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The influence of land use on the spectrum of landform transformations (a case study of the Russian Arctic)

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Human activity has a profound effect on relief. Therefore, it is crucial to study the anthropogenic relief transformation. The field of study is relatively young, although rapidly developing. This work outlines the influence of human activity on the relief. A vital point of the work was to identify the differences in the influence on morphogenesis by varying types of land use. Norilsk mining district was chosen as a study area because of its intensive and complex human activities, vast mineral resources, and a large population, which implies an extensive anthropogenic transformation of the area. As a result of the research, land use types with the most profound influence on relief have been identified. Moreover, both the direct and indirect effects on morphogenesis, as well as the resulting processes, have been outlined.

Keywords: Norilsk, Arctic, anthropogenic relief, mining, anthropogenic impact, hazards of land use.

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1 Introduction

The history of land use in the Russian Arctic can be traced back for several thousand years, however the influence of man on the landscape during the early stages of settlement was miniscule and often negligible. The population in the area was sparse and mainly consisted of hunter-gatherers and reindeer herdsmen.

As 18th and 19th centuries brought industrial development to the area, it implied a more pronounced anthropogenic influence on the landscape. More types of land use became present, as the first housing and industrial areas were established. Most of these settlements with a complex use of natural resources were situated in the European part of Russia Arctic. The turn of the 20th century brought forward the most intensive industrialization of the Arctic, especially the Asian part. This process promoted the development of various types of anthropogenic transformations of relief [*Bredikhin et al.*, 2020].

2 Defining anthropogenic transformation of relief

Economic development of the area may be described as recent, yet extremely intensive due to the rich mineral resources. The intensive development promotes an ever-increasing environmental load. Moreover, during the recent years the Arctic has become one of the pivot points of social and economic policies of Russia [*Pilyasov*, 2016]. Evaluations of the landscape dynamics at varying spatial and temporal scales in the area paint a picture of an increasing extent of major anthropogenic change [*Tishkov et al.*, 2019]. The intensification of economical development in the area implies a need to examine the human influence on the environment, including the effects on both the relief and morphogenesis.

Anthropogenic transformation of relief is a set of processes that arise from land use and affect both the relief and relief-forming processes of the area. These processes can be classified as either direct or indirect. Direct transformation can be described as any change to previously unaffected relief, may it be creation or destruction of it altogether. The indirect changes may arise as a result of influence of human activity on relief-forming processes. Impacting both the relief-forming factors and conditions, the human activity causes a change of the intensity over all of the spectrum of morphogenesis.

Anthropogenic relief is a product of human changes to ecosystems applied to morphogenesis. It comprises of various landforms that are changed

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or made by humans [*Shchukin*, 1980]. The consequences of human activity, including building, agriculture, industry (mining, water engineering, etc.) and military actions, present themselves as the previously mentioned landforms. As the scale and morphology of anthropogenic relief transformation, as well as its indirect transformation spectrum, are in great dependance on the engineering and technological aspects of the development in the area, it is necessary to view the relief transformations through the lens of land use [*Bredikhin et al.*, 2020].

In order to classify the prevailing land use types and define the ones with the greater effects on morphogenesis, an array of resources has been used. Firstly, a comprehensive analysis of the available literature helped to establish the possible types of landuse and their influence on relief. Secondly, the morphology of anthropogenic landforms was retrieved via GIS software. Finally, the use of satellite imaging provided an extensive overview of the area, so that seven principal land use in Arctic have been outlined. They include traditional and agricultural, forestry, military, transportation, housing and industrial. Each one is characterized by a specific set of anthropogenic landforms and a unique array of indirect transformations that are presented in the table below (Table 1).

The largest scales and intensities of anthropogenic landform and sediment transformation can be observed in the areas of housing, industry and transportation. Anthropogenic landforms in industrial and housing zones occupy a greater area than those influenced by indirect effects. Housing can be distinguished by an overwhelming majority of accumulative anthropogenic landforms over denudative (in terms of area and volume). As for the zones with industrial and military land use, the majority of landforms in the area are subrelief, while the reliefoids are prevalent in the housing zone. Forestry, herding and agriculture present little to no direct effects on relief and are mainly influencing landforms through indirect anthropogenic transformations.

