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Article

Assessment of the morphometric conditions of the modern relief of the Semipalatinsk nuclear test site

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Abstract: In recent years, the issue of involving part of the former Semipalatinsk Nuclear Test Site (SNTS) in the economic turnover of local agricultural producers has become acute. This is facilitated by comprehensive environmental studies of the landfill territory. However, studies of morphometric conditions with obtaining numerical characteristics of the landfill relief are practically absent. This study is aimed at studying the morphometric conditions of the relief: slope, aspect, density, and depth of dissection to assess the morphometrically determined factors in the development of a number of modern exogeodynamic processes. The study of morphometric conditions was carried out on the basis of processing and analysis of DEMs, which became the input criteria for scoring. Maps were created and their statistical parameters were extracted: slope, aspect, vertical and horizontal dissection and susceptibility of the relief surface to the factors of development of relief formation in the territory of the SNTS. Thematic information is presented on maps of two types: in the context of elementary areas represented by cells (1×1 km) and interpolation of these elementary areas. The results have practical significance for the development of the principles of an adaptive landscape farming system within the study area.

Keywords: nuclear test site; morphometric conditions; relief; slope; DEM; adaptive landscape farming system.

1. Introduction

The territory of the former Semipalatinsk nuclear test site still remains a place for scientific research in various directions; this situation is due to the fact that for more than 50 years, this territory was exposed to nuclear tests carried out by the Soviet Union. More than 450 nuclear explosions over an area of just 18,500 km^2 changed the natural conditions of area (Parfitt, 2010). First of all, we are, of course, talking about radioactive contamination, which to this day plays a certain negative role in both the development of natural and social processes. Today, scientific and applied research of a wide profile, including monitoring, ecology, the impact of man-made radiation on the environment, radiation safety issues, etc., is carried out by employees of the National Nuclear Center of the Republic of Kazakhstan ("The periodic scientific and technical journal of the National Nuclear Center of the Republic of Kazakhstan," 2024). In the territories affected by nuclear tests at the Semipalatinsk test site, a set of measures is being implemented with the aimed at improving the natural environment, state and public environmental assessment of economic and other activities. Furthermore, are being implemented measures to return radiation-contaminated territories to economic circulation (On social protection of citizens affected by nuclear tests at the Semipalatinsk nuclear test site, 1992).

To date, in the relevant scientific literature there are no publications devoted to the study of the morphometric conditions of the relief surface of the SNTS territory, assessing it from the point of view of the potential for the occurrence of exogenous natural and anthropogenic processes. Relief is one of the main factors determining the landscape differentiation of the territory (Bondarenko, 2015; Ismailova, 2016). The study of the components of relief morphometry (slope, exposure, erosion network, horizontal and vertical dissection) on the territory of the test site using modern research methods remains insufficient. At the same time, the territory is of particular scientific interest due to the unique-ness of its geological structure, geographical location and the development of relief-forming exogenous processes on it. Various morphometric indicators of relief are widely used in areas where quantitative assessment of the properties of a topographic surface is necessary (Pogorelov, 2015). Taking into account the morphometric characteristics of the relief allows for the rational use of land for economic purposes. Since quantitative indicators of relief are the most visual indicators of the dynamic conditions for the development and functioning of ecosystems, and morphometric analysis plays an important role in ecogeomorphological studies (Khalilov, 2014).

It is worth noting the adoption of the law on the creation of the Semipalatinsk nuclear safety zone on the territory of the former test site. The law provides for the return of suitable land to economic use (Official website The President of the Republic of Kazakhstan). Knowledge of terrain conditions allows the most correct approach to the allocation of buffer, water protection, sanitary protection zones, not only from the point of view of the norms established in the legislation, but taking into account the specific conditions of the territory (Pozachenyuk, 2016). Understanding the values of the morphometric situation allows us to scientifically identify zones with different environmental management regimes by determining the basis of erosion, the transfer of solid particles, and the development of exogenous processes. Among the transfer agents, linear erosion, planar washout, coastal erosion, and gravitational processes stand out; they all form morphometric components that together characterize the relief (Ismailova, 2021). Since the relief of the earth's surface, along with the lithogenic base, is the basis of landscapes, it performs certain functions: 1) participates in the distribution of gravitational energy in space and time: the relief directs the movement of material flows; 2) the relief promotes two types of movement of gravitational flows of matter - radial and lateral - and coordinates the ratio of these flows (Kashiro et al., 2012).

The purpose of this study is to assess the morphometric conditions of the modern SNTS relief to understand the spatial distribution of the development of modern exodynamic processes and their impact on the accumulation and distribution of pollutants, including radioactive ones. A comprehensive morphometric analysis of the territory based on DEM processing in a GIS environment allows you to quickly and effectively assess the critical properties of the relief, incl. for forecasting and landscape planning purposes (Mikhailov, 2015). Experience in carrying out similar work includes: assessment and ranking by scores using morphometric parameters was carried out to analyze the landscape diversity of the territory (Egemberdieva, 2021), the degree of morphometric intensity of landscape belts and zones, as well as their spatial differentiation throughout the study area (Ismailova, 2021), assessment of the degree of dissection of the relief by linear forms (coefficient of horizontal dissection) (Pavlova, 2013), comprehensive morphometric assessment of the territory (Mikhailov, 2015), assessment of the degree of dismemberment, the degree of ecogeomorphological tension of morphosystems (Khalilov, 2014).

2. Materials and methods

2.1. Description of the Study Area

The Semipalatinsk nuclear test site is located at the intersection of three regions of Kazakhstan: Abay, Pavlodar and Karaganda and covers an area of 18 000 km². Physical geographically, the test site occupies the northeastern part of the small hills of Sary Arka. It is a plain, to the south gradually changing to hilly and low-altitude terrain. During the period of the SNTS functioning (1949-1989) 466 nuclear tests were conducted on its territory, including 30 above-ground, 88 aerial and 348 underground nuclear explosions, with 13 explosions resulting in the release of radioactive gases into the atmosphere (On social protection of citizens affected by nuclear tests at the Semipalatinsk nuclear test site).

