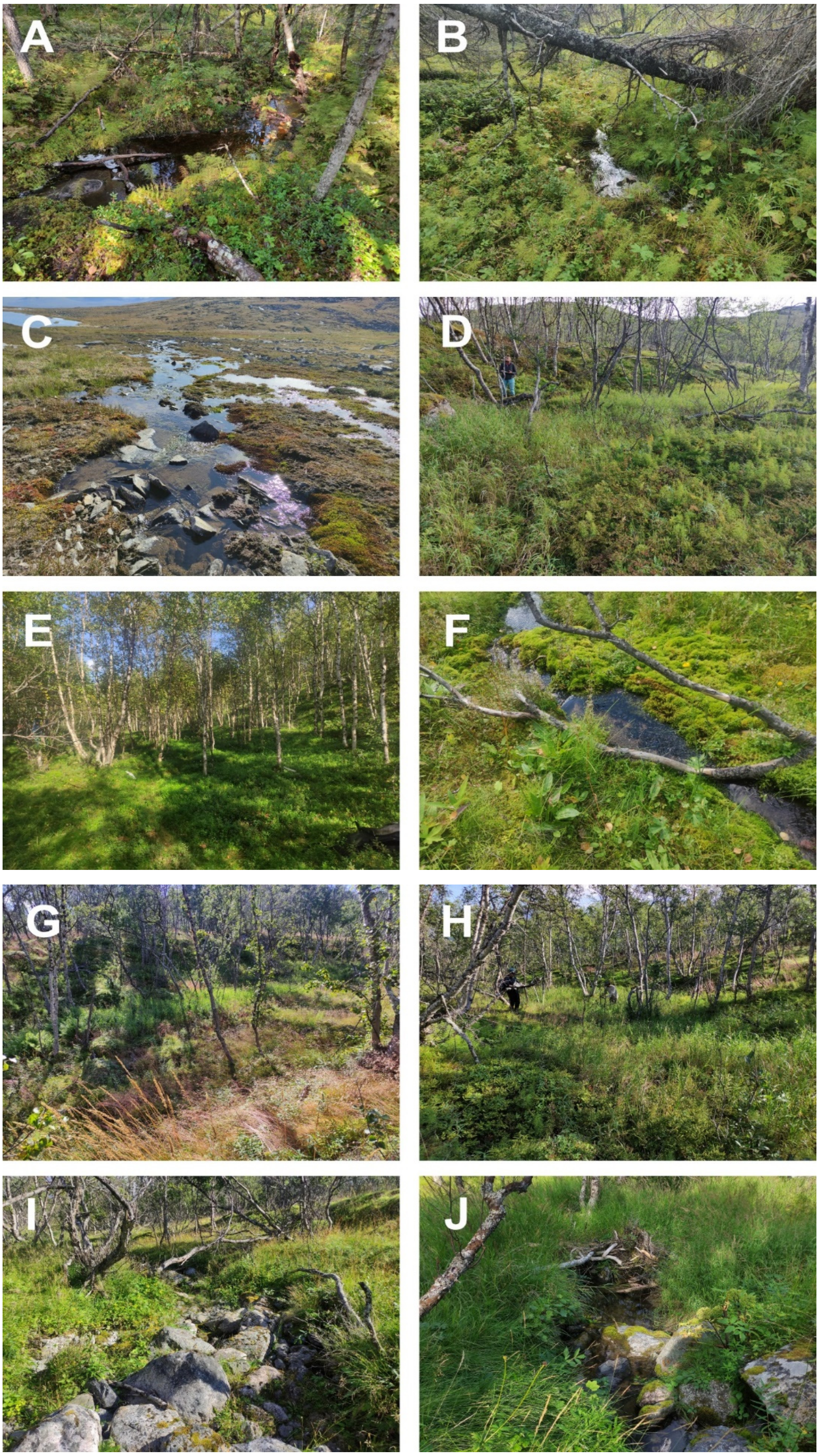

Figure 2 Photos of selected channels identified during the 2020, 2023 and 2024 field campaigns. (a) Channel measured in 2020 and 2023 field campaign; (b), (c) and (d) Channels measured in 2023 field campaign; (e), (f), (g), (h), (i) and (j) Channels measured in 2024 field campaign

Table 2 summarises the morphological parameters measured in the study. The table presents significant and average. Individual values are not shown to help the interpretation of the results.

