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ASSESSMENT OF WATER BODIES COASTAL EROSION AND SURFACE SOLIFLUCTION RISKS BASED ON RCP CLIMATE CHANGE SCENARIOS (2.6, 4.5, 8.5)

1. Risk assessment of coastal erosion of water bodies in the context of RCP climate change scenarios

1.1. Features of the Lithuanian hydrographic network

The waters belonging to the territory of Lithuania are divided into internal and external. Inland waters include rivers, lakes, artificial water bodies, Curonian lagoon. According to the area occupied, lakes predominate, making up almost half of the area of all water bodies.

Table 1. Diversity of Inland Waters of Lithuania

Type of water body	Number	Area (km^2)	Share of the total area of Lithuania (%)
Lakes (> than 0.5 ha)	6000	913,6	1,4
Rivers	22 200	332	0,51
Curonian Lagoon	1	413	0,63
Artificial water bodies (dams, ponds, quarries)	4132	244	0,37
Total	42 465	1902,6	2,91

In the territory of Lithuania, about 6000 lakes of natural origin larger than 0.1 ha are counted. 2850 of them are larger than 0.5 ha. The total area of the lakes reaches almost 914 km^2. Most of them are located in troughs of glacial or fluvial origin, the largest being formed by glacier activity.

The second most extensive by area hydrographic element is rivers. The territory of Lithuania is distinguished by the abundance of rivers and streams. It is estimated that > 22,000 rivers longer than 250 m flow in Lithuania, of which 4418 are longer than 3 km. The total length of the latter is 37,600 km. In number and length, small streams (between 3 and 10 km in length) predominate, with a total of 3,600 counted, accounting for 50 % of the total length of the rivers. There are only 17 longest rivers, >100 km long, with a length of only 8.4 % of the total length of all rivers. More than 80% of Lithuanian riverbeds are artificially regulated and straightened by man (Kažys, 2013).

The third most abundant element of the hydrographic network is artificial water bodies. There are 1159 ponds larger than 0.5 ha in Lithuania, the number of smaller ones is over 3,000, their number and area are constantly growing (Kažys, 2013).

The last element of the hydrographic network and the largest inland water body in Lithuania is the Curonian Lagoon. It is the largest lagoon of the Baltic Sea, its area is 1584 km^2, the northern part (381.6 km^2) belongs to Lithuania, the southern part is owned by Russian Federation's Kaliningrad oblast (state – aggressor) (Žaromskis, 2018).

In addition to inland water bodies, Lithuania also owns part of the Baltic Sea territorial waters and its coastline. The length of the Lithuanian sea coastline is 90.66 km (the shortest of all the Baltic states). The length of the coastline of the Curonian Spit is 51.03 km, between the northern pier of Klaipeda port and the border with Latvia is 38.49 km, by connecting the shores of the Klaipėda Strait in a straight line on its southern and northern sides – another 1.14 kilometres are added (Žaromskis, 2018).

1.2. Types of erosion factors

In a general sense, erosion is understood as the activity of natural factors that gradually break down the Earth's surface – water, wind and ice. The narrower meaning of the phenomenon of erosion is limited to the destructive activity of water. Water erosion is one of the most important exogenous (external) factors that shape and change the relief of the Earth today. The main groups of factors describing it and related processes are distinguished (Table 2).

Table 2. Types, effects and forms of water erosion (according to: Česnulevičius, 1998)

Type of factors	**Type of destruction (denudation) process**			
	The process affecting the rocks	**Surface impact**	**Mode of transportation**	**Created forms**
Erosion of surface running water	Washing, planar erosion, linear erosion	Resurfacing, carrying away	Rolling	Slopes, pediments, valleys, ravines
Erosion of riverbed flows	Linear erosion	Displacement, pushing, whirlpool erosion	Rolling, jumping, tearing out	Valleys
Groundwater activities	Leaching, dissolution	Shaving, pushing, whirlpool erosion	Dissolution	Corridors, galleries, wells, shafts, caves, tunnels
Waves	Scraping	Scraping, whirlpool erosion	Rolling, dissolution, jumping	Cliffs (scarps), platforms, niches

The complex of current geographical and paleogeographic conditions in a set of types of water erosion factors in the Lithuanian landscape allows to distinguish the erosion of riverbed flows or running water erosion. The linear erosion associated with it forms one of the brightest, most volatile and largest elements of the present landscape – river valleys. The other important factors include waving, groundwater activity, surface runoff erosion. However, the traces left by them in today's landscape for a number of reasons are not so bright or often found. The effects of the factors mentioned in more detail are described in Table 3.

Table 3. The expression of water erosion in the landscape

Types of erosion factors	**Impact on the landscape**
Groundwater activities	In rare cases, traces of groundwater activity are found in the karst region of Northern Lithuania, where karst pits and small karst lakes are formed.
Swell (waving)	Associated with the process of wave formation in the bodies of standing water: lakes, seas, oceans. Since most of the lakes of Lithuania (except for the oxbow, lagoon, karst and man-made – ponds) appeared, formed after the end of the last ice age (the glacier left the territory of Lithuania about 13,000 years ago), the swell and its consequences in them are suspended by a belt of the shelf (an underwater terrace formed as a result of coastal abrasions, swells and water currents) formed over thousands of years, often quite wide. As a result, the scale of erosion on the shores of standing water bodies is relatively small and difficult to measure, and the coasts are little changeable.
Erosion of temporary surface water flows	Erosion of temporary surface water flows is manifested on condescending surfaces not covered with grassy vegetation, most often, where active human economic activity is carried out (in Lithuanian conditions). In some cases, ditches arising in this way are also found in steep-sided river valleys, on their banks. The risk of the appearance of these forms is also included in further modelling of coastal erosion.
Erosion of riverbed flows (fluvial erosion)	In constant riverbeds, deepening and lateral erosion occurs. The current scraps, washes, melts and otherwise mechanically erodes the rocks of the river bed, and carries the destruction products, rolling the larger ones down the stream. In this way, both, the riverbed and its valley also deepen. As a result of deepening erosion, steep-sided valleys, sieves, ravines, waterfalls are formed. Lateral erosion can be caused by various

	obstructions of flow and floodings. Lateral erosion is affected by the force of Coriolis. With the development of lateral erosion, rivers begin to meander, creating meanders, oxbow lakes and wide valleys.

The process of riverbed (fluvial) erosion. Erosion of running water is divided into linear and planar. Linear erosion manifests itself in temporary and constant water flows. Temporary water flows form wash-outs, ditches, ravines. Erosion of an unconcentrated stream of water that erodes the entire surface on which it flows (slopes), is called planar, or superficial; this erosion is one the soil erosion forms. It depends on the intensity of the rain, its duration, the steepness and length of the slopes, the vegetation cover.

Both lateral and deepening (form of linear erosion) erosion of rivers and scale of its expression are influenced by a wide range of natural factors: the characteristics of the flow and rocks along which water flows, the geometry of the river-bed, local climatic conditions, subsoil moisture, vegetation cover, as well as anthropogenic activity. These factors, in turn, can be decomposed into a set of even smaller ones (Table 4).

Table 4. Factors and indicators of river erosion

Factors influencing river erosion	**River erosion indicators**
Features of flow	Current speed, discharge
Features of rocks on which water flows	Lithology, granulometry
Riverbed geometry	Width, length, depth, angle of slope of the riverbed, steepness and length of bank slopes, bending of the riverbed
Local climatic features	Amount, intensity, frequency and duration of precipitation, negative temperatures, duration and frequency of the freezing period
Properties of subsoil moisture	Infiltration, soil moisture content, groundwater level and capillary phenomena
Vegetation cover	Type of vegetation cover, density and depth of root systems
Fauna	Wildlife-forming floods and obstacles, the destruction of slopes and shores
Human (anthropogenic) activity	Urbanisation, agriculture, shipping, shoreline management and anti-erosion measures

1.3. Simulation of the risks of riverbank and coastal erosion

Quantitative assessment of bank & coast erosion factors and process dynamics is a complex task that requires detailed empirical hydrological, geomorphological, climatic, even biogeographic studies and a dense network of measuring stations. It is even more difficult to assess bank & coast erosion in a spatial sense, by carrying out large-scale studies in extensive areas with a variety of natural conditions. The complexity of the task is determined by the lack of high-precision spatial (not point) data and tools for spatial modelling, the abundance of indicators/variables of the erosion phenomenon.

To solve the problem in this case, surface relief data, various GIS (Geographical Information System) databases and GIS modelling tools obtained with the help of modern technologies were employed. The essential indicators that potentially best convey the risk of occurrence and manifestation of the phenomenon were also selected, and an algorithm for assessing the risks of bank & coast erosion at the local level was developed. The graphic scheme of the algorithm, the input data used in it, the intermediate and final results obtained, as well as the actions and sequences of data manipulation are presented below.

1.3.1. Indicators of bank and coast erosion

The dynamics of erosion processes on the shores and banks of water bodies is determined by the factors (Tables 2, 3, 4) affecting the complex of the coastal system and the intensity of their expression in space and time. In this case, to assess the risk of erosion and carry out statistical analysis of the links, the following hydrographic (geometrical) and surface terrain morphometric indicators of water bodies – rivers, lakes, ponds and dams, the Curonian Lagoon and the Baltic Sea coast – were used:

1. Meandering (curvature) of the stream beds;
2. Riverbed slope (angle of inclination of the water surface);
3. Angle of inclination of coastal slopes.

An assessment of the risks of coastal erosion of water bodies was carried out within the boundaries of the coastal protection strip. The width of the coastal protection strip is assigned to individual water bodies on the basis of the order of the Minister of Environment of the Republic of Lithuania (Table 5) (Dėl Paviršinių vandens telkinių apsaugos zonų..., 2023).

Table 5. The width of the coastal protection strips of water bodies used for the coastal erosion risk assessment

Category of the water body	**Width of the coastal protection strip**
The east coast of the Curonian Lagoon (from the southern boundary of Klaipeda State Seaport to the state border of the Republic of Lithuania and the Russian Federation);	100 m
Near rivers of 100 km or more in length, near lakes and ponds with an area of 200 ha and more;	30 m (in river sections with a river width of 5 m and less, the coastal protection strip is reduced to 10 m)
Near rivers of more than 10 km but less than 100 km in length, near lakes and ponds with an area of 10 to 200 ha, artificial impassable surface water bodies with an area of 2 ha or more, and near all channels;	10 m
Rivers, lakes and ponds with an area of up to 10 ha of 10 km or less, artificial impassable surface water bodies with an area of up to 2 ha.	5 m

The study was guided by the following premises:

1. The most changeable element of the hydrographic network in Lithuanian territory is rivers, so their banks are located in the zone of increased risk of erosion. In the river environment, deepening and lateral erosion occurs. Lateral erosion manifests itself in strongly winding – meandering sections of rivers, so for its assessment an analysis the

curvature of the riverbed needs to be carried out. Deepening erosion can occur for several reasons: changing the orographic properties of surface relief and large mesoforms, in the upper reaches of rivers. In areas of this kind of erosion, river rapids are found, steep eroded shores, outcrops, cliffs are formed, and the riverbed slope increases sharply. If the river winds, the banks are most often eroded on the convex outer sides of the bends. In sections of rivers where the riverbed slope is small/unremarkable, and the curvature is of low-grade risk of developing coastal erosion will be low. If it is possible to show by statistic analysis that the slope of riverbanks is related to the gradient and/or meandering of the riverbed, only the coastal slope indicator could be used for erosion risk calculations.

2. The change and degradation of the sea coast is determined by coastal currents, shoreline configuration, coastal morphometry and morphology (for example, the width of shallows and beach areas, the type of sediments), wave energy, storms, etc. factors. The areas most at risk of erosion will be found in the steepest sections of the seashore (for example, the Dutchman’s Hat Cliff and the Būtingė section).
3. Erosion of lake shores can intensify due to a sharp fluctuation in water levels and, as a result, the reorganization of the littoral shelf zone. The latter also determines to the destruction of the shores. Lithuanian lakes were formed during the last ice age (except for lakes of karst and oxbow type, but their number and area are relatively small) as the glaciers advanced and subsequently retreated, thermokarst processes taking place. The maximum of the last glaciation is considered 20-22 thousand years ago, while from the territory of Lithuania, the ice sheet retreated about 12-14 thousand years ago. During this period the water level in the lakes stabilized with the formation of a stable littoral shelf belt. For these reasons, erosion of the lakes shores is unlikely.

According to the projections of climate change, a significant decrease in the amount of annual rainfall in Lithuania is not expected. For this reason, there should be no particularly significant fluctuations in the water level of lakes.

1.3.2. Projection of changes in coastal erosion factors according to RCP scenarios

Table 6. Projections of coastal erosion risk indicators from RCP scenarios 2.6, 4.5 and 8.5 used in the study

Risk factors for coastal erosion potentially volatile due to climate change processes	**RCP 2.6**	**RCP 4.5**	**RCP 8.5**	**Sources**
Rise in the water level of the Baltic Sea	0.1 m	0.2 m	0.3 m	According to the Data of the European Environment Agency, the water level in the Baltic Sea of 2081-2100 will rise 0 to 60 cm (depending on the climate change scenario). For the projection of 2060-2070, the maximum values of the presented ranges are divided by two. In the simulation, the water level of the Baltic Sea was raised by the above-mentioned values, the flooded area was assessed and the new shoreline and its parameters were modeled. https://www.eea.europa.eu/data-and-maps/Figs./projected-change-in-relative-sea-level/projected-change-in-relative-sea-level

Rise/fall in the water level of lakes	In all scenarios, data from the current situation are used to assess coastal erosion risks	There are no quantitative data on the dynamics of changes in the water level of lakes in Europe and Lithuania in the future. The projected changes in the amount of annual and summer rainfall (%) in the period 2071-2100, compared to the base period of 1971-2000, according to scenario RCP 8.5, indicate that in the future a slight, but positive trend of precipitation change will be observed in the territory of Lithuania (precipitation will increase). For this reason, it is assumed that the water level of lakes and ponds will not change or change slightly. This will not create the prerequisites for the erosion of the shores and the renewal of the littoral shelf zone. Thus, for all three future scenarios, actual data on the current water level of lakes and ponds were used/retained to assess the risks of coastal erosion. https://www.eea.europa.eu/data-and-maps/Figs./projected-changes-in-annual-and-6 */Precipitation model data are based on the average of assembly of several RCM models by the EURO-CORDEX initiative.*
Increase in river runoff (the distribution of the amount of precipitation in the year, the constancy of snow cover, the frequency of spring floods are also associated with this, therefore, the precipitation indicator is not allocated separately)	In all scenarios, data from the current situation are used to assess coastal erosion risks	The resurgence and intensification of erosion of riverbanks is theoretically possible in several cases: with the trend of a sharp increase in river runoff, with the increase in spring floods frequency and magnitude, by lowering of the erosion base (in case the water level of the Baltic Sea subsides). All named cases in RCP 2.6, 4.5, and 8.5 scenarios are unlikely. This is also proven by the recent years studies of the modelling of the parameters (runoff, the amount of sediments, dissolved nitrogen and phosphorus) of the Nemunas basin. https://www.sciencedirect.com/science/article/pii/S0022169421004698 https://www.mdpi.com/2073-4441/11/4/676 The study of Cherkasova, Umgiesser and Ertuk (2021), conducted on the rivers of the Nemunas basin, states that in the future the most likely result will be a warmer climate at all times of the year. Precipitation patterns differ in different GCMs (general circulation models), but neither one nor the other shows a significant annual increase or decrease, although the number of days of water stress is predicted to increase according to all scenarios, and the largest of them will increase almost 5 times. This means that less precipitation is possible, higher temperatures will lead to more droughty conditions. The average annual forecasts of the Nemunas discharge do not show a clear trend of changes, the Mann-Kendall test (Mann, 1945, Kendall, 1975) did not identify any trends, which indicates that the indicators of the annual flow of the river are quite stable. The variability of the GCM (general circulation model) is higher in rcp4.5 conditions. While there are no clear predicted average annual discharge trends, volatility between GCM becomes lower by the end of the century, meaning that the GCM output indicators under RCP4.5 and RCP8.5 overlap in the long run. The hydrological shift of the Nemunas runoff toelderships a higher winter flow rate and a lower late summer-early autumn flow values is likely to be observed in the future, provided that the global development and emission trends correspond to the stabilization scenario (RCP4.5)t, and the downeldership trend in runoff continues with the long-term forecast period (referring to the decrease in runoff during June-October). On the basis of the information provided, it can be seen that the results of the modelling of river runoff do not indicate an upeldership trend in runoff. The validity of the results of the studies carried out is beyond doubt, and therefore, within the framework of the work being carried out, we continue to assume that the scale of the river erosion process will not increase in the future since: the trend of an increase in total runoff is

		unlikely; the number of days with snow cover will decrease, and hence the frequency of spring floods and their magnitude; as the average annual temperature rises, the vegetation season is likely to increase, so the riverbanks will be secured with grassy vegetation for a longer period of time, which will additionally contribute to arresting possible erosion.