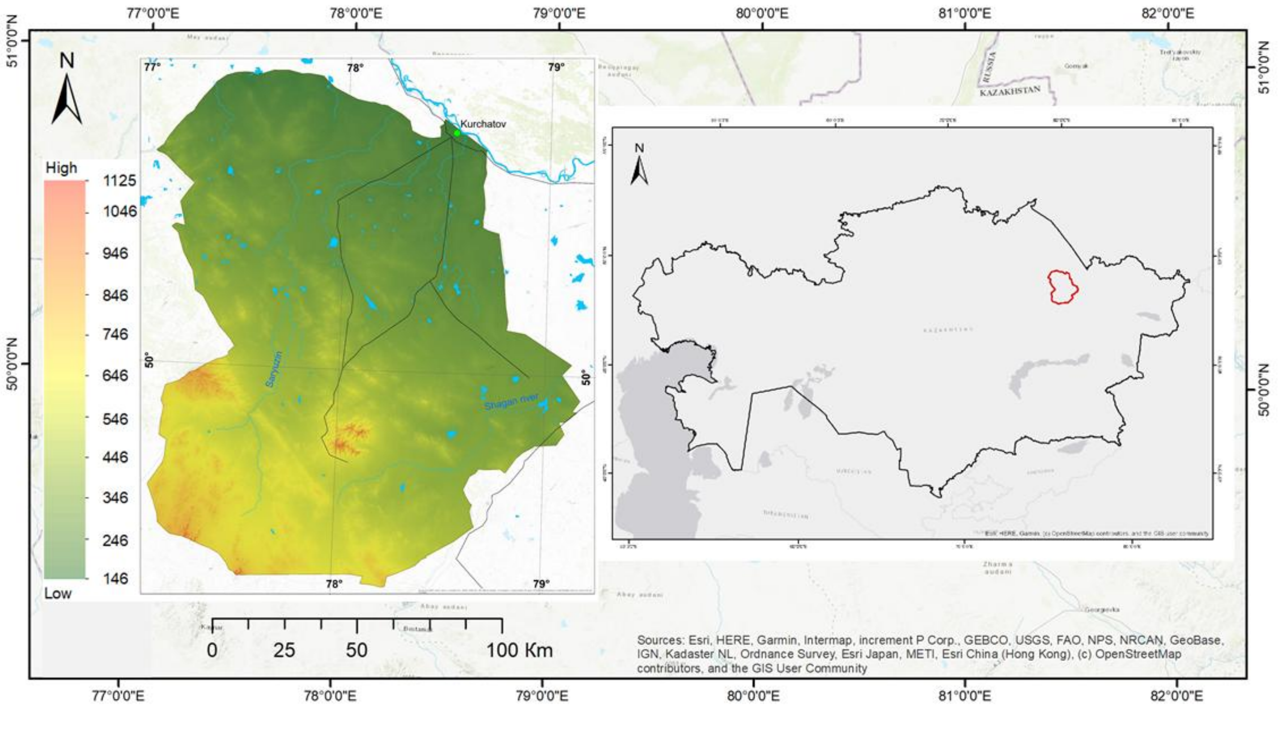


Figure 1. Location map of the SNTS territory

2.2. Data and Methods

Morphometric analysis is one of the methods of geomorphological research in which the quantitative characteristics of landforms are studied using special measurements (Ismailova, 2016). The methods and fundamental principles of morphometric work in the study of geomorphology were studied in great detail in the 1940s and 1950s by Canadian scientists Horton, R.E. and Strahler, A.E. (Pidwirny, 2006). Today, the methodology for morphometric analysis of relief is carried out using remote sensing data, in particular with the use of geographic information systems and digital elevation models. The study of morphometric conditions based on DEM processing has become widespread among geographers near and far abroad in the study of geomorphology, landscapes, exogenous processes, etc. (Bilous et al., 2020; Bondarenko, 2015; Pogorelov, 2015; Xiong et al., 2022; Zhou & Chen, 2011).

The basis for the work was data from radar interferometric satellite surveys TerraSAR-X and TanDEM-X, and the Airbus WorldDEM4Ortho digital elevation model (Table 1) (https://elevation.arcgis.com/arcgis/rest/services/WorldElevation). The available Airbus WorldDEM4Ortho data is in the form of a digital elevation model (DEM) raster file in which the pixel value is the altitude at a given point. The horizontal datum is the World Geodetic System (WGS84-G1150) and the vertical datum is the Earth Gravity Model 2008 (EGM2008) **)** (*Airbus WorldDEM4Ortho in ArcGIS Living Atlas of the World*; DLR Document: TD-GS-PS-0021; DEM Products Specification Document). The Airbus WorldDEM4Ortho data is a DEM with a cell size of 0.8 arcseconds (with a pixel side of 24 m). The resolution of the DEM increases in the direction of longitude from the equator towards the poles. Naturally, the spatial resolution of the DEM affects the spatial accuracy of subsequent mathematical calculations of the relief surface. This applies to the slope, slope aspect and other variables, the values of which respond to the given dimensions of the model cell, and sets the limits of detail of the modeled surface. To obtain a modern layer of water area objects, we used 2 Landsat satellite images (Table 2) (https://earthexplorer.usgs.gov/).

Table 1. Digital elevation model used

DEM	Resolution, m	Pixel spacing	Vertical Unit	File format	Projection	Year
Airbus WorldDEM4Ortho	24	0.8 arcsec	Meter	GeoTIFF	Geographic Coordinates	2017

Table 2. Landsat satellite images used

Satellite	Resolution	Acquisition date	Sensor
Landsat-8	30	09.05.2023	Operational Land Imager
Landsat-8	30	12.09 2022	Operational Land Imager

DEM processing, extraction of morphometric indicators, geospatial mathematical calculation and analysis of results were carried out using ArcGIS 10.5 software. To solve problems, program modules were used in stages:

- Surface (creation of hypsometry, slope, exposure and extraction of contours) (Valeev, 2016);

- Reclassification (mathematical calculations in raster attribute tables, calculation of areas, percentages, processing of Landsat satellite images to extract water areal objects) (Medeu et al., 2023);

- Sampling (Data management – sampling – build a grid) - creation of a Gridfish grid, a vector layer of 1×1 km cells for the study area. The Gridfish grid with cells of 1×1 km is the basic basis for which calculations are made of 4 morphometric indicators (slope, exposure, horizontal and vertical dissection), as well as a complex indicator of morphometric conditions - relief susceptibility. For each cell, the values of indicators per 1 square are determined. km., which are converted into a point object and then a thematic map is constructed by interpolation.

- Zonal statistics into the table (Spatial Analyst – Zonal – Zonal statistics into the table) – absolute elevations and decreases in the territory, as well as their differences, were automatically calculated. In this study, the difference between maximum and minimum heights is the relative height parameter. The result is calculated and presented in dBASE table format, under the column name RANGE. The data is the input parameters for creating a vertical density map). Connecting a table (Links – Connection) of geodata with a layer of 1×1 km cells. Creation of a map of the amplitude of vertical dissection on a cell scale of 1×1 km.