3 Case study of Norilsk

Complex morphology is a prominent attribute of anthropogenic relief in areas with industrial activities. During mining and later processing of raw materials the environment experiences the most notable and pronounced impact. Norilsk and its surroundings were chosen in order to assess the scale of direct and indirect anthropogenic transformations, as this particular area experiences one of the most prominent effects of human activity.

Norilsk mining district consists of Norilsk itself and the Norilsk-1 mineral deposit. The Norilsk-1 mineral deposit includes the “Zapolarniy” mine and the “Medvezhiy ruchey” quarry. The area of the research polygon is 140 km^2. To assess the direct anthropogenic transformations and identify the anthropogenic landforms, a DEM of the key research area was used. ArcticDEM was chosen because of its fine spatial resolution of 2 meters [*PGC*, 2021]. The areas and volumes of anthropogenic landforms were evaluated using GIS software. As a result of the evaluation, a medium-scale map of anthropogenic relief has been produced (Figure 1).

The total extent of areas that are prone to direct anthropogenic transformations is estimated at 41 km^2. Accumulative landforms are most prominent and are mainly comprised of embankments under the housing and industrial zones. The average height of these embankments is 2–3 meters, while the tailings have a thickness of up to 50 meters. The embankments for roads and train tracks are not displayed on the map due to the scale. A collection of the largest waste dump fields of the “Zapolyarny” mine is located in the southern part of the research area. These waste dumps have a serrated edge, the slopes of which have characteristic heights of 10 to 50 meters and steepness up to 45–50 degrees.

The denudational landforms are represented by isometric quarries of the “Zapolyarny” mine. The largest of them is the “Medvezhiy ruchey” quarry with a maximum depth of 310 meters and a width of 1200 meters. As the mining in the area includes both open-air and underground miming, the subrelief of the area is also developed. The mines reach a maximum depth of 230 meters. Accumulative landforms form a majority of those present with a 90.7% share by area and an 82% share by volume. A considerable area is occupied by earthworks for housing and industry, which mainly consist of levelled terraces and moulds of compacted soil and represent 34.5% of the zone area.

The deposition of waste in forms of waste fields, dumps and tailings is accompanied by a change of the lithological composition of the near-surface rocks, as well as a change in slope steepness and a near complete obliteration of all vegetation. These changes prompt an extensive increase in the intensity and scale of slope processes (primarily, rock falls at the slopes of quarries and dumps), suffusion, linear erosion and plane washing. Consequently, an increase of horizontal riverbed deformations and sediment flux in waterways nearby can be observed. The deflation experiences a growth in intensity on the flat surfaces of tailings [*Butiugin and Gulan*, 2005]. Land use and mismanagement cause deeply affect the underlying permafrost by subjecting it to substantial anthropogenic heat fluxes, which causes an in-

Table 1: Direct and indirect landform transformations typical for different types of land use

Land use	Localization	Direct transformation (typical anthropogenic landforms)	Indirect transformations (impact on the morphogenesis)
Agriculture	Background spatial	Irrigation and drainage channel cavities, furrows, and reindeer path microrelief	Amplification of thermokarst, thermal erosion, sheet washing, defluxion and waterlogging
Forestry	Focused spatial	Sawdust pseudo-terraces and stockpiles	Cutting areas – emergence of sheet erosion, linear erosion, thermokarst and thermal erosion, defluxion, and waterlogging Processing areas – decomposition and subsiding deformations of anthropogenic deposits (sawdust and waste)
Military	Linear, linear-spatial, and nucleated spatial	Earthworks – moats, dams, ditches, sod walls, explosion craters, tunnels	Intensification of defluxion, deluvial washing, slope processes, and waterlogging
Transport and infrastructure	Linear and clustered linear-spatial	Road and train track embankments, ditches, rolls of pipeline fillings	Emergence of frost weathering, thermal erosion, thermokarst, solifluxion, linear erosion, thermal abrasion of coasts, suffusion
Housing	Large-parcel clustered	Embankments, artificial terraces, a sub-relief of underground structures – tunnels	Emergence of regressive erosion. More pronounced suffusion, defluxion, slope processes (especially landslides), subsidence deformations, and ice formation
Industrial	Large-parcel clustered, linear-spatial (placer deposits)	Quarries, embankments, waste dumps, tailings, various subrelief landforms – mines, boreholes, and galleries	An increase in slope processes – rockfalls and landslides. A marked intensification of defluxion, suffosion, erosion and deposition in rivers and streams. Pyrolysis (self-ignition of waste dumps), subsidence deformations as well as induced earthquakes