1.3.3. Input data

The methodology for assessing the risks of coastal erosion includes a sequence of mathematical and GIS manipulations and actions that require the following initial input data:

1. Vector data layers of cadastral areas and elderships;
2. The linear and polygon vector data layers of water bodies filtered out of the cadastral spatial data set of the GDB_10 georeferenced base.
3. The digital surface relief data model layer (DTM).

The characteristics of the data are presented in more detail in Table 7.

Table 7. Features of the data used in the modelling of coastal erosion

Data source	Layer name	Data type	Properties and attributes used information
GRPK georeferenced base cadastral spatial data set (GDB_10)	HIDRO_L	Vector linear data	This layer stores information about the axial lines of rivers, streams, canals and land reclamation ditches. GRAKTAS: Watercourse code according to the river classification of the Republic of Lithuania. Column TIPAS (TYPE): Type of watercourse (entering a numeric value): - 0 – unknown, - 1 – river (natural water flow, a stream flowing on the surface of the land in its own carved riverbed) - 2 – canal (artificial surface water body with a constant flow of water, installed in the soil by excavating / installing an open riverbed, the beginning and end of which connects with another surface body of water (river, lake, Curonian Lagoon or pond), intended for irrigation, hydropower, water supply and other purposes, for use in shipping, etc. Rivers with regulated beds are not considered canals, - 3 – Ditch (hydrotechnical structure, installed by excavating an open riverbed in the soil and intended for draining / draining excess water. Rivers with regulated beds are not considered ditches, - 4 – the discarded reclamation ditch, the canal (the discarded reclamation structure, after the removal of the reclamation land from the accounting of agricultural reclamation land), - -9999 – when none of the above meanings are appropriate. Column PLOTIS (*WIDTH*): The width of the hydrographic object, m.
GRPK Georeferenced Base Cadastral Spatial Data Set (GDB_10)	PLOTAI	Vector polygon data	The layer stores information about the areas covered by land use and water bodies. Column: GKODAS Among other land use codes, for the selection of water bodies were used: Hd1: Rivers – an area covered by rivers wider than 12 meters, that may be overgrown with aquatic vegetation (for example, bulrush, reeds, etc.);

			Hd2: Streams, canals, drainage ditches – an area covered by streams, canals, drainage ditches wider than 12 m, that may be overgrown with aquatic vegetation (for example, melds, reeds, etc.); Hd3: Lakes - an area of visible water surface of a natural body of water in a slowly changing bed that has no direct connection with the sea, which can be overgrown with aquatic vegetation (for example, bulrush, reeds, etc.); Hd4: Ponds and other non-flowing water bodies (hydrotechnical structures) – the area of visible surface water of an artificial closed water body installed in the natural ground, replenished by surface runoff, which may be overgrown with aquatic vegetation (for example, bulrush, reeds, etc.); Hd5: Baltic Sea, Curonian Lagoon – the territory covered by the Baltic Sea and the Curonian Lagoon, which may be overgrown with aquatic vegetation (for example, bulrush, reeds, etc.); Hd9: Dams - an area of the visible surface of an artificial flowing body of water, which is installed by blocking the flow of water in a stream bed, which may be overgrown with aquatic vegetation (for example, bulrush, reeds, etc.);
Vector data layers of the administrative division of Lithuania (Data on the boundaries of cadastral areas and elderships)	SENIUNIJOS, KADASTRINES_ VIETOVES	Vector polygon data	The layer stores information about the boundaries of Lithuanian elderships; The layer stores information about the boundaries of Lithuanian cadastral areas;
Lithuanian Surface Relief Digital (DTM) Relief Model		Raster data layers	The layer stores the altitude data of the Lithuanian surface, the size of the cell (spatial resolution) – 2m; The average square vertical error of lidar points is 30 cm; the data are based on LIDAR (SEŽP) data.
RCP climate change scenario data			Projections of the rise of the water level of the Baltic Sea according to RCP scenarios 2.6, 4.5, 8.5.

Fig. 1. Vector data of Lithuanian cadastral areas and elderships and their attribute information

Fig. 2. Data from the GRPK Georeferenced Base Cadastral Spatial Data Set (GDB_10) HIDRO_L Vector Linear Data Layer

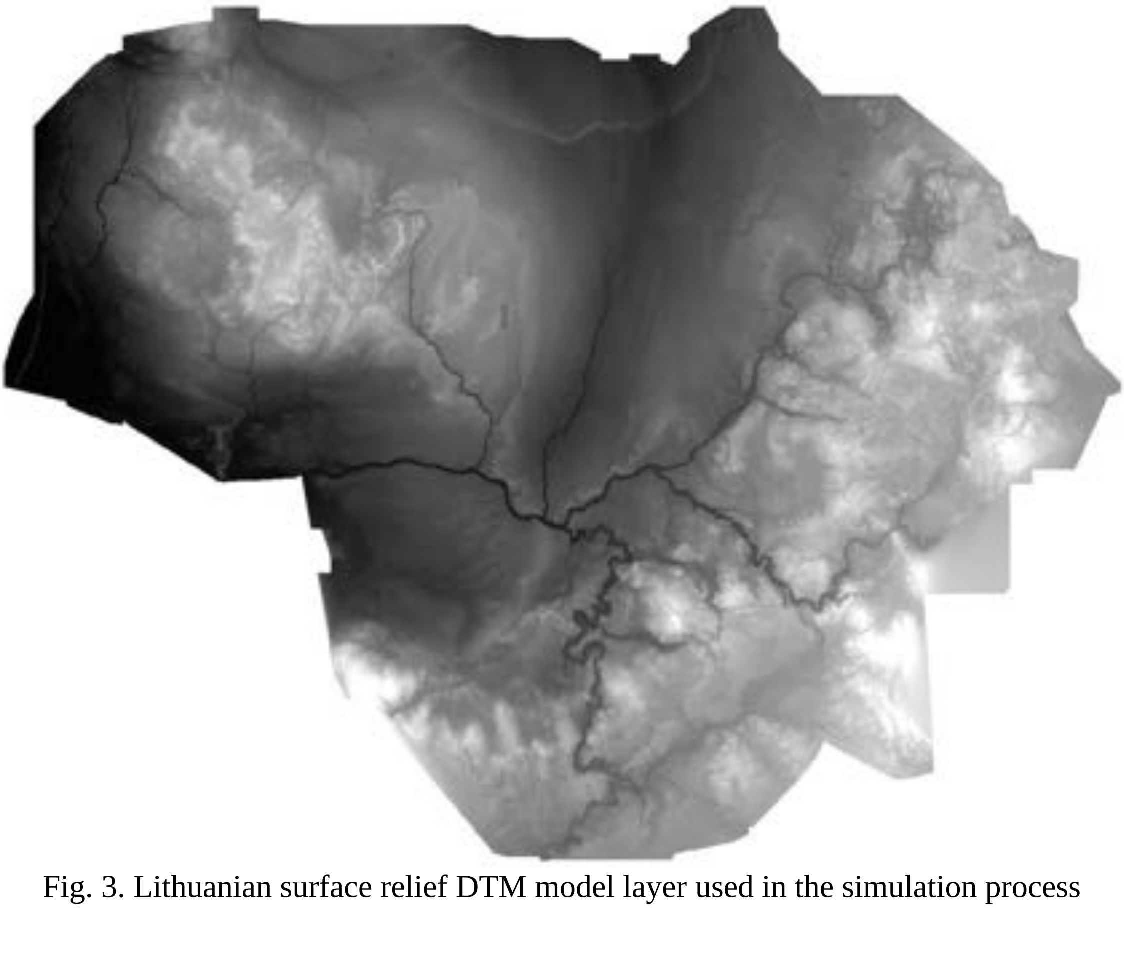


Fig. 3. Lithuanian surface relief DTM model layer used in the simulation process

1.3.4. Stages of the coastal erosion risk assessment

1. *The stage of preparation of the initial data*. The data of the cadastral spatial data set (GDB_10) of the georeferenced base of GRPK was used for the selection of water bodies in the territory of Lithuania. The boundaries of lakes, ponds, dams, and the Curonian Lagoon were selected from the vector data layer (PLOTAI) of polygons. Riverbeds were selected from the linear (HIDRO_L) data layer, canals eliminated from further analysis, as well as artificial and straightened water streams (it was assumed that erosion in the straightened, used for reclamation and artificially man-made riverbeds of canals and reclamation ditches would not take place or be controlled). Since the resulting river layer from the GDB_10 database is presented by sections of rivers, they are combined using GIS into lines of continuous riverbeds, creating a layer of rivers and their tributaries (a hydrographic network according to the ranks of the rivers). To create the layer, hydrology tools from GIS spatial analysis and the following algorithm were used.

   DTM → Fill → Flow direction → Flow Accumulation → Map Algebra → Stream order → Stream to Feature

   On the basis of the resulting layer, using (assigning to them) the information of the attributes of their width and length, a buffer layer is created that corresponds to the spatial expression of the riverbeds. Layers of riverbeds and lakes (including ponds, dams, the Curonian Lagoon) were combined into one layer.

2. *Stage of distinguishing the coastal zone*. An assessment of the risks of coastal erosion of water bodies was carried out in coastal protection strip areas. For each body of water (according to the procedure established by the current legislation: https://e-seimas.lrs.lt/portal/legalAct/lt/TAD/TAIS.153823/asr), the coastal protection strip is assigned according to its area or length. A more detailed width of the intended strips is presented in Table 5. In accordance with this condition, water bodies are classified according to: lakes by area, rivers by length, and for the coastline of the Curonian Lagoon and the Baltic Sea the width of the coastal protection strip was assigned separately (in accordance with the values of the width of the coastal protection strip established by the Ministry of Environment of Republic of Lithuania). With the help of GIS, segregated classes of objects are assigned the width data of the coastal protection strips according to their geometrical information, and they are preserved in the attribute data. For each object, along its shoreline, a buffer zone of a defined width has been created that corresponds to the aforementioned meaning of the coastal protection strip's width.

3. *Calculation of the slope of the coastal surface*. The vector data layer of *coastal protection strips* (hereinafter *coastal*) was further used as a mask for cropping terrain data from the DTM digital surface. For the analysis of the data, a DTM surface altitude model of high spatial resolution (2*2 m), was chosen, which made it possible to distinguish the banks and their slopes even of very small rivers and streams.
   During the GIS manipulations, the resulting relief layer of the coastal surface of water bodies (in which the values of the coordinates of x, y and z are assigned to each raster cell) was further used to calculate the angles of inclination. The angles of inclination are calculated with the help of GIS tools using the equation indicated bellow. The slope was calculated as the rate of change of the surface (delta) in the horizontal (dz/dx) and vertical (dz/dy) directions from the center of the raster to each adjacent cell.

$$\Theta = \boldsymbol{Arctan(\sqrt{([dz/dx]^2 + [dz/dy]^2)}) * 57.29578}$$

4. *The stage of assigning coastal slope classes*. The vulnerability of slopes to erosion is defined by a series of indicators (angle of inclination (slope), type and characteristics of rocks/ sediments, length of the slope, vegetation cover and its nature, etc.), but perhaps one of the most important is - the inclination of the slope, that is, its steepness. The formed raster layer of coastal inclination is further classified according to the intervals of the steepness classes of the slopes, thus distinguishing level surfaces, classes of very flat, flat, moderately steep and steep slopes.

Table 8. Classes and categories of slope inclination and potential susceptibility to erosion

Angle of inclination (in degrees)	**The character of the slope**	**Risk of erosion**	**Risk correction coefficient.**
0-1	Level surfaces	Very low	0
1-3	Gently inclined	Low	0,25
3-7	Inclined	Moderate	0,5
7-15	Moderately steep	High	0,75
>15	Steep	Very high	1

5. *Calculation of the riverbed slope (the angle of inclination of the water surface) for rivers*. The angle of inclination of riverbeds is calculated using the tool described above. The difference from the process of calculating the coastal slopes is the determination of the middle axis of the riverbeds and the formation of their layer. For the layer of the central axis of the riverbeds (which was used as a mask for the surface relief layer of the DTM), a linear vector layer of continuous/ connected riverbeds formed in stage 1 was used.
6. *Classification of riverbed sections according to their meandering indicator*. For the analysis of the meandering of riverbeds, the GIS extension (set of open access tools) of "river gradient and meandering" was used, which works on the basis of two principles/stages of data processing and analysis:
    a. At the beginning, all lines of the linear layer are merged, then dissected in such a way that each line has its own row of attributes, end points are generated for lines, hanging nodes are identified, which are further used to remove unnecessary line vertexes, leaving only the points of the confluence of rivers (real nodes). The lines at the real nodes are divided into sections.
    b. For the linear layer, the starting and end points (from the sections of the line) are created, the coordinates of X and Y are assigned to them, all the points are combined into the original line file, and the meandering is calculated as the ratio of the length of the line to the length of the line between its beginning and the end point ***Sqr(((X1 - X2)^2) + ((Y1 - Y2)^2)***. For each separated section of the river, the meandering factor shall be calculated and entered into the attributes.