- Hydrology (erosion network extraction: Fill, Flow Direction, Flow Accumulation, Stream Link, Stream order and Stream to Feature) (Chowdhury, 2023);

- Overlay (Intersection, calculation of the length of the resulting segments inside a cell, spatial connection, calculation of the ratios of the lengths of thalwegs in an area of one cell with an area of 1 km2, creation of a map of horizontal division along the field km/km^2). the density of dissection of the territory by an erosion network, expressed by the length of thalwegs per unit area (Moglen & Maidment, 2006);

- To spatially create a map of horizontal and vertical dissection: -Spatial objects (Object to a point, export with attributes a layer of cells to a point layer, Interpolation of points of OVR methods, trimming raster edges, reclassifying a raster) for spatial creation of maps of vertical and horizontal dissection (Pozachenyuk, 2016). The resulting vector point layer became the source for interpolation calculations using the inverse weighted distance (IWD) method. The resulting raster was reclassified using Spatial Analyst tools to access individual spatial classes. Next, we converted the vertical dissection raster into a vector layer. We preliminary generalized small objects using spatial object removal tools and smoothed the lines. At the final stage, calculations were made of the areas of distribution of various parameters of vertical division (Table 3).

Table 3. The assessment of morphometric conditions is based on ranking by points, according to the developed criteria

Slope, degrees		**Aspect, rhumb**		**Vertical dissection, m**		**Horizontal dissection, km/km²**		**Degree**
Meaning	point	Meaning	point	Meaning	point	Meaning	point	Meaning
0-1	1	N	1	0-20.1	1	0-0.5	1	Low
1-2.9	2	NE, NW	2	20.1-44.6	2	0.5-1.5	2	Weak
2.9-6.4	3	E, W	3	44.6-85.7	3	1.5-2.5	3	Average
6.4-12	4	SE, SW	4	85.7-167.9	4	2.5-3.7	4	Increased
12-43.9	5	S	5	167.9-349.7	5	3.7-7.2	5	High

The criteria include 4 morphometric indicators (slope, aspect, horizontal and vertical division), their physical values and ranking unit. Obviously, these criteria were developed after receiving the numerical results of geoinformation processing of the DEM. For the comprehensive morphometric scoring, all four initial indicators (slope, aspect, horizontal and vertical dissection) were used. In accordance with the parameter values, the gradation and value in points were selected. Scientists use various approaches to defining a comprehensive assessment. For example, to determine a complex morphometric indicator, the addition of all points was used (Mikhailov, 2015), to assess the degree of ecogeomorphological tension of morphosystems, we used a combination of density and depth of division into categories (weak, medium, and high) (Khalilov, 2014), we used the average value of the sum 4 morphometric characteristics of the relief to assess the tourism potential (Sedrette & Rebai, 2022).

Figure 2 shows the study design. A literature review of the methods used to investigate landform morphometry and the study area was conducted. Data was collected for the study area, followed by the processing and extraction of the required geospatial data. The obtained data was analysed and evaluated to determine the susceptibility of the relief.

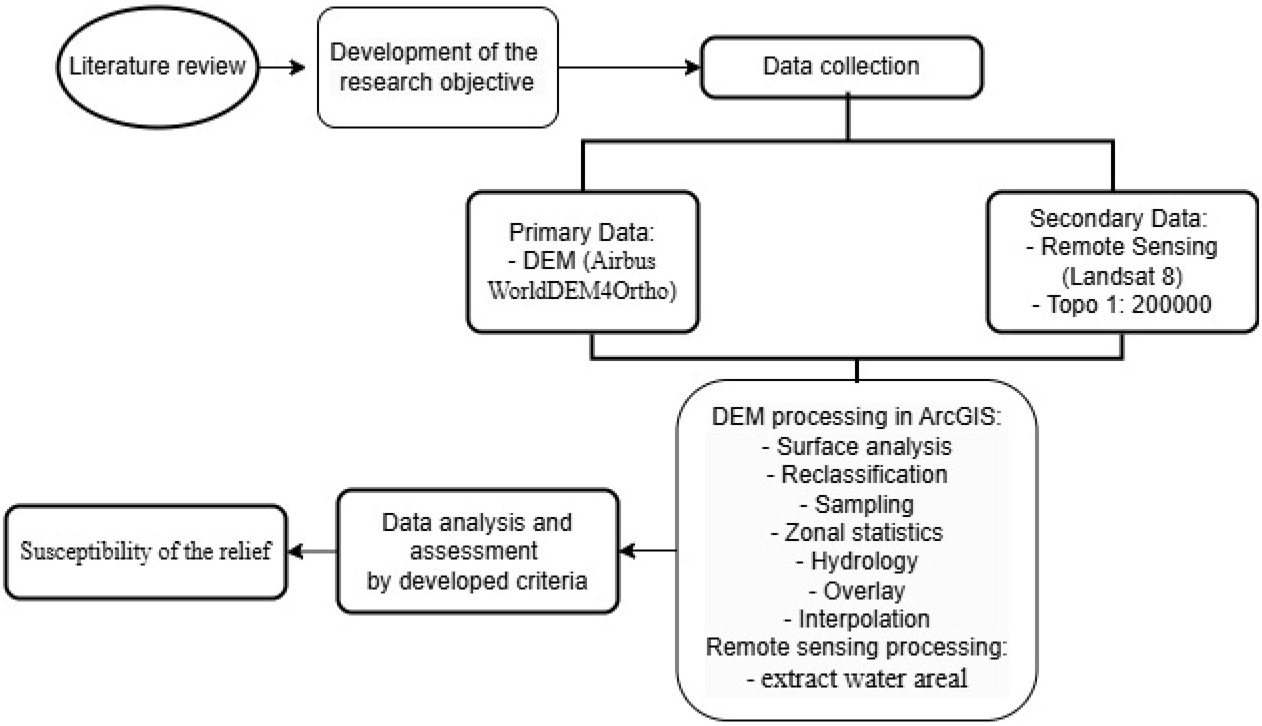
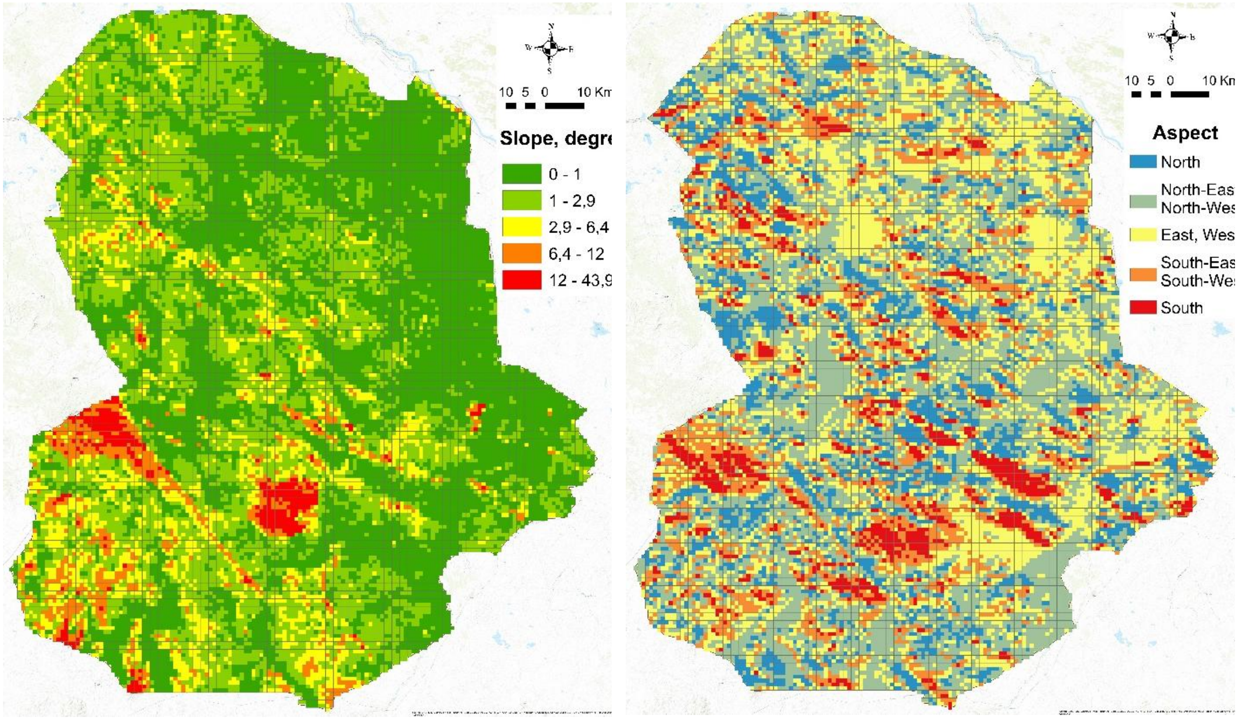