Table 2 Summary of morphological parameter measurements. Table shows the average value for each morphological parameter, as well as significant observations

Morphological parameter	Unit	Average value	Significant observations
A-channel reach length	m	25.49	50% values within 16.78 to 32.02
Distance from ridgeline to channel's head	m	784.22	High variability in values, range from 19.73 to 2,449.01. This parameter is not applicable in geomorphic designs (see text for explanation)
Sinuosity	Dimensionless	1.10 (>4% slope channels) 1.13 (<4% slope channels)	Generally low sinuosity values observed, max value of 1.22
Drainage density	m/ha	18.66	Range of values go from 3.09 to 50.66
Width/depth ratio (bankfull)	Dimensionless	8.86	50% values within 4.24 to 10.20 >25% values over 10.20

4.1 A-channel reach length

A total of 113 values were obtained for the A-channel reach length, from 24 distinct channels. The measured values range from a minimum of 5.62 m to a maximum of 64.13 m, with an average value of 25.49 m (Figure 3). Fifty percent of the measurements fall within a relatively narrow range, between 16.78 m and 32.02 m.

The results for this parameter fall within a similar range to those reported in for natural reference sites located in semi-arid climates (Martín Duque et al. 2020, 2021, 2024; Sánchez Donoso et al. 2023; Zapico et al. 2018).

The A-channel reach length influences the surrounding hillslope topography, as it defines the toe of the swales and ridges on the valley wall slopes adjacent to the channel. In nearly all of the zigzag channel reaches analysed in this study, the typical swale-and-ridge morphology associated with such channels could not be clearly identified. This is likely due to the influence of glacial legacy landforms on the landscape configuration, which appears to dominate over fluvial erosion processes.

4.2 Distance from ridgeline to channel's head

A total of 34 ridgeline to channel's head distance measurements were obtained during the 2024 campaign. The values range from a minimum of 19.73 m to a maximum of 2,449.01 m, with an average value of 784.22 m (Figure 3). As shown by the results, no clear pattern can be identified, and the range of values is notably large with the maximum value exceeding the minimum by more than two orders of magnitude.

The values are also considerably higher than those reported for the same parameter in natural areas within semi-arid environments (Martín Duque et al. 2020, 2021, 2024; Sánchez Donoso et al. 2023; Zapico et al. 2018). This disparity between the values obtained in this study and those from other climatic regions, along with the broad dispersion observed in the data, supports the idea that fluvial processes exert limited control over the formation and dynamics of channels in the Norbotten region.

The ridgeline to channel's head (overland flow path length) distance is a parameter intrinsically linked to surface fluvial erosion processes and the dynamics of first-order channels in drainage basins within arid and semi-arid environments. This is because this parameter defines the point at which first-order channels begin – that is, the point where sheet flow transitions into concentrated flow.

In the case of the channels analysed in this study, this distance is highly heterogeneous and significantly greater than what is typically observed in channels dominated by fluvial processes. This observation could be considered evidence that the head position of first-order channels in the study area is not primarily governed by fluvial erosion processes. Instead, the location of channel heads appears to be controlled by other factors, such as soil saturation levels and subsurface water infiltration and groundwater flow dynamics.