Fig. 4. Classification of rivers by meandering indicator (example of results)

7. *The test for statistical relationships between the riverbank slopes, the riverbed slope and meandering indicators*. Coastal slopes relationships and dependence with other calculated hydrographic indicators (gradient and meandering of the riverbed) was substantiated by a statistical spatial analysis of Local Bivariate Relationships. Its results showed a clear and strong statistical relationship between the gradient of the riverbed and the slopes of the river banks in 100 m segments (in 90.25% out of >420,000 segments the reliable relationship was detected). Therefore, for further coastal erosion risk assessment will be used the slopes of the surface cells as calculated within the coastal protection strips.

8. Calculation of risk scores for coastal erosion (for all objects) and correction coefficients, the compilation of final layers of results. The coastal erosion risk assessment for the three RCP scenarios was carried out within the coastal protection strip, for the input using raster with a resolution of 2*2 m and previously mentioned vector data. The choice of initial data determines that a large number of cells (polygons) with different values of inclination and, therefore, of risk of erosion, were included into the coastal strip of each water body. The area occupied by their classes is also different (Table 8). At the same time, administrative territorial units (cadastral areas and elderships) are characterised by a different area of water bodies and their density. In this regard, and in order to assess (assign) and present the potential risks of erosion as objectively as possible, the following calculations, conditions and coefficients were applied.

*RIZIKA_GRID_PROC = (Proc_GRID1*0/100) + (Proc_GRID2*0.25/100) + (Proc_GRID3*0.5/100) + (Proc_GRID4*0.75/100) + (Proc_GRID5*1/100)*

Here: RIZIKA_GRID_PROC - the total erosion risk score
PROC_GRID1 is the percentage of the area of coastal slopes of 0-1° (level surfaces) of the total coastal area (%) per individual administrative territorial unit;
PROC_GRID2 is the percentage of the area of coastal slopes of 1-3° (very flat slopes) from the total coastal area (%) per administrative territorial unit;
PROC_GRID3 is the percentage of the area of coastal slopes of 3-7° (flat slopes) from the total coastal area (%) per administrative territorial unit;
PROC_GRID4 is the percentage of the area of coastal slopes of 7-15° (moderately steep slopes) from the total coastal area (%) per administrative territorial unit;
PROC_GRID5 is the percentage of the area of coastal slopes >15° (steep slopes) of the total coastal area (%) per administrative territorial unit;

The presented equation in each of the administrative territorial units allows to calculate the total risk score for erosion. However, as already mentioned, administrative territorial units (elderships or cadastral areas) differ in the density and area of the water bodies and coasts in them. The overall risk score for erosion does not take into account the relative coastal area values, as a result, territories (elderships/cadastral areas) with a small area of water bodies (and thus coastlines) with, for example, steep coastlines are assigned high values of the overall risk score (and vice versa, areas with a high density of water bodies, but relatively flat shores, will be assigned low values of erosion risk scores). Thus, for the calibrated total erosion risk score, it is necessary to apply a correction also according to the share of the occupied area.

RIZIKA *(RIZIKA_26, RIZIKA_45, RIZIKA_85)* = GRID_AREA_SUM * 2/GRID_AREA_SUM$_{max}$*) * RIZIKA_GRID_PROC*

Here: RIZIKA *(RIZIKA_26, RIZIKA_45, RIZIKA_85) – individually for each RCP scenario recalculated corrected value of the erosion risk score,*

GRID_AREA_SUM is the coastal area per administrative territorial unit,
$GRID\_AREA\_SUM_{max}$ is the maximum value of the coastal area in the administrative territorial units (by dropping out the exclusions from the data sample),
RIZIKA_GRID_PROC is the total erosion risk score without correction to the coastal area in administrative territorial units.

1.3.5. Explanation of the final scores for coastal erosion risk

In the final layers and data tables of coastal erosion risk under climate change RCP scenarios 2.6, 4.5 and 8.5, based on the above methodology, the final erosion risk scores were calculated. They are presented in the GIS polygon shape layers of elderships and cadastral areas boundaries "KADASTRINES_VIETOVES_PAKRANTĖS_RIZIKA" and "SENIUNIJOS_PAKRANTES_RIZIKA". The results are also exported into .xls tabular format (files "KADASTRINES_VIETOVES_PAKRANTĖS_RIZIKA_table" and "SENIUNIJOS_PAKRANTĖS_RIZIKA_table").

In the GIS data layers, each administrative territorial unit (all elderships and cadastral areas) is assigned the values of risk score according to climate change scenarios (RCP 2.3, 4.5, 8.5) and are presented in the columns of the attribute table "RIZIKA_26", "RIZIKA_45", "RIZIKA_85". The attributes data table also contains other information, and is further explained in the examples of tables in the data layers attached below (Tables 9 and 10).

Table 9. A fragment of the GIS shape layer table at the cadastral area level and explanations of information in columns

Unique cadastral area code no.	*Area code*	*Name of the area*	*The name of the municipality to which the area belongs*	*Risk score in RCP scenario 2.6*	*Risk score in RCP scenario 4.5*	*Risk score in RCP scenario 8.5*	*The perimeter of the cadastral area*	*The area of the cadastral area*
FID_CADAST	**AREA_CODE**	**AREA_NAME**	**MUNICIPALITY**	**RISK_26**	**RISK_45**	**RISK_85**	**LENGTH**	**AREA**
1	3601	AnciScoundrels	Biržų r.sav.	0.87	0.87	0.87	37049.43	44310520.23
2	3603	Anglers	Biržų r.sav.	0.97	0.97	0.97	38103.75	38418902.54
3	3604	Biržai mst.	Biržų r.sav.	0.39	0.39	0.39	30293.80	17822483.75

Table 10. A fragment of the GIS shape layer table at the eldership level and explanation of information in columns

Unique eldership code no.	*Eldership code*	*Name of the eldership*	*Type of self-government of the eldership*	*Risk score in RCP scenario 2.6*	*Risk score in RCP scenario 4.5*	*Risk score in RCP scenario 8.5*	*Perimeter of the eldership*	*Eldership area*
FID_ELDERSH	**ISN**	**NAME**	**DESN**	**RISK_26**	**RISK_45**	**RISK_85**	**LENGTH**	**AREA**
1	4504	Klaipeda	City municipality	9.59	10.21	10.12	77110.883083200000	88316869.51
2	4505	Neringa	Municipality	29.79	29.70	29.70	100541.58325800000	89452356.87
3	4504	Palanga	City municipality	10.46	11.65	11.50	61656.737664800000	78910015.86

The final erosion risk scores obtained in the data layers and data tables provided after the normalization procedure performed (after calculating the correction factors) cover the range of values between 0 and 10. These values are divided into 6 classes. Separately distinguished areas where there is no risk of coastal erosion (usually these are cadastral areas or elderships, the boundaries of which have no water bodies or their area is extremely small), the remaining classes of the 5 value ranges are divided into groups of very low, low, medium, high and very high risk of erosion (Table 12).

Table 11. Ranges and risk classes of final coastal erosion risk scores

Risk of erosion	**Risk Score**
None	0
Very low	> 0<2,5
Low	>2,5<5
Medium	>5<7,5
High	>7,5<10
Very high	>10

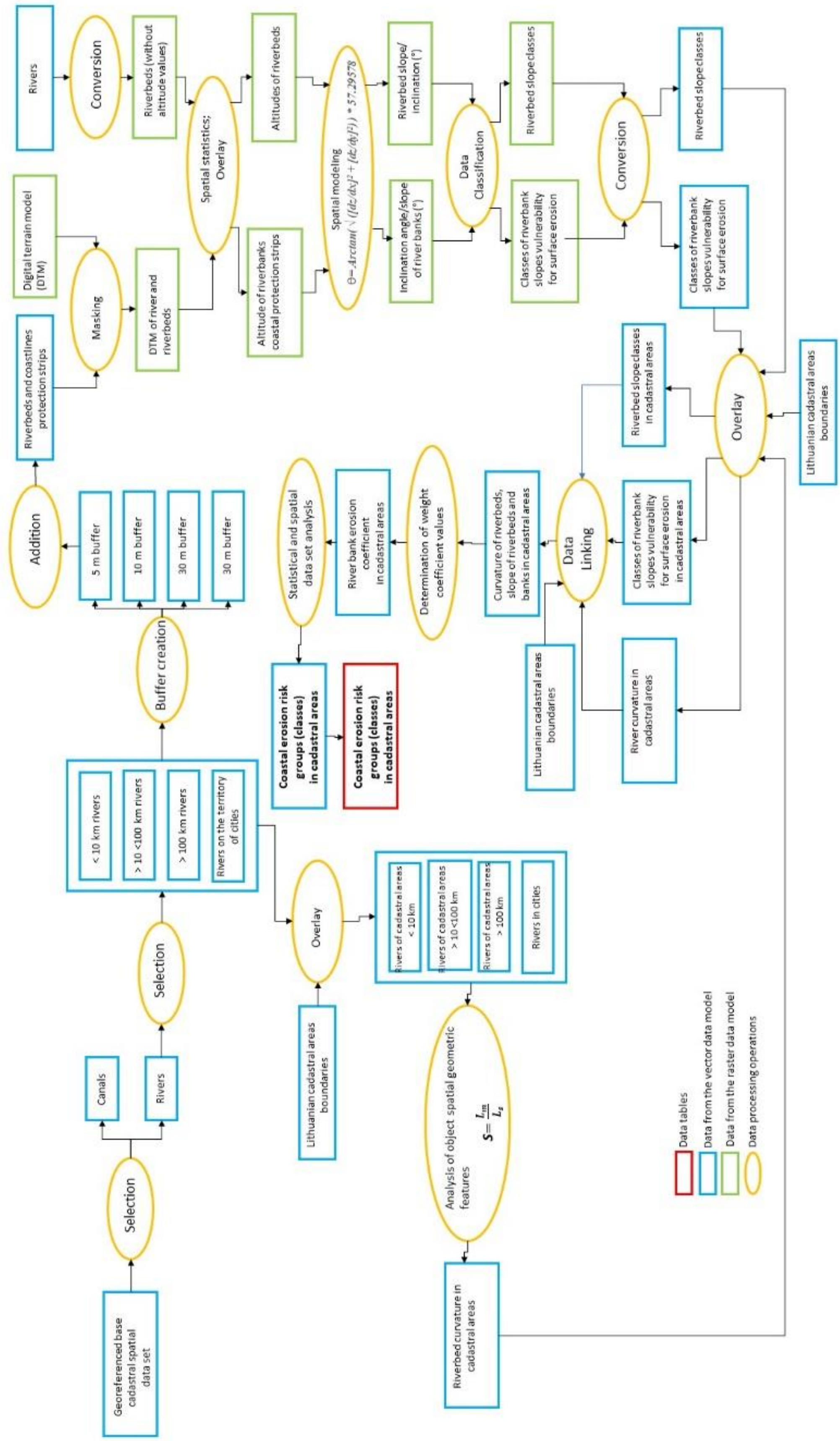


Fig. 5. Exemplary logical diagram of the GIS modelling of the coastal erosion process (prepared on the example of cadastral areas and the actual situation, the process for assessing risks under RPC scenarios is repeated by changing the input data)

1.4. Results of modelling riverbank and coastal erosion risk projections according to RCP scenarios (2.6, 5.4, 8.5)

The obtained results of the modelling of the risks of riverbank and coastal erosion show that the greatest risks are characteristic to the cadastral areas of Western Lithuania – the Seaside region and the territories of Vilnius (very high), as well as the territories of Kaunas (high). In the case of the Seaside region, very high-risk values are determined by the instability of the coasts and their change due to the prevailing natural conditions, as well as due to the rising water level of the Baltic Sea (currently the Baltic water level on the Lithuanian sea coast is rising by approximately 2 mm/m). It is predicted that in the future, as the Baltic water level continues to rise according to RCP scenarios 4.5 and 8.5, there will also be a higher risk of coastal erosion in the cadastral areas of the Nemunas delta and the coast of the Curonian Lagoon, which have a very low altitude (without taking engineering decisions, a gradual flooding of the territories will be observed in this area in the future) (Figs. 7 and 8).

In the case of Vilnius, in all simulated scenarios, a very high risk of riverbank and coastal erosion was obtained. The results are explained by the relatively large number of water bodies and the presence of deep terraces and valleys of the Neris, Vokė, Vilnia and some smaller streams affected by erosion (Figs. 6, 7, 8).

The high-risk scores of Kaunas are influenced by the indicators of the banks of the Nemunas, the Neris and coast of Kaunas Reservoir (its part within the territory of Kaunas City) (Figs. 6, 7, 8).

In various parts of the territory of Lithuania, in individual cadastral areas, the moderate risk of riverbank and coastal erosion is distinguished. This score in the mainland of the country is largely due to the characteristics of the eroded river valleys in the areas (Figs. 6, 7, 8).