Figure 2. Flow diagram for methodology

3. Results

3.1. Slope, aspect

Slopes and surface aspect are fundamental geomorphological parameters that are naturally associated with the formation of landscapes and the development of exogenous processes and phenomena. The SNTS area is part of the left bank catchment of the Yertis River, so in general the slope trend is towards the main waterway. The northern and eastern territories are plains, in the southern part there are hills and mountains, stretching from southeast to northwest, only the Degelen mountains with the highest elevation (1084 m) have the shape of a circle. The hilly terrain of the eastern end of Sary Arka causes non-uniform surface slope conditions (Figure 3a). Statistical analysis of the ratio of areas with different surface slopes above the edge of local lakes indicates that 91.4% of the SNTS area is characterized by slopes of up to 2.9 degrees, which generally indicates low speeds of the processes of formation of the relief of the plains (Table 4). The development of denudation-erosion phenomena is potentially possible; they are observed in local areas with slopes from 12 to 43.9 degrees, confined to local mountain formations, in total occupies 0.5% of the area of the SNTS. Statistical parameters of the surface slope of the territory are classified into 5 degrees.



(a) (b)

Figure 3. Slope (a), and aspect (b) of the SNTS territory

Slope aspect is considered as the direction of inclination in terms of location to the cardinal direction or compass direction. Measured clockwise in degrees from 0 degrees north to 360 degrees. The value of each cell in the aspect of the data set indicates the direction of the slope (Figure 3b). The aspect of a slope characterizes its orientation in relation to the flow of solar rays, and therefore to the amount of radiation received by the earth's surface (*GIS-Lab online resource*). Due to this, the slope aspect significantly affects the local climate (microclimate) of the site, vegetation, landscape development and relief formation. On the slopes of the relief, northern, northeastern and northwestern aspect predominate and occupy 42% of the study area. Taking into account the heterogeneity of the relief, southern, southeastern and southwestern aspect are widespread, which are located on 33.3% of the territory. These slope aspect are characterized by aridity. The main intensity of erosion is tied to the seasonal processes of snow melting at these aspects. Similarly, the western aspects of the slopes of local mountains fit this description. Western aspects account for more than 10%, and eastern aspects account for more than 13% of the entire territory.

Table 4. Statistical characteristics of the slopes and aspect of the SNTS

Slope, degrees	Area, km²	Area share, %	Point	Aspect	Area, km²	Area share, %	Point
0-1	26396.7	59.2	1	N	6881.9	15.4	1
1-2.9	14357.6	32.2	2	NE, NW	11910.2	26.7	2
2.9-6.4	2865.8	6.4	3	E, W	10901.8	24.4	3
6.4-12	762.,2	1.7	4	SE, SW	9718.5	21.8	4
12-43.9	221.8	0.5	5	S	5109.6	11.5	5
Total	44604.2	100			44604.2	100	

3.2. Drainage network

An drainage network of temporary and permanent watercourses has been created. After visual viewing of the drainage network vector, it was necessary to refine geometrically flat polylines constructed in places of natural large lake basins and sorrows: Lake Toresor, Lake Zhaksytuz, Lake Shagan, Lake Karasor and others, where dominant accumulative geomorphological processes take place. The parameters of the drainage network depend on the given detail or generalisation, if the output scale allows, the drainage network can be maximally branched and takes into account almost all shallow thalweg of temporary watercourses (Figure 4). Given the flat relief of the territory and the interval of absolute heights between 150 and 1100 metres, the catchment network of watercourses is developed up to the 6th order. There are four large river basins located on the territory of the SNTS. These are the Saryuzin rivers from south to north, Aschyozek and Karabulak from the center to the north, and Shagan from the south to the northeast. They are all left tributaries of the Yertis River.