crease in temperature, melting and an emergence of thermokarst, suffusion and thermal erosion.

Due to the climatic features of the area, inversions of temperature in lower atmosphere are frequent. When coupled with smog and poor air mixing, these features imply another indirect factor as the properties of rain may change significantly as pollutants accumulate in lower atmosphere and are then washed out. As a result of rain acidification and frequent acid showers in the area, the vegetation in the areas adjoined to the processing plants has been destroyed to the point of an absence of any form of it whatsoever [*Telyatnikov and Prystyazhnyuk*, 2014]. An influence on relief forming factors can be expressed as a change in rates of plane washing and linear erosion.

A technical need of disposal of acidified waters facilitates the development of a variety of indirect hydrological transformations. During the exploitation of pipelines, a number of failures have been observed (Figure 2). The preliminary causes for these failures are both natural (climatic) and man-made. As a result of these failures, mining waters are leaking into the surrounding ecosystems, causing contamination with toxic elements and heavy metals. The water seepage also provokes linear erosion, flooding and development of gullies.

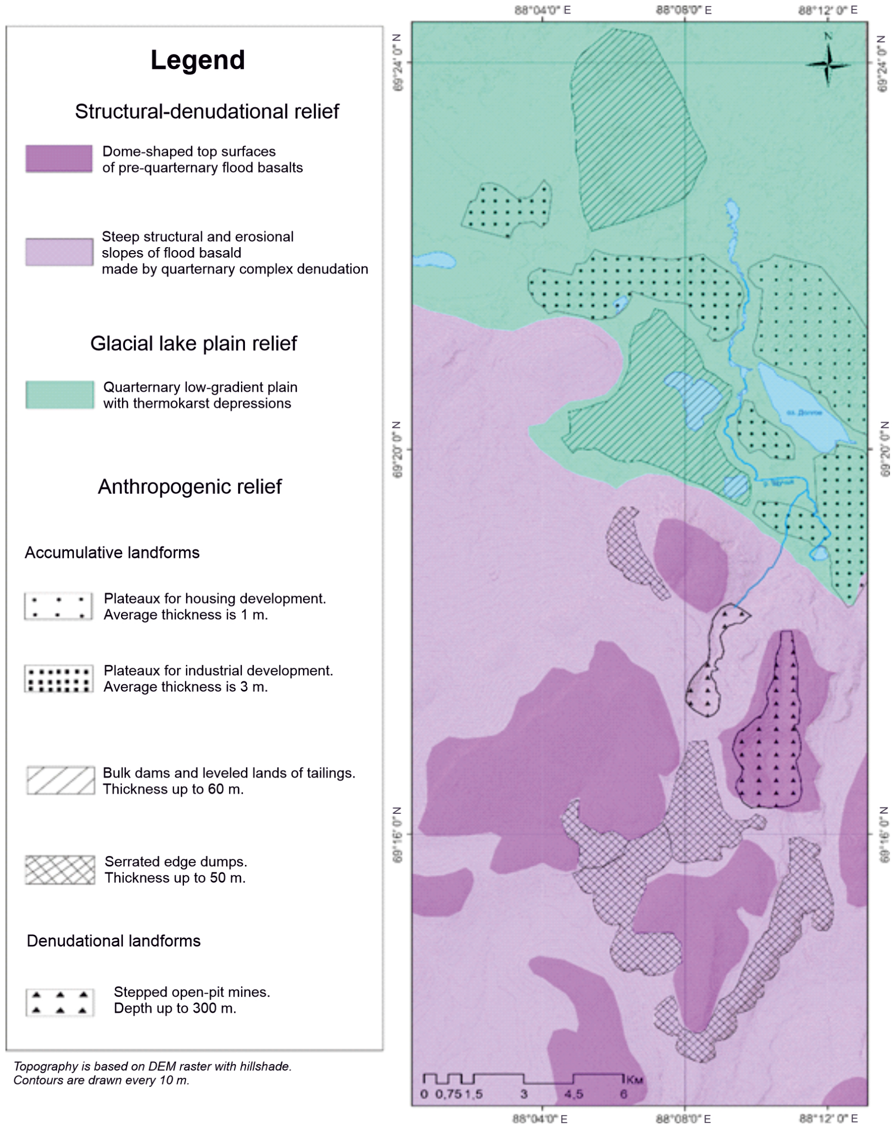

Figure 1: Natural and anthropogenic landforms within Norilsk mining district.

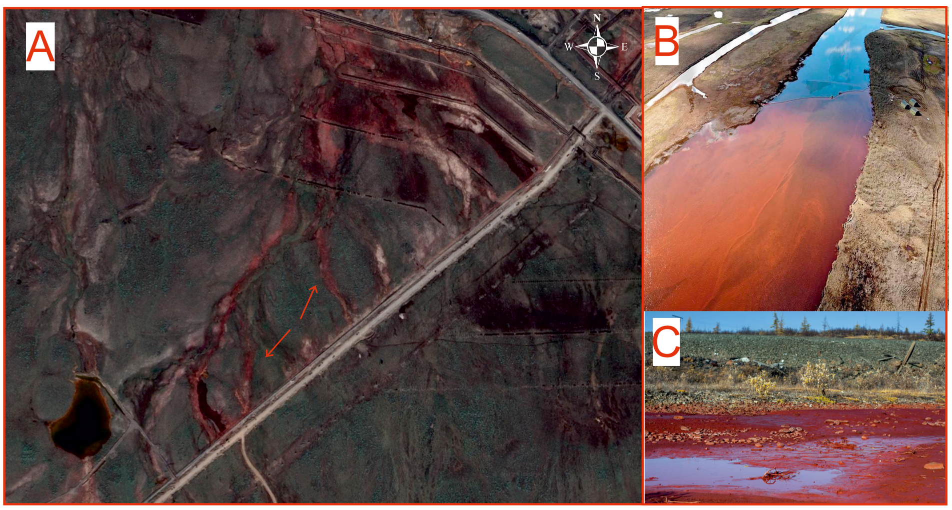

Figure 2: Consequences of a failure of a pipeline between the processing plant and the tailings. The delves formed by mine waters are marked with arrows. A – overview [*Google*, 2022], B – failure of 2020 at Ambarnaya river [*Pettit*, 2020], C – failure of 2016 at Daldykan river [*Tribune*, 2016].

4 Discussion and conclusions

Firstly, the largest scale of anthropogenic landform transformation is observed in the areas of industrial, transportation, military and housing land use. Forestry and agriculture have an impact on the conditions of relief formation, that explains a relatively low direct transformation of natural landforms.

Secondly, the assessment of scale of anthropogenic relief transformation in Norilsk ore district outlines a majority of direct relief transformations in the areas of industrial land use. Moreover, these transformations are mostly accumulative in terms of area and volume metrics.

Thirdly, a wide spectrum of indirect influence of land use on landform development can be observed. The effects of industrial land use include changes in vegetation, as well as climatological, lithological, and hydrological factors of relief formation. If the excessive heat flux into the permafrost is continued and coupled with the effects of a rapidly changing climate of the Arctic, a strong possibility for large scale man-made catastrophes will arise.

It remains vital to mitigate the negative effects of anthropogenic relief transformations, therefore further research in this developing field is crucial for a sustainable future.

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