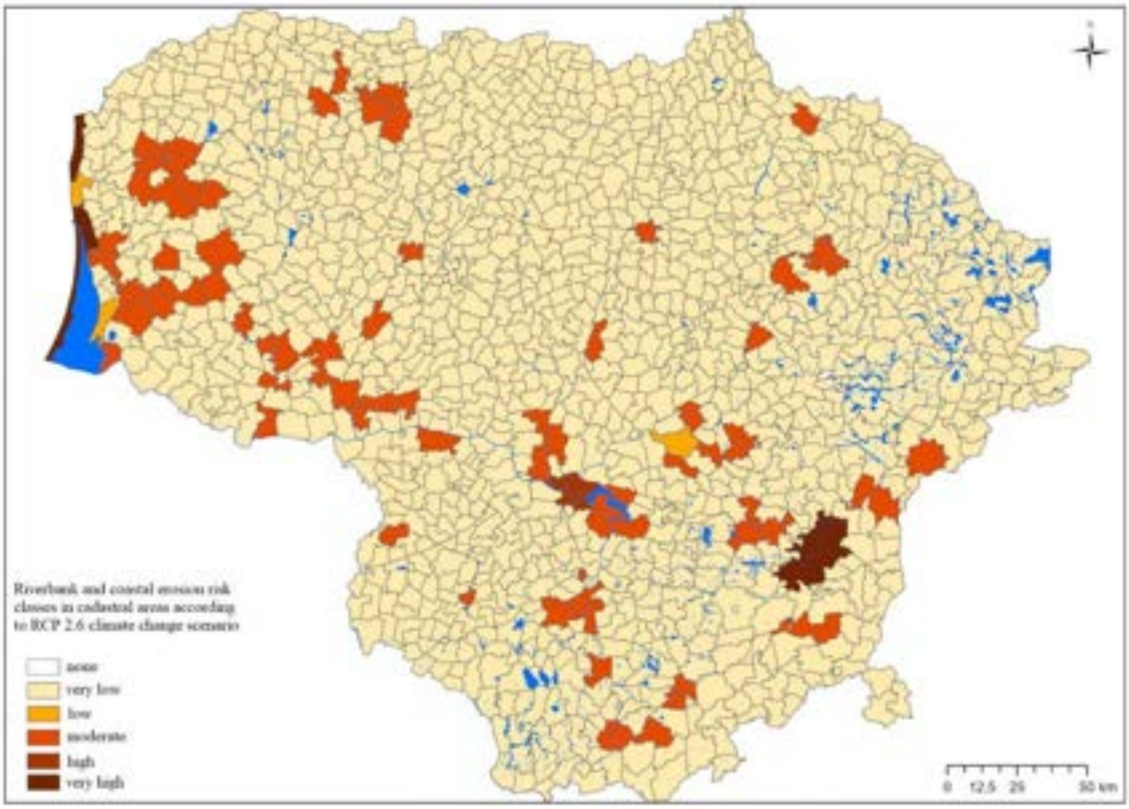


Fig. 6. Riverbank and coastal erosion risk classes in cadastral areas according to RCP 2.6 climate change scenario

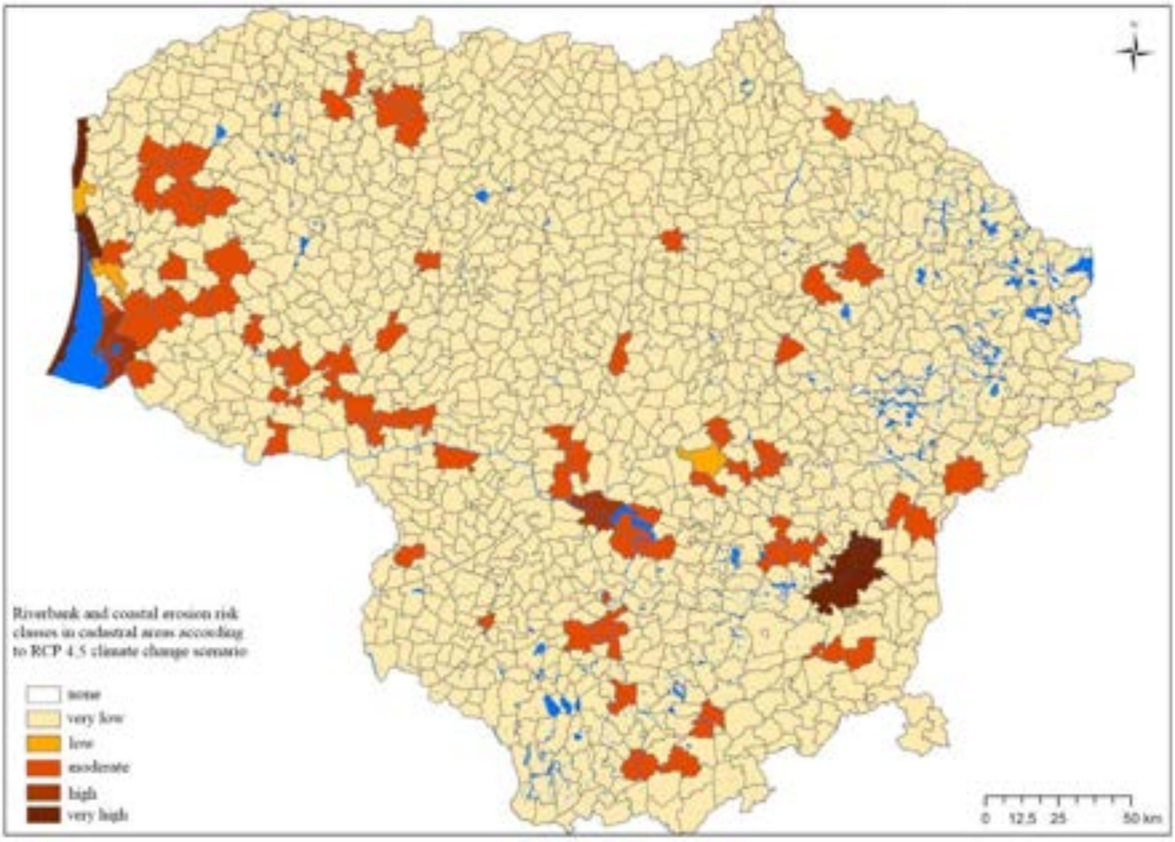


Fig. 7. Riverbank and coastal erosion risk classes in cadastral areas under RCP 4.5 climate change scenario

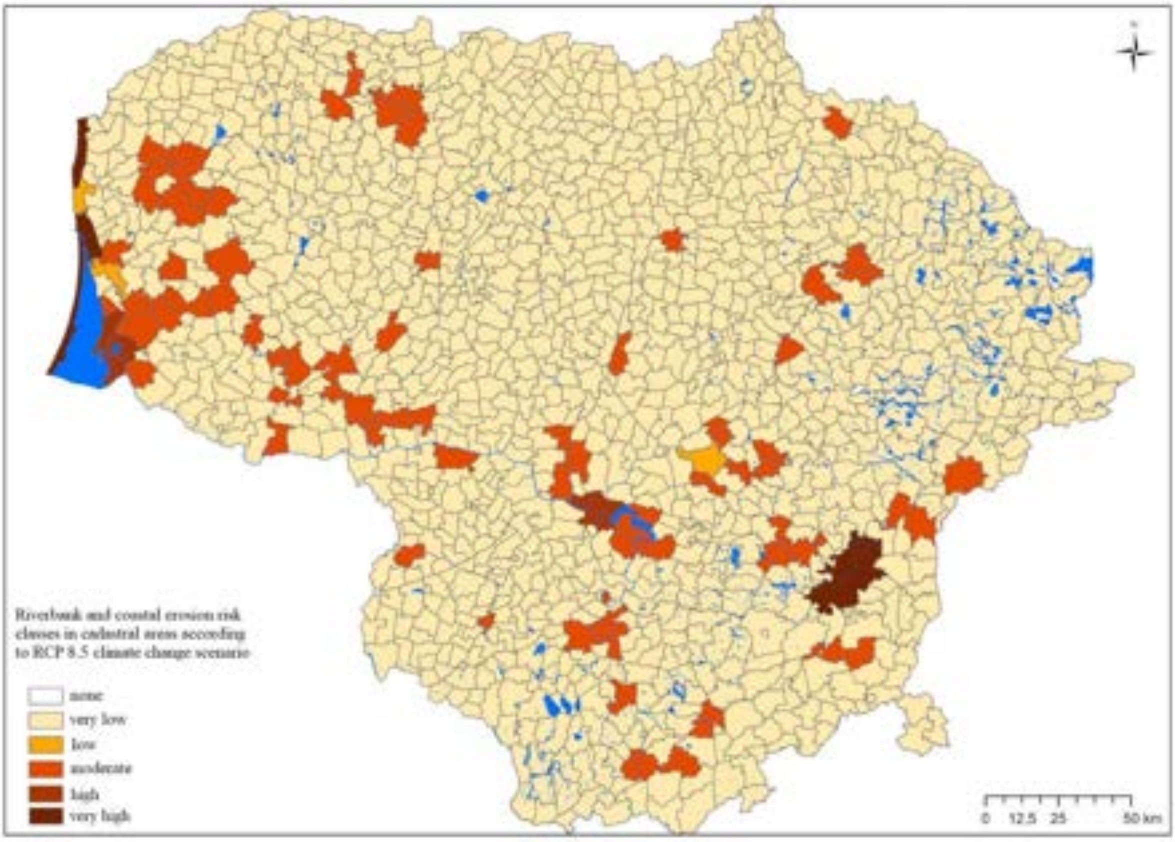


Fig. 8. Riverbank and coastal erosion risk classes in cadastral areas under RCP 8.5 climate change scenario

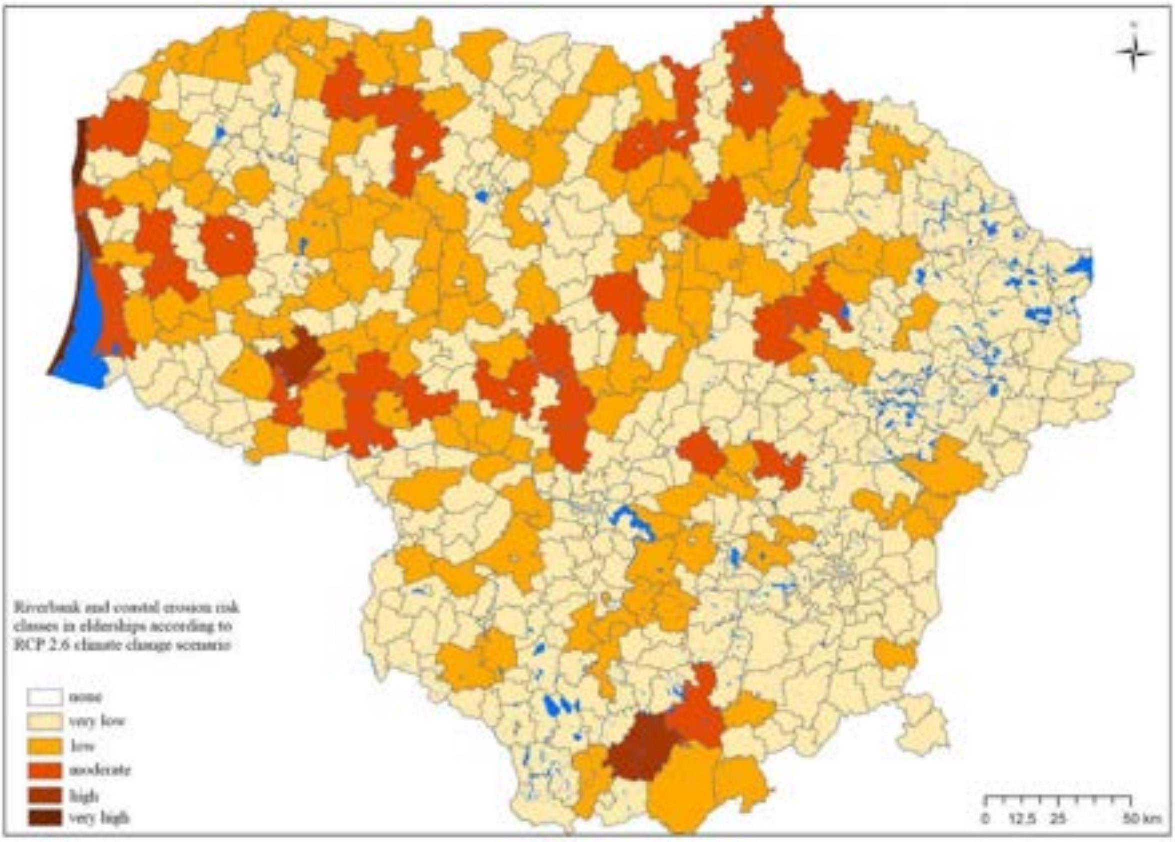


Fig. 9. Riverbank and coastal erosion risk class elderships under RCP 2.6 climate change scenario

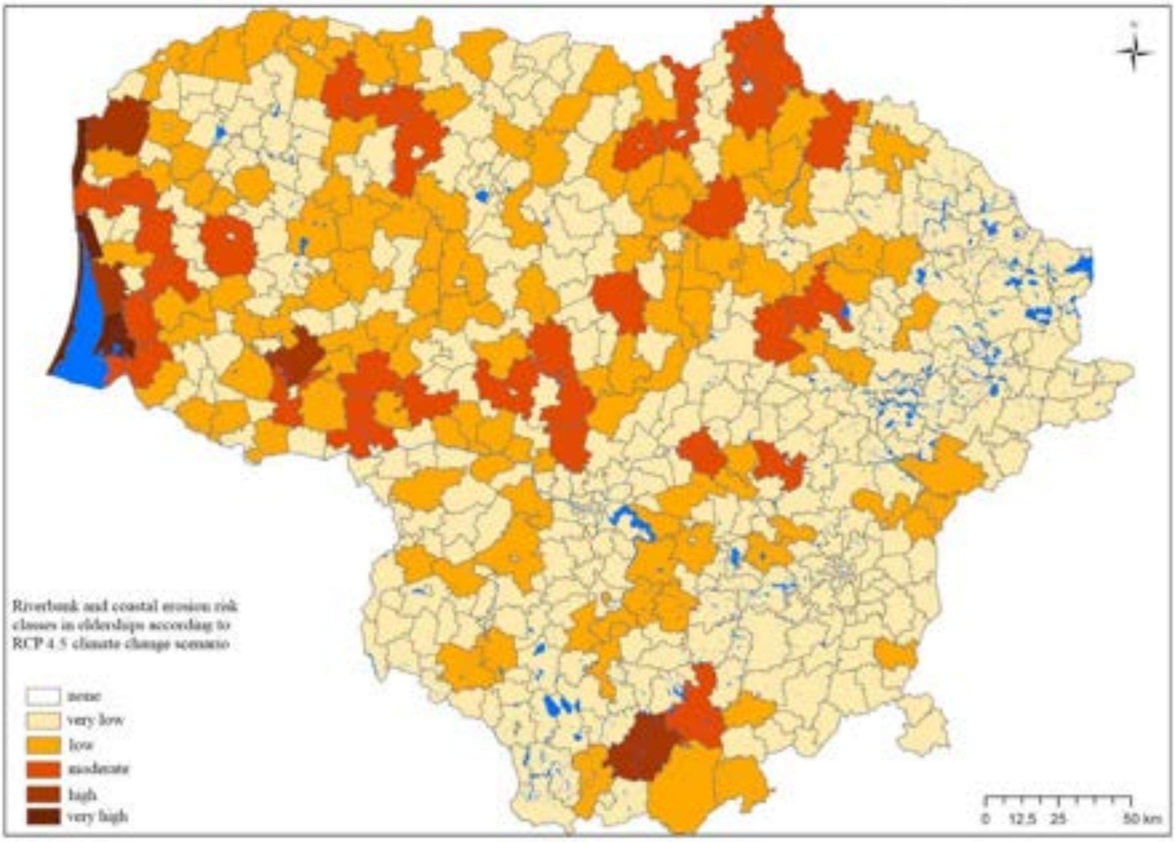


Fig. 10. Riverbank and coastal Erosion Risk Class Elderships under RCP 4.5 Climate Change Scenario