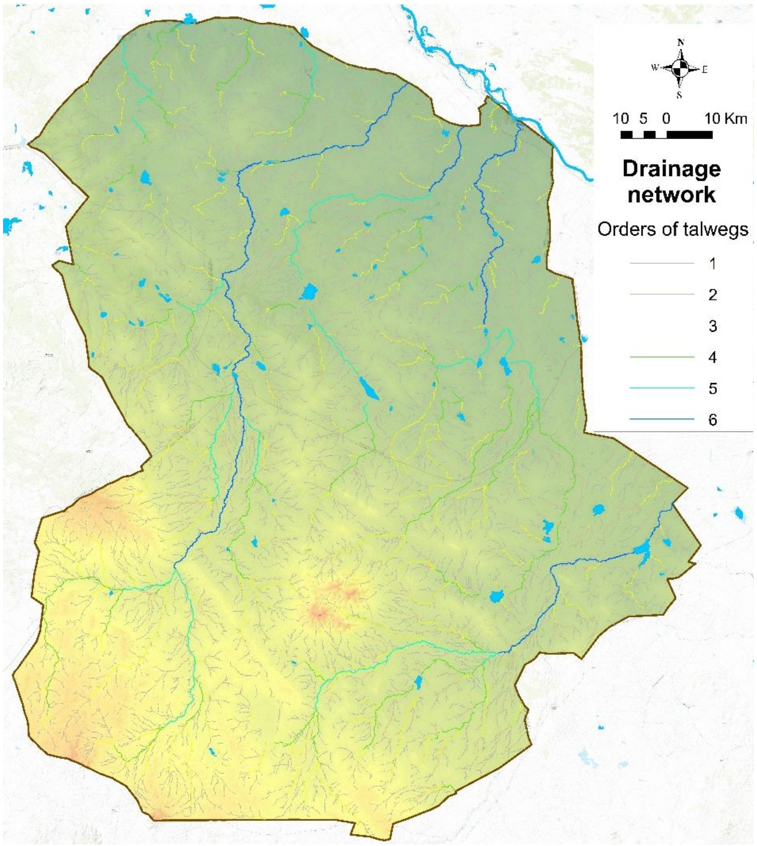


Figure 4. Drainage network of permanent and temporary watercourses, water bodies

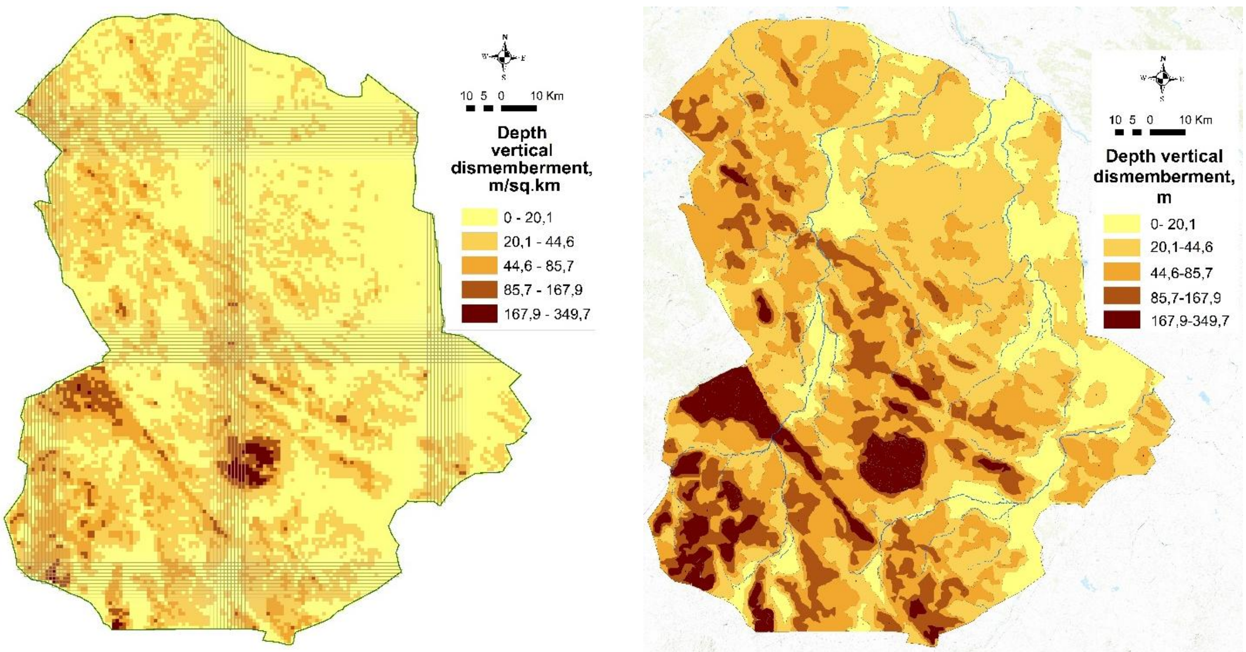
The total length of the talwegs of the rivers in the study area is 13,874 km, with sixth-order watercourses accounting for about 361 km or 2% of the total length of temporary and permanent watercourses (Table 5). The main length of 95% of the talwegs, considering the factors of arid climate and steppe landscapes, falls on temporary watercourses. In summer, they form a dry gully-beam network or inconspicuous depressions. They are formed mainly during floods due to meltwater flows, as well as during precipitation in the warm season. The drainage network is formed by the transport of clastic material by first-order water flows, then by 2nd-order water flows and so the solid runoff is carried into the river Yertis. It should be noted that along with solid runoff, the transfer, distribution, and transportation of technogenic pollutants, including radionuclides, occurs. For example, there is radiation contamination of territories outside the SNTS perimeter, the Shagan River has been found to exceed the norm of radioactive contamination also outside the test site (Aktayev et al., 2021).

Table 5. Statistical characteristics of the drainage network

Order of talwegs	Total length	
	km	%
1	7292	53
2	3394	25
3	1647	12
4	754	5
5	426	3
6	361	2
Total	13874	100

3.3. Vertical dissection

A vector grid (gridfish) has been constructed, elementary areas with an area of 1 km^2, (1×1 km). In total, the SNTS study area covers 18,423 cells. The relative heights of the RANGE field were previously ranked into five classes using the Natural Boundaries approach. The obtained ranking results formed the basis of the map "The amplitude of the vertical division of the SNTS territory in a section of 1 km²" (Figure 5a). The map is of practical interest for working on medium and large scales work, as the cell displays the values of vertical dissection over an area of 1 km. In general, the map has the appearance of a pixel form, which does not convey the natural boundaries of the distribution of morphometric conditions (vertical and horizontal division) and spatial display. In this connection, to solve the existing uncertainty, a map of the spatial distribution of vertical division indicators was constructed, also ranked into 5 classes (Figure 5b). The resulting map of the areal distribution of vertical dissection made it possible to carry out statistical calculations of the areas of distribution of indicators, as well as to effectively display phenomena on the scale of the study.



(a) **(b)**

Figure 5. Amplitude of vertical division: (a) in the context of 1×1 km cells; (b) areal

The general hypsometry of the relief, geology, tectonics, linear erosion processes, landscapes and anthropogenic activities are responsible for the formation of vertical dissected relief. The highest dissection is confined to mountain formations in the central and southern parts of the SNTS.