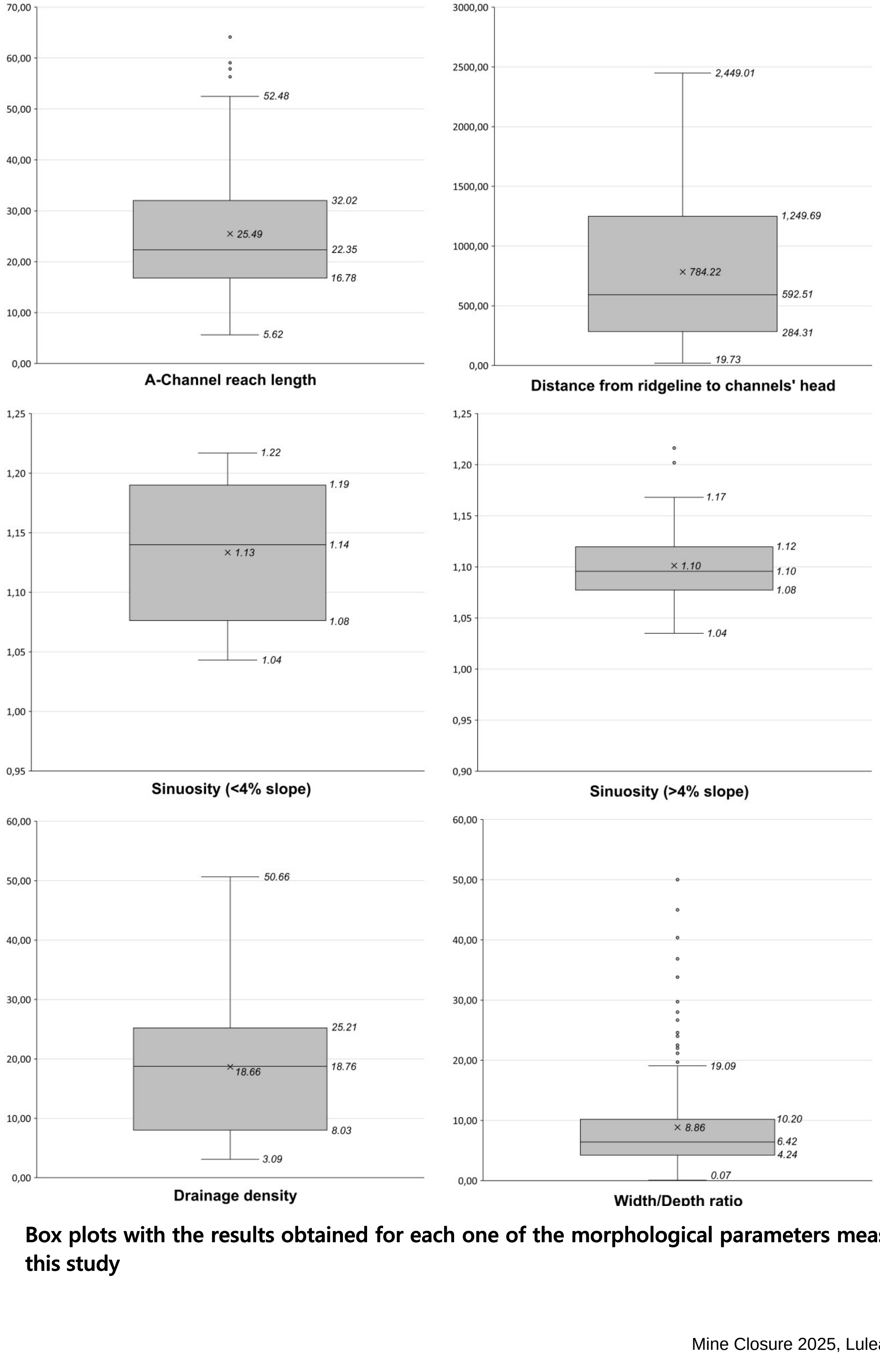

Figure 3 Box plots with the results obtained for each one of the morphological parameters measured in this study

The measurement of this parameter in the study, does not provide meaningful insight into erosional behaviour of landforms and channel development in this region, due to the fact that almost all channels start on bedrock of the glaciated landscapes, and thus lacks practical value for application in the GeoFluv method.

4.3 Sinuosity

Channel sinuosity was measured in 61 channels. For channels with slopes greater than 4%, the average sinuosity value was 1.10. The majority of values fall within a range between 1.04 and 1.17. For channels with slopes less than 4%, the average sinuosity was 1.13, with values ranging from 1.04 to 1.22 (Figure 3).

According to the Rosgen classification – adopted by the GeoFluv method – type A-channels generally have sinuosity values below 1.2, while type B/C channels are characterised by sinuosity values greater than 1.2. As observed in the results, sinuosity values for the corresponding channel types are very similar, with only slightly higher values for channels (B/C) with slopes below 4%. The small variation observed in sinuosity values for the two channel types analysed in this study may indicate a low influence of fluvial processes in channel morphology.

Instead, infiltration and groundwater flow processes that affect channels in environments such as the study area, as well as the presence of glacial legacy landforms, might play a more significant role in the sinuosity values and channel morphology. In some observed cases, surface flow disappeared or diminished in certain sections of the channels, re-emerging a few metres downstream. This behaviour alters the surface trajectory of the channel and therefore its sinuosity.