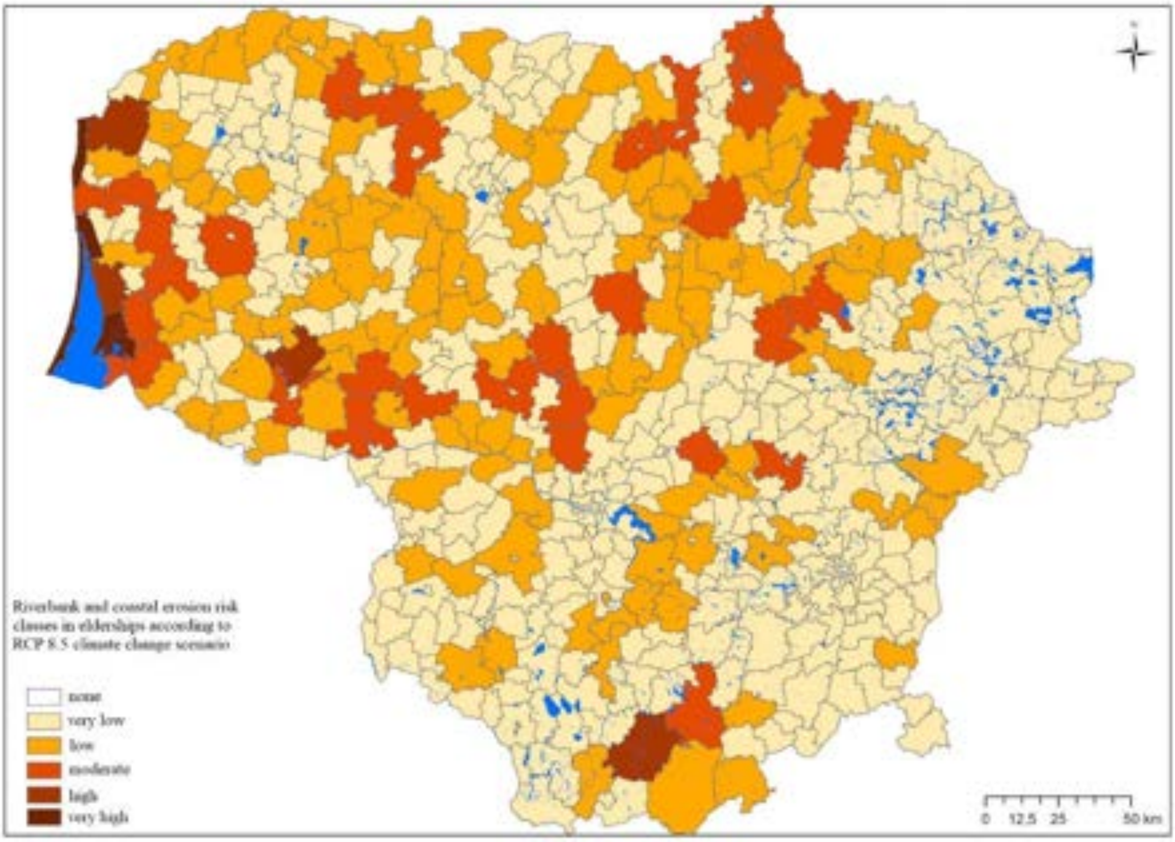


Fig. 11. Riverbank and coastal Erosion Risk Class Elderships under RCP 8.5 Climate Change Scenario

Picture of riverbank and coastal erosion risk distribution in elderships is different because of altered generalization level. Large cities, when dividing their territory into smaller territorial units, lose the high value of erosion risk scores, but in the general Lithuanian context, there are elderships which are characterized by a higher density of the river network (Central and Western Lithuania, Southern Lithuania with rivers of the Nemunas and Merkys basins (Merkinė eldership)) (Figs. 9, 10, 11). In Eastern Lithuania – in the Baltic Uplands, due to the rarer river network, the risk of erosion is very low, and the same remains in the Dzūkai and Sūduva uplands.

As the results show, the greatest risks are represented by seaside elderships. In the future, as the water level of the Baltic Sea rises, risk of coastal erosion in this part of the country will remain very high, and in the coastal elderships of the Curonian Lagoon (Rusnė, Šilutė, Kintai, Priekulė) it will grow even more (Figs. 9, 10 and 11).

2. Solifluction risk assessment in the context of RCP climate change scenarios

2.1. Factors determining the solifluction process

Solifluction is the slow, ductile sliding (streaming) of a weathered thawed and water-soaked material along the frozen surface of the slope downwards. The process is determined by cold temperatures, water and the depth of soil freeze. Solifluction occurs when free soil water, due to soil freeze, unable to penetrate deep, is forced to move down the slope, reducing the clutch of soil particles. As a result, the soaked soil above the frozen horizon begins to slide down. Solifluction occurs on slopes of more than 2°, and most often of 8-15° of inclination. The speed of sliding depends on: the inclination of the slope, the amount of dispersion particles, the thickness and volume of the layer, the granulometric composition, the vegetation cover, the thickness of the frozen layer of the soil, the stability of the frost, soil moisture. As a rule, solifluction is described as a periglacial (cryogenic) process. This means that its is common in areas of the zone under the influence of perennial frost and glaciers (lowered). However, under favourable conditions, solifluction in small areas can also take place in Lithuania.

Most often it is a slow process, the speed of which usually reaches several cm per year (sometimes there are catastrophic, landslides-causing scrolls - up to several hundred meters per hour, but these are exceptional cases that do not occur in our climatic conditions). During solifluction, solifluction terraces, steps, embankments, tongues and other deformations of the slopes are formed. In Lithuania, the most expressive traces of solifluction can be seen in river valleys, but locally this phenomenon can also be found in other territories characterized by a complex of suitable conditions.

2.2. Spatial simulation of solifluction risks

2.2.1. Indicators of the risk of solifluction

Solifluction modelling is associated with the assessment of a series of factors and indicators that influence the possible manifestation and occurrence of a phenomenon in the area. For the assessment of some factors, their direct data can be used, others - derived. Since in the climatic belt of temperate latitudes this phenomenon is not widespread, there are almost no studies related to its modern dynamics, but based on the classical concept of the phenomenon among the relevant indicators, one can name: the angle of inclination of surface relief, the depth of soil freeze, the periodicity of soil freeze, which is associated with another indicator - the negative temperatures of the cold period (their duration), the characteristics of soil-forming rocks and soils (infiltration properties), the amount of precipitation in the cold period, and at the local level - the exposure of the slopes, the type of land cover. All identified indicators are included in the further assessment of solifluction risks. According to the ranges of their values, classes of indicator values are distinguished, they are assigned scores, the sum of which, when summed up, subsequently gives a cumulative risk score for solifluction.

The total risk score for solifluction reveals the risk of solifluction in a cell of 100 m^2 (taken from the initial input data of the terrain slope), therefore, additional calculations were applied to assess the total risk score in the territories of elderships and cadastral areas according to the relative area (and their weight factor) of the different risk cells borne by them. Since administrative territorial units differ among themselves in the area of territories susceptible to solifluction, a correction factor is applied to the total solifluction score according to the

occupied relative area of the potentially affected areas (taking from the total area of the adm. territorial unit), thus obtaining the final risk score for solifluction.
The values of all the the indicators and the scores assigned to them are explained in Tables 12-18, while the data used to calculate the indicators and their sources are discussed in the following subsection (2.2.3.).

Table 12. Indicators for modelling the phenomenon of solifluction

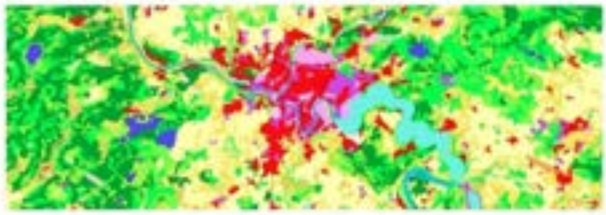
Indicator	Scores				
The character of the land cover	The risk of solifluction was assessed only in areas covered with non-woody vegetation. It was assumed that the root system of woody vegetation (tree roots) strengthens and inhibits the sliding of the slope. For this reason, the following classes of land cover according to the CORI NE (© European Union, Copernicus Land Monitoring Service 2018, European Environment Agency (EEA)) classification were selected for the analysis process: 141 Green urban areas; 122 Road and rail networks and associated land; 142 Sport and leisure facilities; 231 Pastures; 321 Natural grassland.  Corine Land Cover Layer Fragment Example				
Slope (angle of inclination)	1	1	2	3	4
Precipitation in the cold period	1	2	3	4	5
Infiltration (permeability) coefficient	1	2	3	4	5-6
Depth of the soil freeze (max.)	1	2	3	4	5
Slope exposition	1	2	3	4	5
Negative temperatures (sum of days in 10 days)	1	2	3	4	5
Solifluction risk classes according to the sum of the scores of partial indicators	L. small	Small	Average	Large	L. big

Table 13. Surface Inclination Angle/Slope Classes

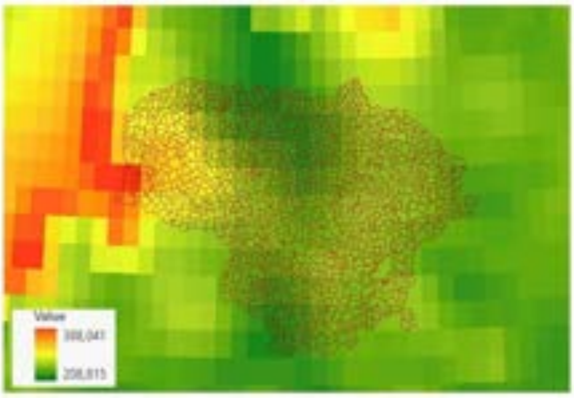
Surface relief tendency angle (°)		
Indicator values	Inclination angle classes	Slope steepness classes
1	**2-3**	**Very flat**
2	**3-7**	**Flat**
3	**7-15**	**Moderately steep**
4	**>15**	**Steep**
The classes of inclination angles are distinguished according to the categories of steepness of the slopes (according to Kavoliute, 2004) each by assigning the score value of the indicator from 1 for very flat, up to 4 for steep slopes. Since the sliding of the material along the slope begins at the slope of > 2°, all cells with lower angles of inclination have been eliminated from the further analysis process.		

Table 14. Classes of the indicator of precipitation (mm) during November to March

Indicator values	Precipitation in the cold period (November-March, mm)
1	200-250
2	250-300
3	300-350
4	350-400
5	>400
One of the prerequisites for solifluction is a heavily water-soaked soil. Directly related to this condition is amount of precipitation. In the cold period, a strongly soaked layer above the frozen soil layer begins	

to move. Thus, the precipitation that has fallen in the cold period strongly contributes to the appearance of soil moisture conditions that influence the phenomenon of solifluction.

Despite the fact that the used data cover the entire territory of the European continent, the distribution of precipitation during the cold season periods was assessed within the boundaries of the territory of Lithuania. The classes of precipitation ranges are determined on the basis of data on the perennial distribution of precipitation (in the cold period). At the bottom is an example of the 2022 situation (calculated on the basis of a multi-year average) of the raster layer of precipitation during the cold period, which was used to analyse the data. The specification of data for climatic future projections is presented in Table 14.



Raster data layer for precipitation during November-March (average rainfall values for 2022 derived from the multi-year average method)

Table 15. Classes of the permeability coefficient indicator of soil-forming rocks

Indicator values	**Soil-forming rocks**
1	s – sand; s1 – knotted sand; d – peat;
2	ps – loam; sp – sandy light loam; dps – silty loam;
3	da – silt (aleurites); dp – silty light loam; p1 – moderate loam;
4	sp2 - sandy heavy loam; dp1 – silty moderate loam; p2 – heavy loam; dp2 – silty heavy loam;
5	sm – sandy clay;
6	dm – silty clay; m – clay;

The mechanical composition of the soil (quaternary sediments) determines its properties to absorb, transmit or retain water. By filling all the pores of the soil during infiltration and displacing air with water, soil saturation is achieved.

In ground/soils with a lighter granulometric composition, water filtration is faster, and retention is lower than in heavier soils. As a result, water is worst retained by sand and peat, best – by silty clay and clay.

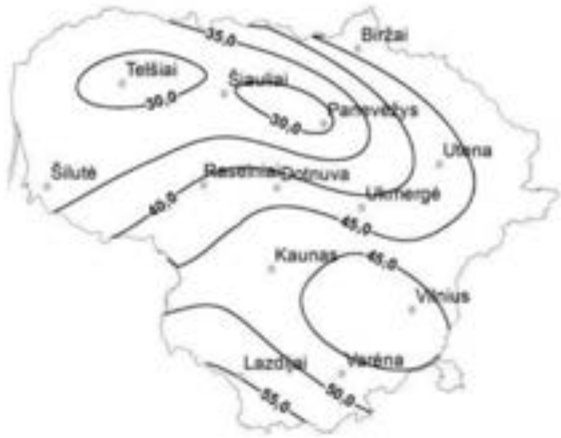
Within the framework of this study, the water permeability coefficient of soil-forming rocks was calculated taking into account the granulometric composition and the RUSLE (Revised universal soil loss equation) methodology for the assessment of the soil erosion factor (K factor) and its partial indicator – soil permeability, developed by the US Department of Agriculture.

Table 16. Soil freeze depth indicator classes

Indicator values	**Depth of soil freeze**
1	30-35
2	35-40
3	40-45
4	45-50
5	>50

The depth of soil freeze is an important indicator of the phenomenon of solifluction. Solifluction occurs when favourable conditions prevail for the appearance of soil freeze and periodic (simultaneously during the impregnation of the soil or when the soil is waterlogged) thawing. The upper thawed layer of soil, having accumulated a limit amount of moisture and not being able to pass more or absorb, begins to move down the slope.
The depth of soil freeze depends on several main factors: duration of the negative temperatures during the day and the season, the mechanical composition of the soil. Within the territory of Lithuania, the depth of freeze is different. According

to a study conducted by V. Mačiulytė and E. Rimkus (2016), in Western Lithuania the maximum depth of frost is the smallest, in Southern Lithuania – the highest.

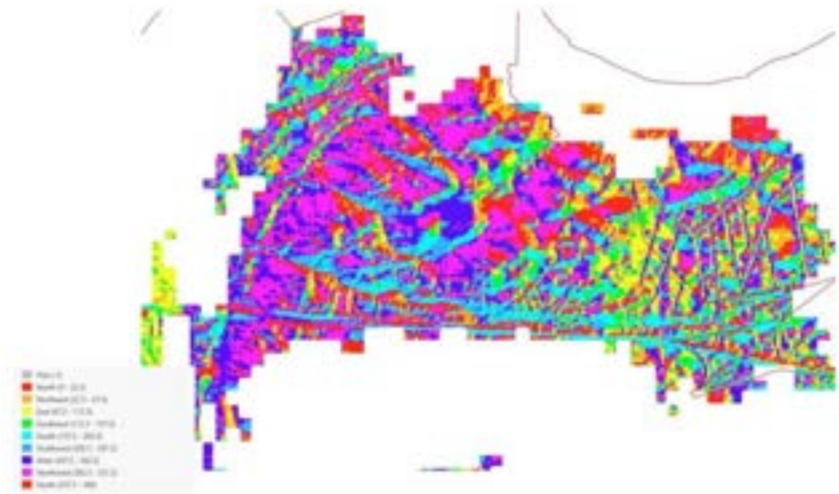


Maximum depth of soil freeze (cm) in the territory of Lithuania in 1981-2010 (Mačiulytė, Rimkus, 2016)

Table 17. Aspect (slope exposition) indicator classes

Indicator values	Exposure
1	Lunch
2	Southeast, Southwest
3	East, West
4	Northeast, northwest
5	North

Aspect is an indicator contributing to the soil moisture regime. Due to the higher amount of solar radiation received by the earth's surface (during the day), conditions of the lower humidity regime will prevail on the slopes of the southern aspect, and vice versa - the slopes of the northern exposition, which stay longer and more in the shade, will, as the year progresses, be characterized by a higher amount of moisture. Snow cover also lasts longer on the northern slopes.
The study assumed that the increased soil moistening regime on the slopes of the northern exposition (with a favourable complex of other conditions) may contribute to the intensification of solifluction.