The values of the depths of vertical dissection are not evenly distributed throughout the territory (Table 6). Low vertical dissection (0-20.1 m/km²) in the relief mainly occupy the northeastern and eastern parts of the SNTS, and are also found sporadically throughout the territory in flat areas. Weak depth of dissection (21-44.6 m) is most widespread, occupying 38.5% of all territories. These areas are located in the northern, eastern and central parts of the SNTS, also in flat areas. Low and weak degrees of vertical dissection occupy 54.5% of the territory of the SNTS, which are plains. The average degree of vertical dissection occupies 27.8% of the entire territory. It is mainly developed on the foothill plains located in the central, northwestern and southern parts of the site. An increased and high degree of vertical dissection occupies slightly more than 15% of the territory. It is developed in the central, northwestern and southern parts of the site and is confined to hills and mountains. The range of relative height marks is from 85 to 350 meters.

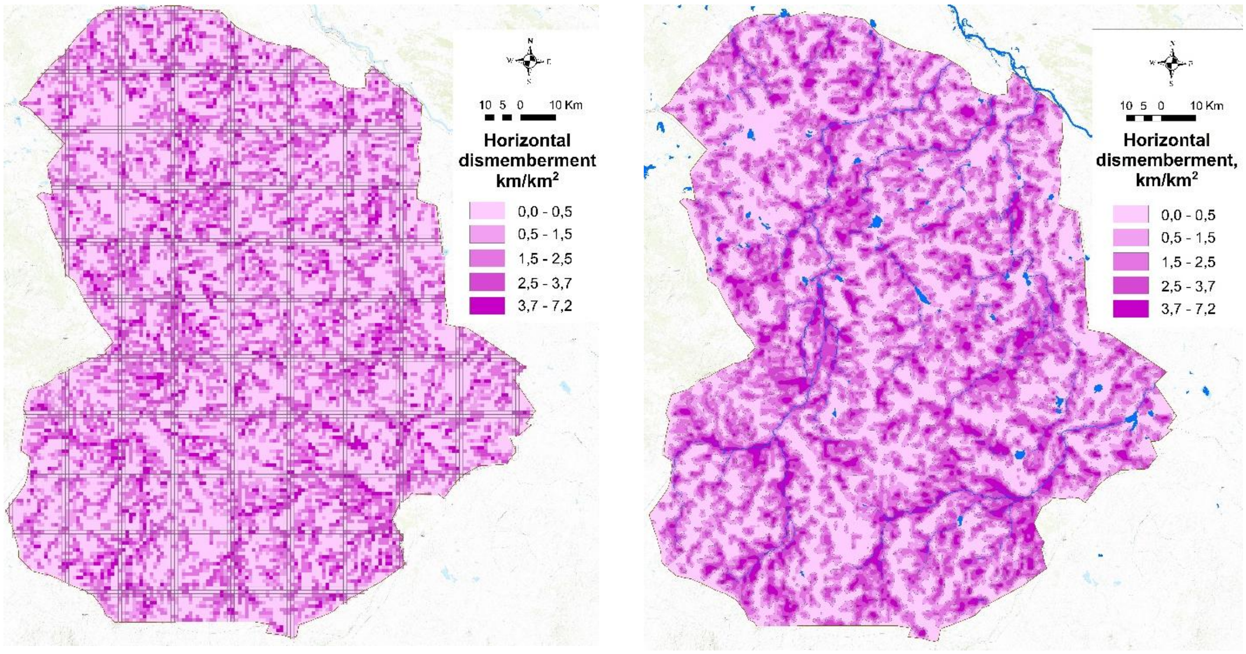
Table 6. Statistical parameters of dissection depth values

Depth of dissection, m/km²	**Area, km²**	**Per cent of total area, %**
0 – 20.1	2 935	16
21 - 44.6	7 064	39
44.6 - 85.7	5 114	29
85.7 - 167.9	2 140	12
167.9 – 349.7	1 109	4

3.4. Horizontal dissection

A horizontal dissection map has been created. As an indicator of horizontal dissection, the length of talwegs of erosional forms from 1st to 7th order (permanent and temporary watercourses) per unit cell area, km/km², was used (Figure 6a). The horizontal division values on the map are ranked into 5 classes, where the general interval ranges from 0.0 to 7.2 km/km². In 905 km², the value of horizontal dissection ranges from 3.7 to 7.2 km/km². A map of horizontal dissection at a cell scale of 1 km² (gridfish grid) is of practical importance for work on a medium and large scale. To obtain natural contours and areas of the spatial distribution of horizontal dissection conditions, an aerial location map was produced (Figure 6b), based on interpolation of cell values.

The distribution of horizontal division values across the territory is uneven. So low levels are confined to watersheds and local lake basins. Obviously, the watersheds are composed of crystalline rocks and are at the stage of insignificant erosional influence, while in lake basins the processes of accumulation prevail over erosion. Medium and high degrees are observed along the river valleys of the SNTS in both flat and mountainous areas. The pattern of distribution of large values of the density of horizontal erosion is characteristic of intermountain depressions and plains.



(a) **(b)**

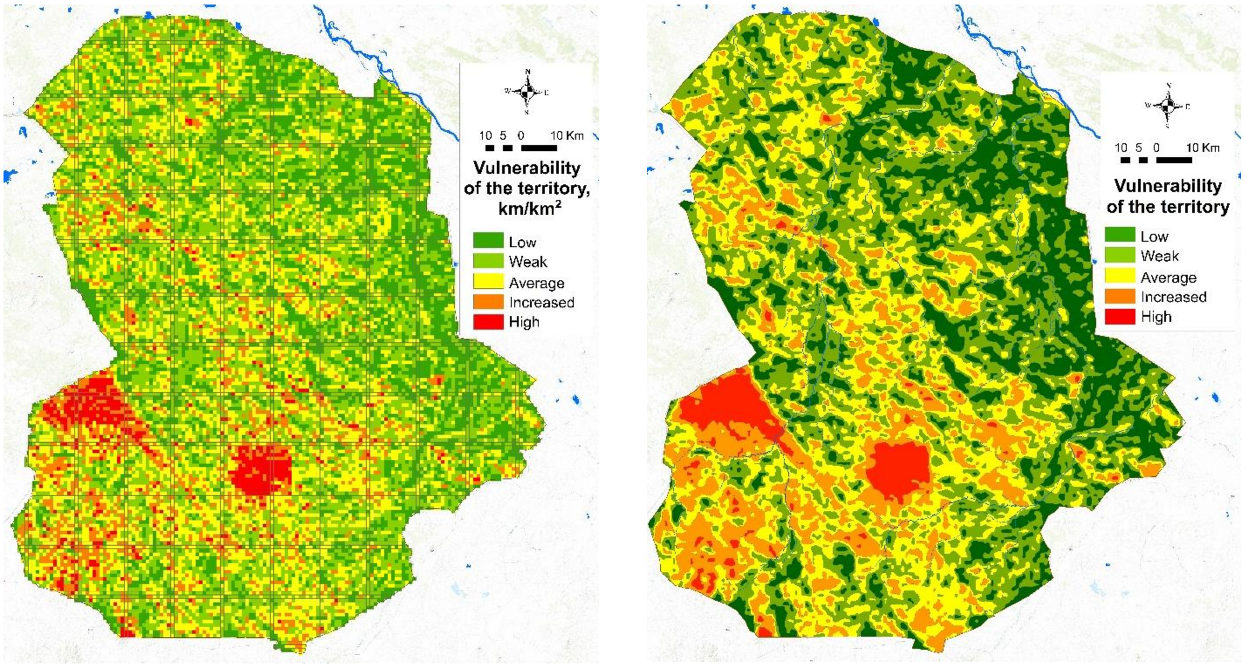
Figure 6. Horizontal dissection of the relief: (a) in the context of 1×1 km cells; (b) areal distribution