4.4 Drainage density

A total of 31 drainage density measurements were conducted with an average value of 18.66 m/ha. The maximum and minimum recorded values were 50.66 m/ha and 3.09 m/ha, respectively (Figure 3).

Compared to drainage density values reported in similar analyses conducted in semi-arid regions (Martín Duque et al. 2020, 2021, 2024; Sánchez Donoso et al. 2023; Zapico et al. 2018), the results of this study are slightly lower. These lower values may be attributed to several factors. First, drainage density in this study was determined using remote sensing tools, as in-field measurement of this parameter is complex. As a result, there may be an uncertainty of the total channel paths and length used to calculate drainage density due to it being calculated assuming contributing area.

In addition, lower drainage density values may be associated with higher infiltration rates of surface water into the ground, resulting in reduced surface runoff, fewer channels, and thus lower drainage density. Increased infiltration in the study area is favoured by the extensive taiga and birch forest with dense understory vegetation including mosses, which covers much of the natural terrain and enhances water retention.

4.5 Width/depth ratio

A total of 227 width/depth ratio measurements were obtained across 40 channels. As shown in Table 2, the average width/depth ratio for the bankfull section of the measured channels is 8.86. Individual values range from a minimum of 1.10 to a maximum of 50.00. Fifty percent of the data falls within the range of 4.24 to 10.20 (Figure 3).

The width/depth ratio results for the bankfull section largely fall within the range defined by Rosgen for type A-channels, typically characterised by a ratio of 10 (Rosgen 1994). This value is used by the GeoFluv method, in combination with precipitation data, to design channel cross-sections. However, a substantial number of results (27% of total) obtained in this study exceed that value. In the field, these higher ratios correspond to channels with wide, flat channel bottoms covered with vegetation.

Such channels, which are common in environments at similar high latitudes, exhibit higher width/depth ratios than typical type A-channels. This is because their cross-sectional geometry must accommodate not only runoff generated by precipitation but also snowmelt. In such channels, surface flow is generally confined to a small section of the channel bed throughout most of the year. During snowmelt, surface water spreads across the entire channel bottom, functioning similarly to a floodplain but confined within the channel banks. These channels are wide enough to resist erosion by spreading the flow area and maximising the effective channel roughness by preventing vegetation from becoming submerged (i.e. overtopped). The higher width/depth ratios may also be influenced by the glacial legacy landforms and semi-alluvial channel dynamics (Mason & Polvi 2023).

4.6 Recommendations for current geomorphic landform design approaches

The GeoFluv method, as well as other current geomorphic landform design approaches, are mostly based on fluvial geomorphology concepts for the design of landforms and channels. As such, these methods use morphological parameters of channels and watersheds as design inputs, which are closely linked to fluvial processes. However, the landforms and drainage networks in the Norrbotten region are strongly influenced by glacial legacy landforms and modern-day ice processes, with fluvial processes – although present – playing a relatively minor role.

Ideally, geomorphic restoration approaches used in such regions should be capable of replicating glacial or fluvioglacial landforms and associated drainage patterns. Since GeoFluv-Natural Regrade is currently the only geomorphic landform design software available commercially, our study provides suggestions that could be incorporated in such software in future geomorphic restorations at mine sites in northern Sweden. Ideally, in the future, specific software would be available either specific for these regions, or capable of incorporating the geomorphic specificities.

In areas where significant snow accumulation is expected throughout the year, channels should be designed with a wider and flatter bottom, capable of conveying water derived from both precipitation and snowmelt. From a design perspective, this translates into a higher width/depth ratio, in line with the results obtained in this study (Figure 4). To more accurately determine the necessary channel width, the estimated volume of snowmelt runoff should be calculated, and the design adapted to accommodate the corresponding peak discharge. It is also advisable to vegetate the channel bed with native understory vegetation species to reduce erosive potential.