Fragment of the slope exposure layer of used in the study

Table 18. Classes of the indicator for days with negative temperatures (sum in 10 days)

Indicator values	Negative temperatures (sum of 10 days)
1	02 - 04
2	04 - 06
3	06 - 08
4	08 - 1
5	>1

An indicator of days with negative temperatures is an important determinant of the solifluction process, since the formation of soil freeze, the distribution of snow and liquid precipitation (the dynamics of the soil moistening regime) depend on it. The analysis used spatial data from Europe, which conveys the sum of days with negative temperature values over a period of 10 days. This data is also projected according to future climate change scenarios.

2.2.2. Input data

The methodology for assessing the risks of solifluction includes a sequence of mathematical and GIS manipulations and actions, the realization of which requires the following initial input data:

1. Vector data layers of cadastral areas and elderships;
2. CORINE land cover classes data layer;
3. DIRV_10 soil database;
4. Digital terrain model (DTM) data layer;
5. Climatic spatial data on the amount of precipitation (in the cold period) and days with negative temperatures.

In detail, the properties of the data and their sources are described in Table 19 below.

Table 19. Data on modelling indicators of the solifluction phenomenon

Indicator	Character of the data and data source
The character of the land cover	The CORINE database was used for the type of land cover and the selection of the required classes. The CORINE Land cover (CLC) database is a pan-European vector land cover dataset divided into 44 classes (the territory of Lithuania is covered by 30 classes) according to the type of land cover and the purpose of use. The data is presented in a raster GIS file format. Scale: 1:200,000; The following classes of land cover according to the CORINE classification were selected for the analysis process: 141 Green urban areas; 122 Road and rail networks and associated land; 142 Sport and leisure facilities; 231 Pastures; 321 Natural grassland.
Slope	The data of the slope are generated using the LIDAR data-based layer of the Lithuanian surface relief DTM model. Resolution – 10*10 m. The values encoded in the cells are: the values of the coordinates of x, y and z (z is given in meters above sea level).
Precipitation in the cold period	The actual and future data of precipitation during the cold period (according to the RPC scenarios under consideration) are obtained from the COPERNICUS Earth observation data Centre. Copernicus is the Earth observation component of the European Union Space Programme, managed by the European Commission and implemented in cooperation with EU Member States, the European Space Agency, the European Organisation for the Exploitation of Meteorological Satellites, the European Centre for Medium-Range Weather Forecasts. The data is presented in NetCDF-4 format, and therefore requires additional processing and preparation. Resolution – 15*30 km. Spatial coverage – Europe. Temporal resolution (period covered): monthly rainfall data for the period 1991-2022 were used to calculate the multi-year average of the actual situation. https://cds.climate.copernicus.eu/cdsapp#!/dataset/ecv-for-climate-change?tab=form For the projected period (according to RCP scenarios 2.6, 4.5 and 8.5), the multi-year average (2040-2070 m) was calculated using data from the temperature and precipitation climate impact indicators for the period 1970-2100 obtained from the European climate forecasts. The data is presented in NetCDF-4 format, and therefore requires additional processing and preparation. Resolution –60*110 km. Spatial coverage – Europe. Temporal resolution (period covered): monthly rainfall data for 1971-2100.

	The datasets are compiled using climatic models: regional RACMO22E (KNMI, Netherlands) and global HadGEM2-ES (UK Met Office, UK); https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-hydrology-meteorology-derived-projections?tab=form
Infiltration (permeability) coefficient	The permeability classes of the infiltration/soil according to the granulometric composition are calculated on the basis of the soil erosion model/equation RUSLE (Revised Soil Loss Equation) K-factor (K is a soil erosion indicator) values of soil permeability classes. The group of mechanical composition of the quaternary sediments (soil-forming rocks) and the boundaries of their range areas (except wooded areas) were obtained from the soil GIS database DIRV_10. https://www.geoportal.lt/metadata-catalog/catalog/search/resource/details.page?uuid=%7B449450A9-AD8C-6E9E-6FCB-06A0584BF88C%7D The values of the soil permeability classes were calculated from the RUSLE handbook: https://www.nrcs.usda.gov/sites/default/files/2022-10/RUSLE2%20Handbook_0.pdf
Depth of freezing of the soil (max.)	Source of data on the maximum depth of soil freeze: V. Mačiulytė and E. Rimkus scientific publication "Soil thermal regime in Lithuania", GEOLOGY and GEOGRAPHY. 2016. Vol. 2. No. 1. Pp. 1–13.
Aspect (slope exposition)	The aspect data were generated using the LIDAR data-based layer of the Lithuanian surface relief DTM model. Resolution – 10*10 m. The values encoded in the cells are: the values of the coordinates of x, y and z (z is given in meters above sea level).
Negative temperatures (sum of days in 10 days)	Actual and future data on negative temperatures (according to the RPC scenarios under consideration) are derived from the Copernicus Earth observation data centre. Copernicus is the Earth observation component of the European Union space programme, managed by the European Commission and implemented in cooperation with EU Member States, the European Space Agency, the European Organisation for the Exploitation of Meteorological Satellites, the European Medium-Range Centre. The data is presented in NetCDF-4 format, and therefore requires additional processing and preparation. Resolution – 32*56 km. Spatial coverage – Europe. Temporary resolution (period covered) – 1951-2099. For the projected time stamp, the average for 2070-2099 is deducted. Given values: Number of days in 10 days with TX < 0°C, where TX is the highest daily temperature. Climatic models used to GENERATE DATASET: HadGEM2-ES Model (UK Met Office, UK) https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-agroclimatic-indicators?tab=form

2.2.3. Stages of solifluction risk assessment

1. *Exclusion of land cover (land use types) vulnerable to solifluction.* The solifluction risk assessment was carried out for areas overgrown with grassy non-woody vegetation. Wooded areas (with a dense root system of plants) and areas not covered with open vegetation are excluded from the modelling process. It was assumed that under the conditions of the open soil/earth surface and the increase in precipitation and surface runoff, favorable circumstances would be created for the appearance of foci of plane erosion. Meanwhile, the dense vegetation of the forest and its developed root system act in opposite – fixes the slopes and stops the appearance of erosion and solifluction. For these reasons, only those classes of land cover in which grassy and non-woody vegetation is common, that is: urban greenery and green areas (except forest parks), land of the road and railway network (roadsides, embankments, etc.), sports and recreation areas (stadiums, fields, golf courses, etc.), natural meadows and pastures, were selected for the simulation of the solifluction.
   The CORINE land cover dataset was used to distinguish the listed territories and their boundaries. The boundaries of the land cover classes of the current situation were also applied to the compilation of future projections (data on changes in land cover according to RCP scenarios are not available, and there is still no predictions on how the structure of the land

cover will change in the next 50-100, since it depends not only on natural, but also on social and political factors and circumstances).

The selected areas of the Lithuanian land use classes covered with grassy vegetation were further used as a mask for the calculation of other indicators (the remaining solifluction indicators were calculated only for areas falling into the above distinguished areas of grassy vegetation).

2. *Classification of surface relief according to the slopes (steepness of the slope) and calculation of derived morphometric indicators of the earth's surface.* For the classification of slopes, data from the DTM model of the surface relief based on LIDAR data are used. During the course of GIS manipulations, the terrain data are trimmed according to the areas of vegetation cover isolated during the 1st stage. The resulting layer of output data was further used to calculate the slopes (angles of inclination). The latter are calculated with the help of the GIS tool using the equation indicated bellow.

$$\Theta = \mathbf{\mathit{Arctan}}(\sqrt{([dz/dx]^2 + [dz/dy]^2)}) * 57.29578$$

The slope of the terrain in the calculations is understood as the rate of change of the surface (delta) in the horizontal (dz/dx) and vertical (dz/dy) directions from the centre of the raster cell to each adjacent cell. The result is that the angle of inclination of each cell is expressed in degrees. The resulting output data are further classified according to the values of the steepness classes of the slopes, a layer is created in which the groups of steepness of the slopes described in Table 14 are distinguished (very flat, flat, moderate steep, and steep). Surfaces/cells with a slope angle of < 2° were eliminated from further analysis (on level surfaces solifluction does not take place).

Data from the digital surface model DTM, trimmed according to the areas of grassy vegetation and eliminating surfaces with a slope angle of < 2°, were also adapted to the calculation of the slope aspect. Using GIS surface analysis tools, a raster is generated, each cell of which contains a code corresponding to the aspect value. All data for further analysis is converted to a vector GIS file format.

3. *Preparation and processing of data on climatic indicators* is the next stage of work. Climatic data of a different nature were used to assess the solifluction: negative temperatures (the sum of days in 10 days); soil freeze depth (max.); precipitation in the cold period.

The vector GIS layer of the soil freeze data is based on data from research already carried out (data are described in more detail in Table 20).

Meanwhile, data on precipitation and temperature during the cold period are obtained from the COPERNICUS data centre. The data are presented in netCDF_4 format, and their cells, due to the cartographic projection used, have the shape of a rectangle (oriented in the direction of the point of intersection of meridians). At the same time, the data covers a long period of time (weekly, monthly, seasonal or annual data can be provided), temporary information is stored in them in the "bands" of the raster (data is presented in the form of multiband *raster data*). For these reasons, the preparation of data and their primary processing is necessary. This stage of work was implemented using R programming language.

With its help, multi-year data on precipitation and temperature indicators were calculated, layers of multi-year precipitation and temperature indicators (multi-year averages) of future RCP scenarios were calculated and compiled. They were exported into the coordinate system of LKS-94 projection (like other layers in which the operations were performed).

All obtained data layers were further trimmed according to the boundaries of the masks already described above and classified according to the classes of their values (Tables 15, 17, 19). All data for further analysis is converted into a vector GIS file format.

4. *Calculation of the soil permeability indicator.* To assess the soil permeability indicator, the spatial soil dataset of the territory of the Republic of Lithuania M 1:10,000 (DIRV_10) was used. The data contains information about the soil and soil-forming rock cover, its types and properties. With the help of GIS selection tools for this stage, only those areas of soil cover were selected that meet the criteria specified in stages 1 and 2 (fall into the ranges of grassy vegetation cover classes and slope > 2°). In the attributes of the soil data, in addition to a series of other information, data on the type of soil-forming rocks are stored (according to the Fere classification of the mechanical composition of the soils). For this data, according to the soil erosion model/equation RUSLE (Revised Universal Soil Loss Equation) manual, the values of the soil's moisture permeability used to assess the K-factor (soil erosion indicator) were assigned (Table 16).

As a result of the calculations of all partial solifluction risk indicators, one common data layer is generated from the individual GIS vector data layers. In it, in the attribute data, the values of all indicators were assigned to each distinguished polygon, they were further used to calculate the final results and solifluction risk scores.

5. Calculation of solifluction risk scores and correction coefficients, compilation of final layers of results. The assessment by the solifluction risk scores was carried out on the basis of the indicators presented in Table 13. The modelling itself was carried out using spatial data, the basis of which a layer of the digital terrain model with a resolution of 10*10 m was taken (on the basis of the latter, some morphometrics of surface relief were further calculated, which were further used in the assessment of risks). In principle, the total solifluction score is calculated for each selected cell (10*10 m) that meets the evaluation criteria. The evaluation criteria are:

- Only areas covered with grassy non-woody vegetation are analysed;
- Only areas with slope > 2° are analysed*;*

The areas corresponding to the appropriate criteria for the expression of solifluction were further modelled on the basis of the distinguished soliflution risk modelling indicators (Table 12).

In the course of modelling, a total of > 17,600,000 cells were obtained through the procedures for assigning and evaluating indicators and overlaying data. In each cell, the total solifluction score is calculated (it is obtained by summing up the component scores of each indicator as per Table 12) (Table 20).

Table 20. Ranges of total solifluction score values

Total solifluction risk score (sum of the scores of the modelled indicators for each 10*10 m cell)	**The solifluction risk meaning**
6	Very low
>6<12	Low
>12<18	Moderate
>18 <24	High
>24<29	Very high

The sum score of solifluction risk reveals the risk of solifluction in a 100 m^2 cell, therefore, additional calculations were used to assess the overall risk score in the territories of elderships and cadastral areas according to the relative area (and their weight factor) of the different risk cells that fall within them. This resulted in a total risk score for solifluction in an administrative unit.

$$RIZIKA\_PROC = (Proc\_6*0/100) + (Proc\_6\_12*0.25/100) + (Proc\_12\_18*0.5/100) + (Proc\_18\_23*0.75/100) + (Proc\_23\_30*1/100)$$

Where: RIZIKA_PROC – total risk score for solifluction in an administrative unit;
Proc_6 is the percentage of areas (sum of cells) with very low total solifluction score value from the total area at risk of solifluction (%) per administrative territorial unit;
Proc_6_12 is the percentage of areas (sum of cells) with a low total solifluction score value from the total area at risk of solifluction (%) per administrative territorial unit;
'Proc_12_18' is the percentage of areas (sum of cells) with a moderate total solifluction score value from the total area at risk of solifluction (%) per administrative territorial unit;
'Proc_18_23' is the percentage of areas (sum of cells) with a high total solifluction score value from the total area at risk of solifluction (%) per administrative territorial unit;
Proc_23_30 is the percentage of areas (sum of cells) with a very high total solifluction score value from the total area at risk of solifluction (%) per administrative territorial unit.

Since the administrative territorial units are unequal in size and differ among themselves in the area of territories susceptible to solifluction, a correction factor is applied to the total solifluction score according to the occupied relative area of the potentially affected territories (as the share of the adm. territorial unit), thus obtaining the final risk score for solifluction.

*RIZIKA_PROC * (SOLI_AREA_SUM / shape_AREA)*

Here: RIZIKA_PROC – the total risk score for soliflution (obtained according to the order of calculations described above);
SOLI_AREA_SUM is the area (sum m^2) of an administrative territorial unit (eldership or cadastral area) *in which the areas/cells at risk of solifluction are distinguished;*
shape_AREA is the area of the administrative territorial unit (m^2).