A statistical analysis of the horizontal division map was performed, and the areas of distribution of various values were determined (Table 7). The territory of the test site, where the length of the drainage network for 14 square kilometers does not exceed 600 meters, occupies 31% of the total area of the SNTS. In the study, we ranked this area as having a low degree. The plots are distributed evenly throughout the polygon. The weak degree (0.6 – 1.2 km/km²) occupies only 25% and is also distributed evenly throughout the entire SNTS territory. Average values (1.2 – 1.8 km/km²) are located in 23% of the study area. Increased and high rates of horizontal dissection occupy 15% and 6%, respectively. They are distributed throughout the test site, but have local forms. There is an inverse correlation with increasing values of horizontal dissection; the area of distribution decreases.

Table 7. Statistical parameters of horizontal division values

Horizontal dissection, km/km²	Area, км²	Per cent of total area, %
0 – 0.6	5 687	31
0.6 – 1.2	4 632	25
1.2 – 1.8	4 197	23
1.8 – 2.6	2 815	15
2.6 – 6.4	1 033	6

A complex morphometric indicator is the ratio of the sum of indicator values to their number (in terms of cells 1×1 km). The indicator characterizes the general current state of dissection of the relief surface. So, depending on the hypsometric properties, the relief is under the constant influence of denudation or accumulative processes. Therefore, in this study, we consider a complex morphometric indicator as the susceptibility of the relief surface to the development of exogenous processes. Similar to the previous maps, the assessment of the susceptibility of the relief is constructed in terms of cells (1 × 1 km) and areal distribution on a five-point scale (Figure 7).



(a) (b)

Figure 7. Susceptibility of the relief surface to the development factors of relief formation: (a) in the context of 1×1 km cells; (b) areal distribution

The result of geospatial analysis of the obtained maps are the numerical values of the territory's susceptibility to the factors of the territory's relief formation development and the area of distribution (Table 8). Low and weak susceptibility of the relief surface covers 53% of the SNTS territory, mainly the flat areas of the northeastern and eastern parts of the test site. In these areas, low and weak values of vertical and horizontal dissection, weak slopes and slopes with northern aspects are observed. The average susceptibility of the relief surface occupies 28% of the test site, mainly hilly and foothill plains. The sites are distributed in the northern, central and southern parts. They are associated with average values of vertical and horizontal dissection, slopes up to 45% and eastern and western aspects of slopes. Increased and high susceptibility of the relief surface occupies 19% of the landfill area. These are positive forms of relief, where mountains have a high degree of susceptibility and hills have an increased degree of susceptibility. These territories are characterized by an increased and high degree of horizontal and vertical dissection, a slope steepness of more than 45%, and a predominance of southern aspects.

Table 8. Susceptibility of the relief surface to the development factors of relief formation in the territory of the SNTS

Relief surface susceptibility	**Area, km²**	**Per cent of total area, %**
Low	3 649	20
Weak	6 125	33
Average	5 082	28
Increased	2 669	15
High	641	4
Total	18166	100

4. Discussion

The results of the study confirm the basic basis of the relief as a natural environment, where other processes occur due to natural and anthropogenic factors. The presence of erosion network up to 7th order, as well as a number of antecedent valleys confirm the results of studies of solids transport by temporary flows, obtained by (Moss & Walker, 1978). Application of complex morphometric index for relief assessment allows to take into account the main characteristics of the terrain: slope, exposure, vertical and horizontal dissection. The final map of the relief susceptibility to modern exogenous processes provides a general classification of the entire territory by assessment values, which is convenient for perception and study of the relief of the territory. Presentation of the results of morphometric indicators assessment in the grid format has more applied character. And the interpolated version of maps, gives a general concept of distribution of morphometric conditions of the area.

Relief formation processes in steppe landscapes are not highly dynamic, with geological structure and vegetation acting as one of the stabilisation factors. However, the sharply continental climate, spring floods and precipitation figuratively set in motion the transport of solid particles towards local and regional erosion bases. Aspects influencing particle transport include terrain morphometry. Parameters of relief morphometry have a direct correlation with the intensity of exogenous processes.

Thus, terrain slopes up to 2.9 degrees are spread over 91.4% of the SNTS area, which indicates a weak impact of gravitational processes, but a sufficient level for the development of linear erosion and plane washout on the plains.

Relief exposure is responsible for soil moisture content and, consequently, for the level of projective cover of vegetation. Thus 33.3% of the study area is located on southern, south-eastern and south-western exposures. Accordingly, these territories are more susceptible to the transport of solid particles than the northern exposures. The base of erosion of the territory is the Yertis River. Therefore, the development of the network of temporary and permanent watercourses is directed to the north. This is also the direction of particulate matter transport in general.

Vertical dissection of relief is developed practically over the whole territory of the SNTS. However, the contribution of erosion processes to the development of vertical dissection in the mountainous areas of the study area is more significant than in the plains. This is explained by different morphometric conditions of the area (slope, absolute heights, landforms). For example, the vertical dissection in the Murzhik Mountains under the influence of the temporary Saryuzin watercourse, which formed the antecedent valley, is more than 110 meters. On the plains, the erosive activity of permanent and temporary watercourses formed channel valleys with relative heights of 10-17 m in the hilly areas and up to 5 meters in the lower reaches on the plains.

Horizontal dissection is in the range from 0.5 to 7.2 km of linear erosion per 1 km2. High density of linear erosion per unit area is confined to river valleys and erosion network of temporary watercourses. The density decreases only on watersheds, especially the outlines of crystalline rock formations are clearly distinguished. Here it should be noted that the removal of solid particles occurs, respectively, from areas with high density of horizontal dissection.