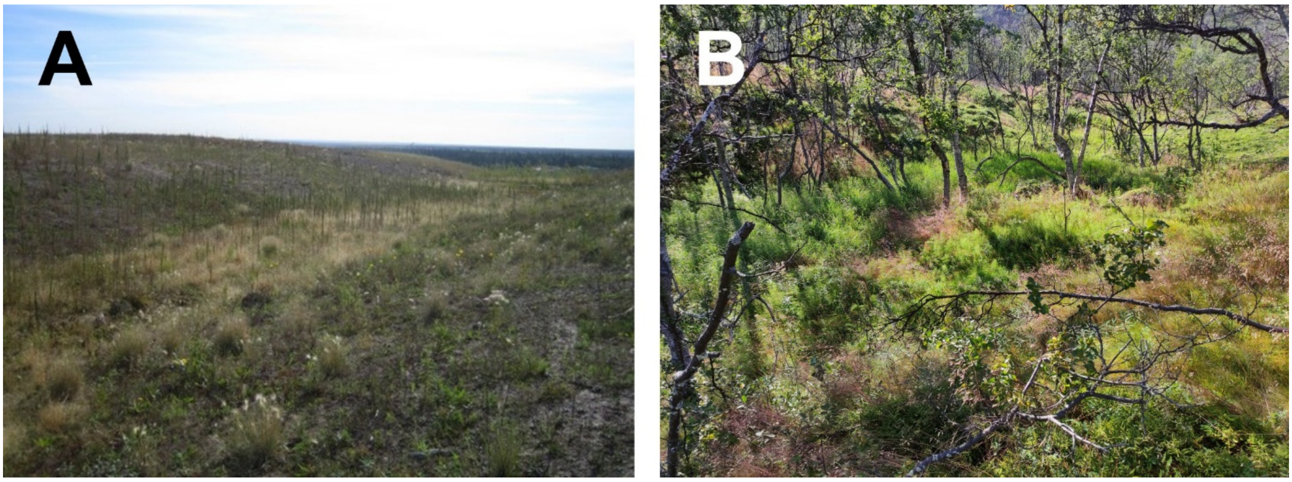

Figure 4 (a) Example of a designed and constructed vegetated waterway, with wide and flat channel bottom covered with vegetation, in a mine restoration project in Canada; (b) Natural channel identified and measured near Abisko during the 2024 field campaign, with similar characteristics

Low sinuosity values are recommended for the potential designed channels. The value ranges obtained in this study may serve as a reference for both type A-channels and type B/C channels. However, a site-specific analysis of nearby reference channels is advised for each project. Low sinuosity values yield smoother, more rounded landscape configurations that more closely resemble glacial legacy landforms.

Although the overall measured values for drainage density in the study area are low, it is recommended to use a higher value within the range observed for each specific project. In the first months following restoration, landforms will be more susceptible to erosion due to the lack of fully developed vegetation cover. A higher drainage density will facilitate proper runoff conveyance and reduce the likelihood of scours, rills, or gullies forming on the landform.

5 Conclusion

In this study, channel morphometric parameters were measured in natural areas around the Norrbotten region using GIS and guided fieldwork, to understand the characteristics the landscape and provide suggestions on how to adapt geomorphic-based solutions in northern Sweden.

The A-channel reach length, width/depth ratio, sinuosity, distance from ridgeline to channel's head and drainage density were measured in 67 first and second-order channels and four drainage basins. Results show that landscapes and drainage networks are heavily influenced by glacial and fluvioglacial processes, and that fluvial processes play a secondary role on channel morphology. Morphometric parameters such as the width/depth ratio and sinuosity show a clear influence of glacial legacy landforms and snowmelt processes, which gives first-order channels a characteristic flat and wide channel bottom and less sinuous reaches than channels in lower latitudes. Findings suggest that morphometric parameters such as the overland flow path length cannot be applied in the study area as described in classic geomorphic literature, due to the fact that a channel's head position seems to be more influenced by groundwater flow processes than erosive processes.

Geomorphic-based solutions applied in northern Sweden can adapt to those characteristics, adjusting the morphometric characteristics of designed channels by widening its channel bottom to accommodate snowmelt water discharge and giving designed channels a lower sinuosity value. More research is required to better understand the processes behind channel head formation in northern Sweden's first-order channels and to be able to adequately transfer that morphologic parameter to geomorphic landform design solutions.

Acknowledgement

The authors want to thank Anders Lundqvist for his hospitality and assistance during the fieldwork campaigns conducted in 2020, 2023 and 2024.

The results exposed in this study are part of the research work conducted in the Waste2Place Project, within the strategic innovation program Swedish Mining Innovation, a joint venture by Vinnova, Formas and the Energimyndigheten (Swedish Energy Agency).

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