6. *Assessment of the risk of solifluction according to the RCP scenarios of the future climate change.* The stages listed above describe the assessment of the risks of solifluction for the actual situation. At the same time, the described methodology (with all the steps and stages described) is also used to model the RCP (2.6, 4.5 and 8.5) climate change scenarios defined in the task. In this algorithm of actions, only the input data used in the design of the mentioned scenarios differ. When assessing the risks of future solifluction manifestations, the most important factors that will be affected by climate change are – the total number of days of negative temperatures (taken in 10 days) and the depth of soil freeze, as well as, in part, the amount of precipitation during the cold period (November-March) (this indicator is more important for the process of solifluction itself taking place).
According to the data of the last *30 years* (available at the Lithuanian Hydrometeorological Service), the depth of soil freeze in Lithuania is rapidly decreasing. This is also demonstrated by the data from multi-year observations of several measuring stations presented below (Figs. 12-15).

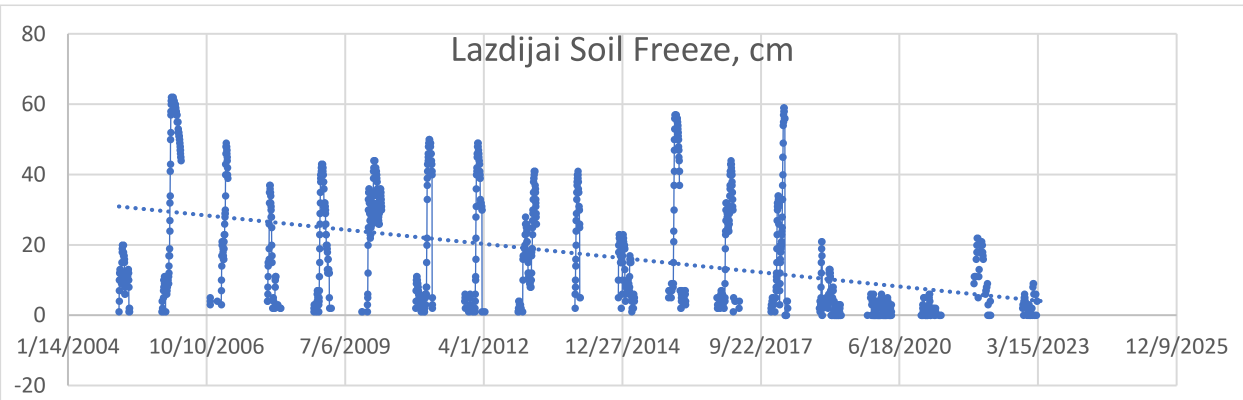


Fig. 12. The dynamics of the depth of soil freeze measured in Lazdijai in the period 2004-2023

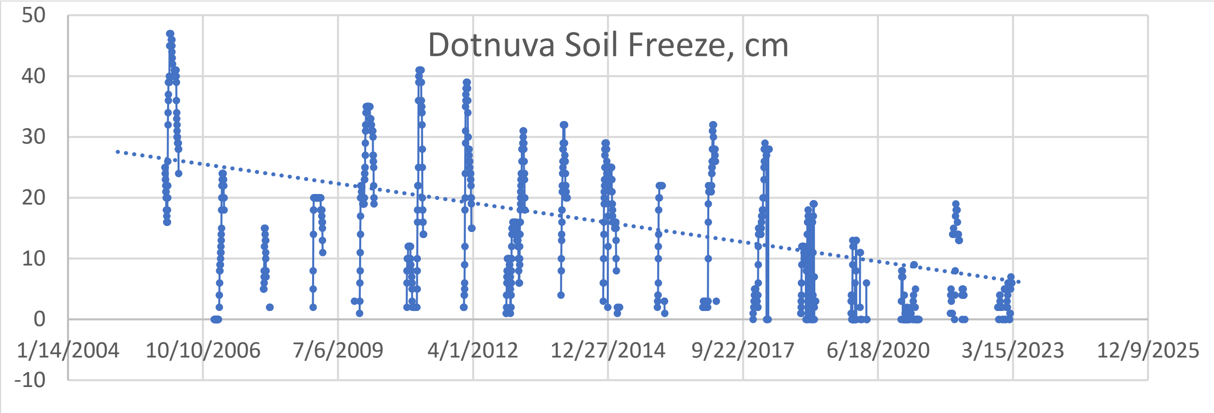


Fig. 13. The dynamics of the depth of soil freeze measured in Dotnuva in the period 2004-2023

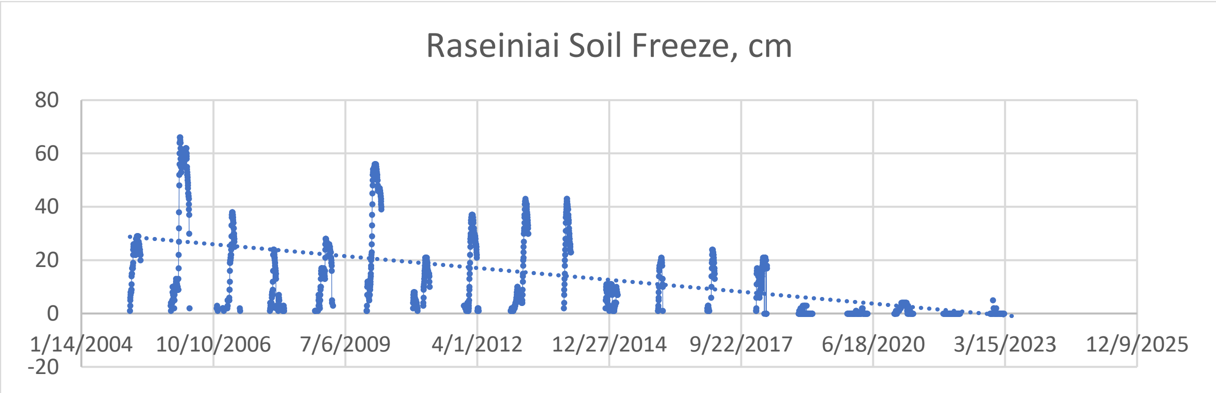


Fig. 14. The dynamics of the depth of soil freeze measured in Raseiniai in the period 2004-2023

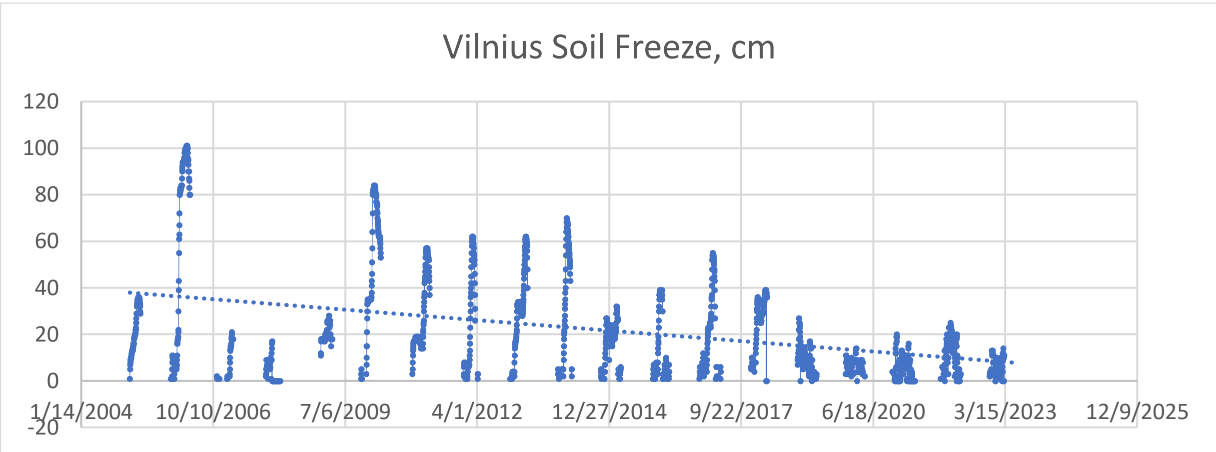


Fig. 15. The dynamics of the depth of soil freeze measured in Vilnius in the period 2004-2025

However, no quantitative forecasts of future soil freezes (including according to RCP scenarios) have been made either in Lithuania or in Europe. The further decrease in soil freeze can be guessed by another indicator that is directly related to this phenomenon, namely the sum of days of negative temperatures (taken within 10 days). For this indicator, as well as for the amount of precipitation during the cold period (November-March), the data from the RCP scenarios of the COPERNICUS data centre were used to estimate future forecasts for the period 2060-2070. The characteristics of the data and their characteristics are presented in Table 20.

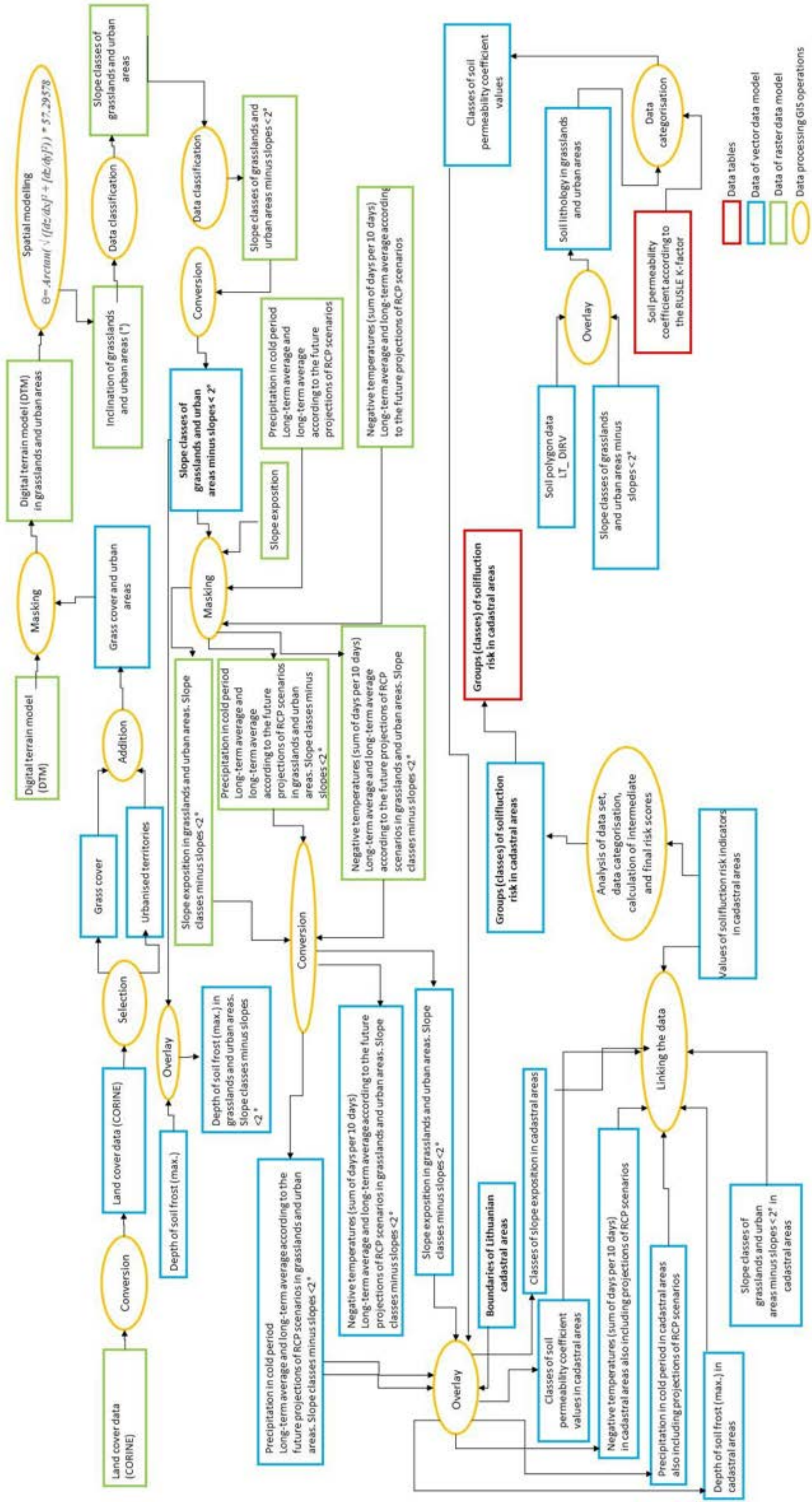


Fig. 16. Sample logical diagram of GIS modelling of the solifluction process (prepared on the example of cadastral areas and the actual situation; the process of assessing risks under RPC scenarios is repeated by changing the input data)

2.2.4. Explanation of the solifluction risk final metadata and risk score values

The final solifluction risk scores calculated based on the above methodology within the final layers of the solifluction risk under the climate change RCP scenarios 2.6, 4.5 and 8.5, as well as the data tables. They are presented in the GIS *shape* layers of the boundaries (polygons) of elderships and cadastral areas named "KADASTRINES_VIETOVES_SOLIFLIUKCIJA_RIZIKA" and "SENIUNIJOS_SOLIFLIUKCIJA_RIZIKA". The results are also exported into .xls tabular format (files "KADASTRINES_VIETOVES_SOLIFLIUKCIJA_RIZIKA_table" and "SENIUNIJOS_SOLIFLIUKCIJA_table").

In the GIS data layers, each administrative territorial unit (all elderships and cadastral areas) is assigned the values of risk scores according to climate change scenarios (RCP 2.3, 4.5, 8.5), they are presented in the columns "RIZIKA_26", "RIZIKA_45", "RIZIKA_85" of the attribute table. The attribute data table also contains other information, which is further explained in the examples of the data layer tables as given bellow (Tables 21 and 22).