According to the results of assessment of the territory's susceptibility to the development of exogenous processes, 53% of the territory of the SNTS have low and weak degrees. These are mainly flat areas of the north-eastern and eastern part of the polygon. These results indicate that half of the territory of the former SNTS with respect to relief morphometry is potentially suitable for the development of adaptive landscapes.

A limitation of the study was not to use the weighted scoring method in the scoring criteria. Since it was the first time that morphometric conditions were assessed on the basis of DEM analysis, and there are no alternative results obtained by this method, and wide access to the territory of the polygon is limited, we decided to first obtain primary data and assess them without weights. However, the criteria of relief assessment, developed solely on the quantitative and qualitative parameters of morphometry of exactly the territory of the SNTS. Therefore, the results obtained are as close as possible to the level of reliability.

Further study of the SNTS territory should be carried out with the involvement of interdisciplinary specialists and empirical research methods. Conduct comprehensive field studies, soil and water sampling for laboratory analyses, linking the sampling sites to the coordinate system, and determining traces of radioactive elements. Link laboratory analysis results with geospatial tools to interpolate similar results and map actual materials. These studies will make it possible to determine the degree of correlation of morphometric conditions with the modern spatial distribution of radioactive contamination areas.

This paper provides a basic framework for understanding the processes of particulate matter transport over the relief surface and identifying areas that meet the requirements of adaptive landscapes. The relief occupies a leading role in natural environments, where the processes of transport and distribution of pollutants, among others, take place. Taking into account this fact and the obtained results are of scientific interest for specialists of science and education in the field of geoecology, radioecology, and agriculture.

5. Conclusion

The activity of permanent and temporary watercourses is the driving force in relief formation, as evidenced by the presence of antecedent valleys within the SNTS. This provision is the basis to assume the transfer of surface and possibly underground radioactive pollutants by permanent and temporary watercourses. With regard to the base of erosion of the Yertis River, it is possible to designate potential areas of spread of secondary radioactive contamination. Thus, the study of the morphometric conditions of the SNTS territory allowed to determine the numerical characteristics of vertical and horizontal dissection and to assess the susceptibility of the territory to the factors of relief formation development. The morphometric characteristics of the relief are an important aspect in the study of geoecology and landscape development. At a glance, the researcher understands the direction of total solid runoff, solar radiation, slope processes and erosion. The fact of anthropogenic influence on the relief and radioactive contamination is of particular relevance. The scale of the study (1×1 km) makes it possible to rationally and effectively zone and involve the landfill territory in agricultural use, taking into account the adaptive landscape farming system. The morphometric conditions of the relief, being the basic basis, allow us to understand the ongoing processes, their cause-and-effect relationships and draw certain, scientifically based conclusions.

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7. Author Contributions

Conceptualization, A.A. and A.V.; methodology, O.T., A.V., M.K.; software, N.Zh., T.I.; validation, A.A., O.T., A.V.; formal analysis, O.T., N.Zh.; investigation, A.A. and M.K.; resources, N.Zh.; data curation, Y.Zh., N.Zh.; writing original draft preparation, A.V.; writing review and editing, A.A., O.T.; visualization, A.V. and M.K.; supervision, A.V.; project administration, A.A.; funding acquisition, A.A. All authors have read and agreed to the published version of the manuscript.

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Семей ядролық сынақ полигонының қазіргі рельефінің морфометриялық жағдайын бағалау

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Аңдатпа: Соңғы жылдары бұрынғы Семей ядролық сынақ полигоны (СЯСП) жерлерінің бір бөлігін жергілікті ауыл шаруашылығы өндірушілерінің шаруашылық айналымына тарту мәселесі өткір тұр. Бұған полигон аумағын кешенді экологиялық зерттеулер ықпал етеді. Алайда, полигон рельефінің сандық сипаттамаларын ала отырып, морфометриялық жағдайларды зерттеу іс жүзінде жоқ. Бұл зерттеу рельефтің морфометриялық жағдайларын: бірқатар заманауи экзогеодинамикалық процестердің дамуындағы морфометриялық анықталған факторларды бағалау үшін көлбеу, аспект, тығыздық және бөлшектеу тереңдігін зерттеуге бағытталған. Морфометриялық жағдайларды зерттеу dem деректерін өңдеу және талдау негізінде жүргізілді, олар ұпай жинаудың кіріс критерийлеріне айналды. Карталар жасалып, олардың статистикалық параметрлері: көлбеу, көрініс, тік және көлденең бөлшектену және рельеф бетінің СЯСП аумағындағы рельефтің пайда болу факторларына сезімталдығы бөлінді. Тақырыптық ақпарат екі типтегі карталарда: ұяшықтармен (1×1 км) ұсынылған қарапайым учаскелер бөлігінде және осы қарапайым учаскелердің интерполяциясы түрінде ұсынылған. Нәтижелер зерттелетін аумақта адаптивті ландшафттық егіншілік жүйесінің принциптерін әзірлеу үшін практикалық маңызды.

Түйін сөздер: ядролық полигон; морфометриялық жағдайлар; рельеф; беткей; ЖСМ; адаптивті-ландшафттық егіншілік жүйесі.

Оценка морфометрических условий современного рельефа Семипалатинского испытательного ядерного полигона

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Аннотация: В последние годы остро встал вопрос вовлечения части земель бывшего Семипалатинского испытательного ядерного полигона (СИЯП) в хозяйственный оборот местных сельхозпроизводителей. Этому способствуют комплексные экологические исследования территории полигона. Однако исследования морфометрических условий с получением численных характеристик рельефа полигона практически отсутствуют. Данное исследование направлено на изучение морфометрических условий рельефа: уклона, аспекта, плотности и глубины расчленения для оценки морфометрически определяемых факторов в развитии ряда современных экзогеодинамических процессов. Изучение морфометрических условий проводилось на основе обработки и анализа данных ЦМР, которые стали входными критериями для подсчета очков. Были созданы карты и выделены их статистические параметры: уклон, вид, вертикальная и горизонтальная расчлененность и восприимчивость поверхности рельефа к факторам развития рельефообразования на территории СИЯП. Тематическая информация представлена на картах двух типов: в разрезе элементарных участков, представленных ячейками (1×1 км), и в виде интерполяции этих элементарных участков. Результаты имеют практическое значение для разработки принципов адаптивной ландшафтной системы земледелия на исследуемой территории.

Ключевые слова: ядерный полигон; морфометрические условия; рельеф; склон; ЦМР; адаптивно-ландшафтная система земледелия.