Table 21. Fragment of the solifluction risk GIS shape layer table at the eldership level and explanation of the information in the columns

Unique eldership code no.	*Unique. Code no of the administer. territorial unit.*	*SHN code*	*ISN code*	*Name of the eldership*	*Type of self-government of the eldership*	*Perimeter of the eldership*	*Eldership area*	*Risk score in RCP scenario 8.5*	*Risk score in RCP scenario 2.6*	*Risk score in RCP scenario 4.5*
FID_ELDERSH	**FID_Admini**	**SHN**	**ISN**	**NAME**	**DESN**	**LENGTH**	**AREA**	**RISK_85**	**RISK_26**	**RISK_45**
1	1	LT032100	4504	Klaipeda	City municipality	77110,88308	88316869,51	0,011	0,012	0,012
2	2	LT032300	4505	Neringa	Municipality	100541,5833	89452356,87	0,000	0,000	0,000

Table 22. Fragment of the solifluction risk GIS shape layer table at the level of cadastral areas and explanations of the information in the columns

Unique cadastral area code no.	*Area code*	*Name of the area*	*The name of the municipality to which the locality belongs*	*The perimeter of the cadastral area*	*The area of the cadastral area*	*Risk score in RCP scenario 2.6*	*Risk score in RCP scenario 4.5*	*Risk score in RCP scenario 8.5*
FID_CADAST	**AREA_CODE**	**AREA_NAME**	**MUNICIPALI**	**LENGTH**	**AREA**	**RISK_26**	**RISK_45**	**RISK_85**
1	3601	Anciškės	Biržai district.sav.	37049,42878580000	44310520,23	0,003	0,003	0,003
2	3603	Anglers	Biržai district.sav.	38103,75099400000	38418902,54	0,001	0,001	0,001
3	3604	Biržai mst.	Biržai district.sav.	30293,80337050000	17822483,75	0,000	0,000	0,000

Table 23. Intervals of final solifluction risk scores and risk classes

Risk	Risk Score
None	0
Very low	> 0 < 0,25
Low	> 0.25 < 0.5
Moderate	> 0.5 < 0.75
High	> 0,75 < 1
Very high	1

The final scores obtained for the risk of solifluction in the data layers and data tables provided after the normalization procedure performed (after calculating the correction factors) include the range of values between 0 and 1. These values are divided into 6 classes. Separately distinguished areas where there are no solifluction risks, the remaining values are divided into 5 ranges representing groups of very low, low, moderate, high and very high solifluction risk (Table 24).

2.3. Results of modelling solifluction risk predictions according to RCP scenarios (2.6, 5.4, 8.5)

Solifluction is not a typical process that often takes place in Lithuanian climatic conditions (it is described in more detail in section 2.1). This phenomenon can be observed in certain localities of a small area that are not widely spread. It is therefore not surprising that only very low risk values were identified when assessing the risk of occurrence of solifluction in relatively large territories (administrative territorial units). The intensification of the phenomenon of solifluction requires wet conditions in a cold climate (with periods of warmer weather). We will not have such under the RCP scenarios in the future, so the growth of solifluction risks is not expected to be observed in the future.

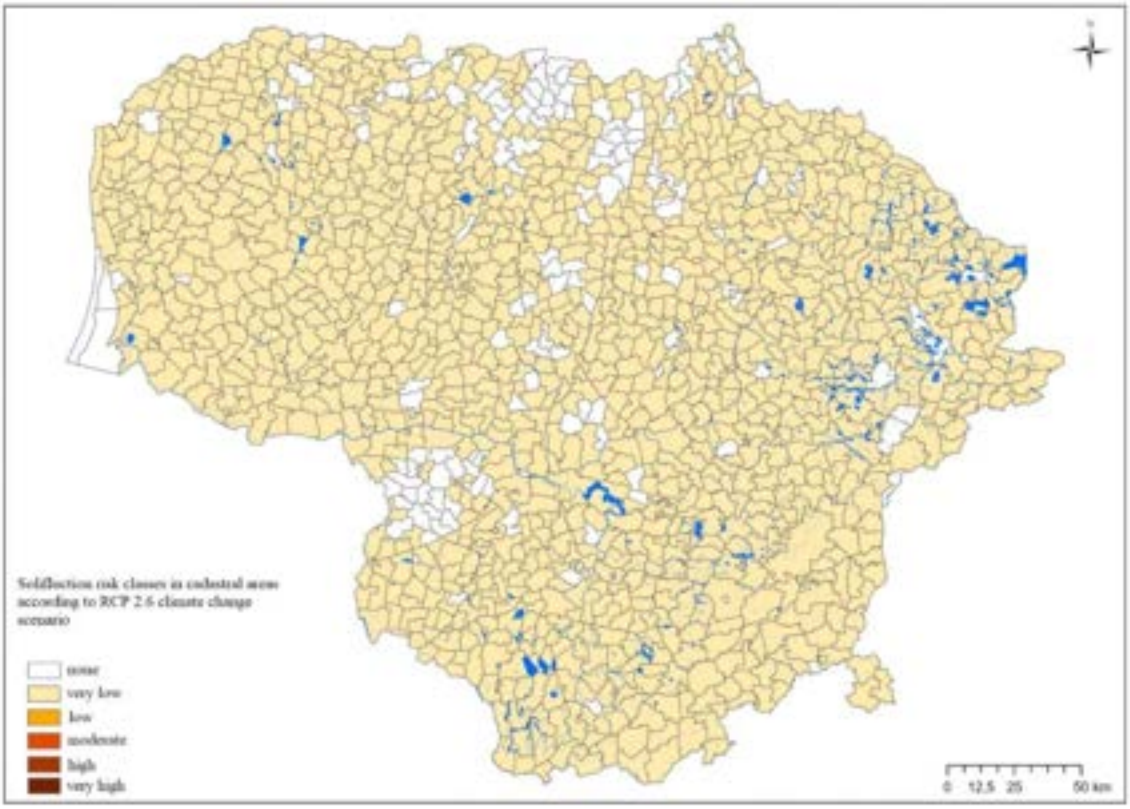


Fig. 17. Solifluction risk classes in cadastral areas according to RCP 2.6 climate change scenario

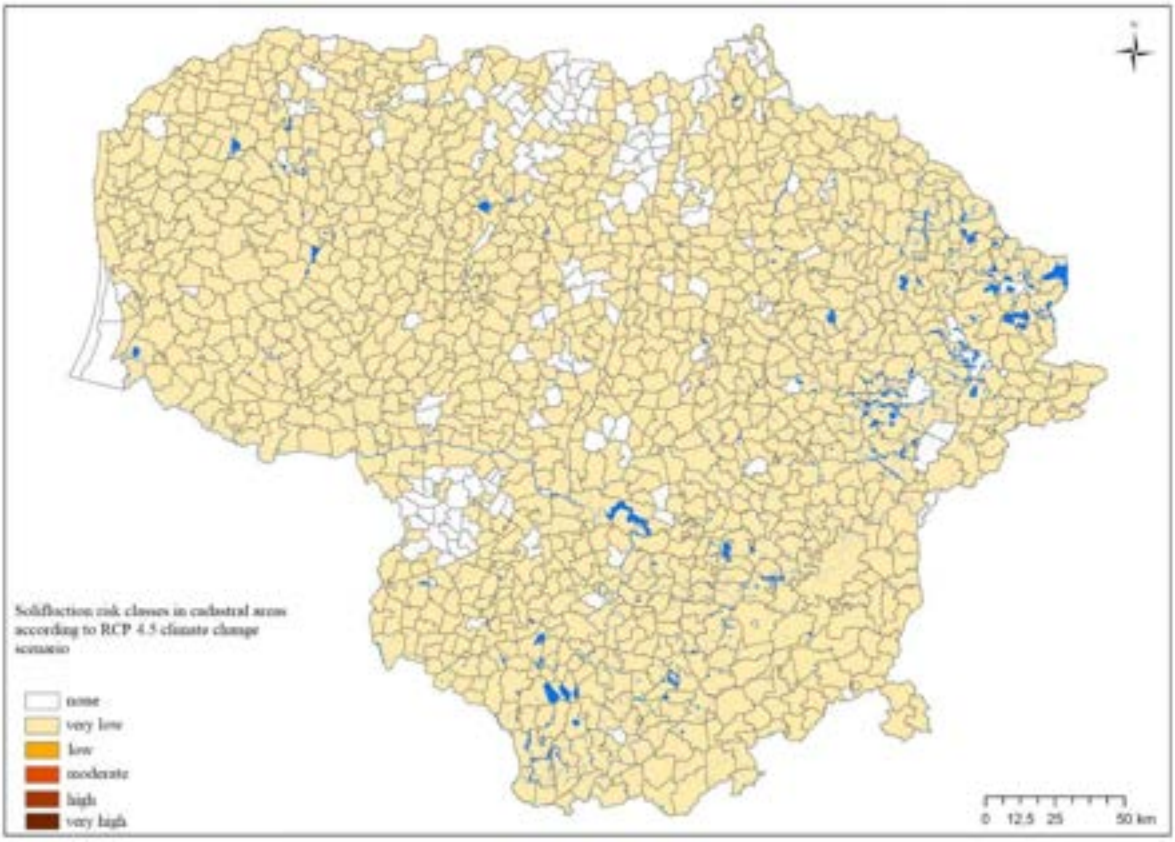


Fig. 18. Solifluction risk classes in cadastral areas according to RCP 4.5 climate change scenario

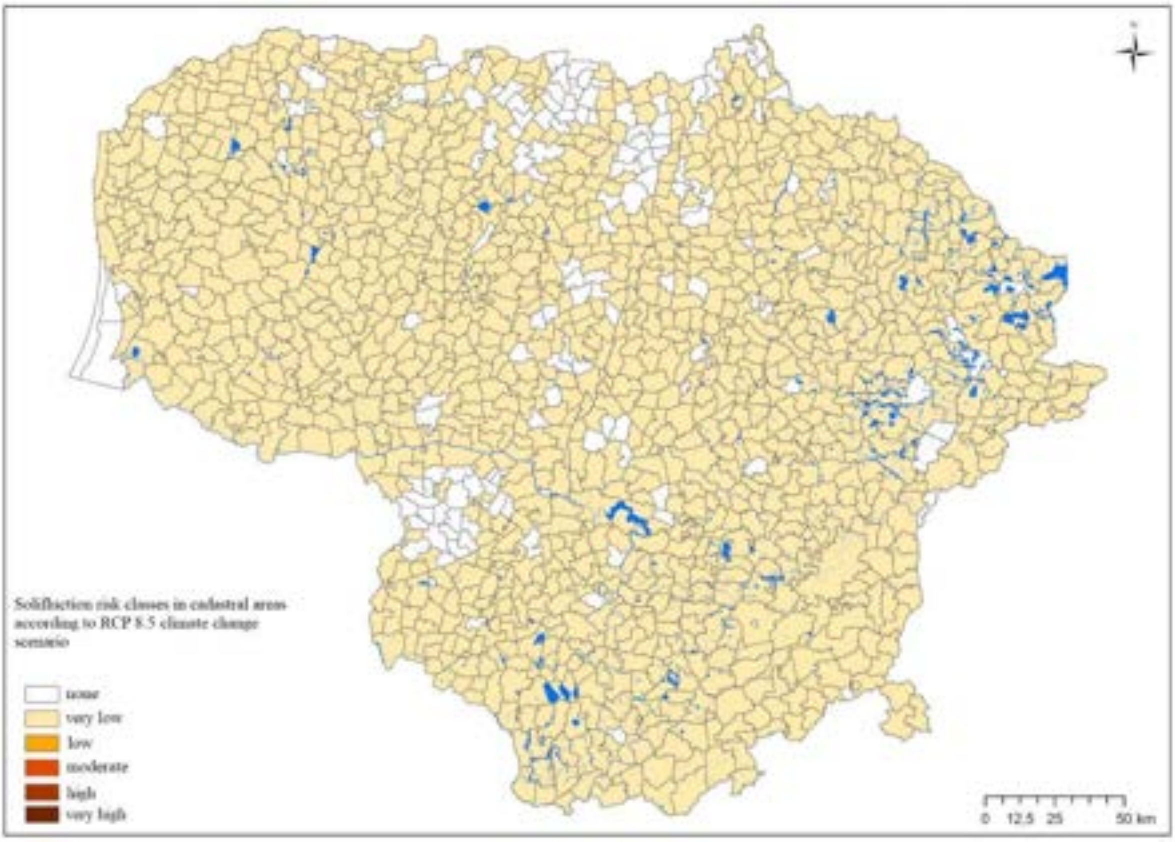


Fig. 19. Solifluction risk classes in cadastral areas according to RCP 8.5 climate change scenario

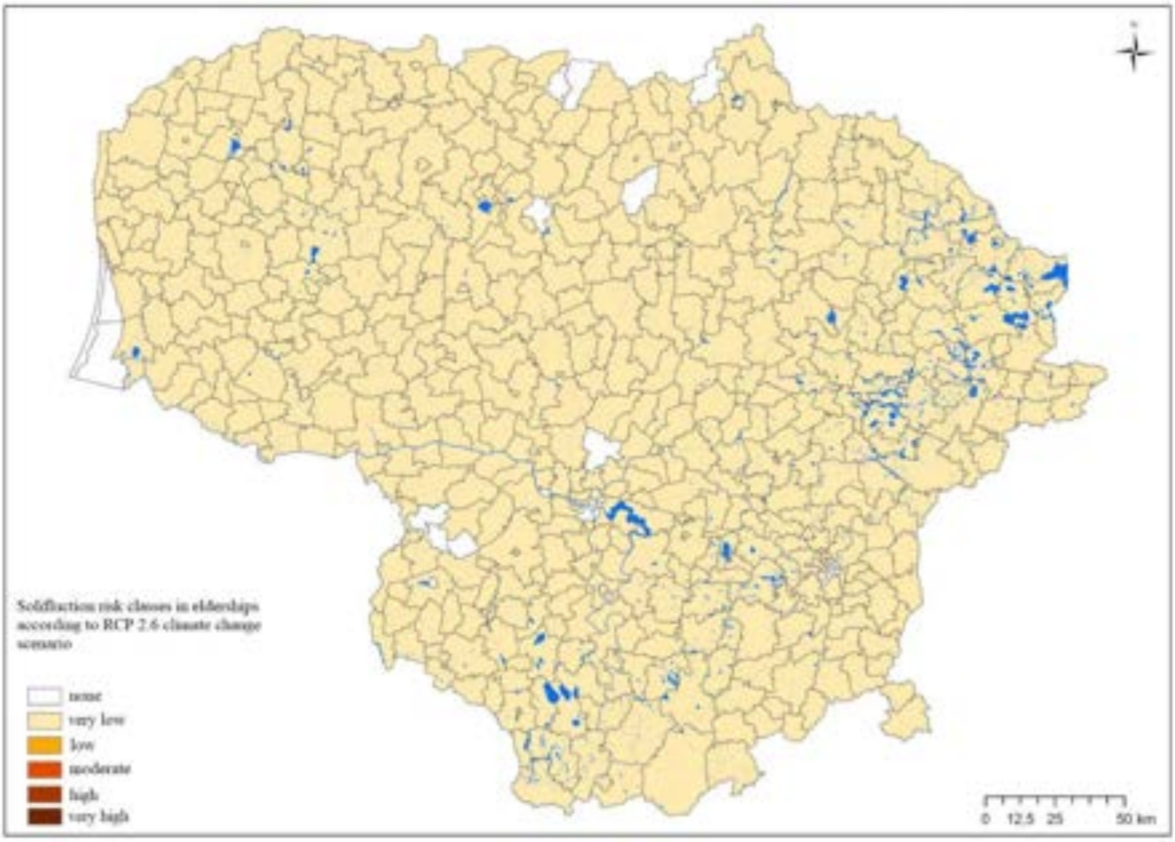


Fig. 20. Solifluction risk classes in elderships under RCP 2.6 climate change scenario

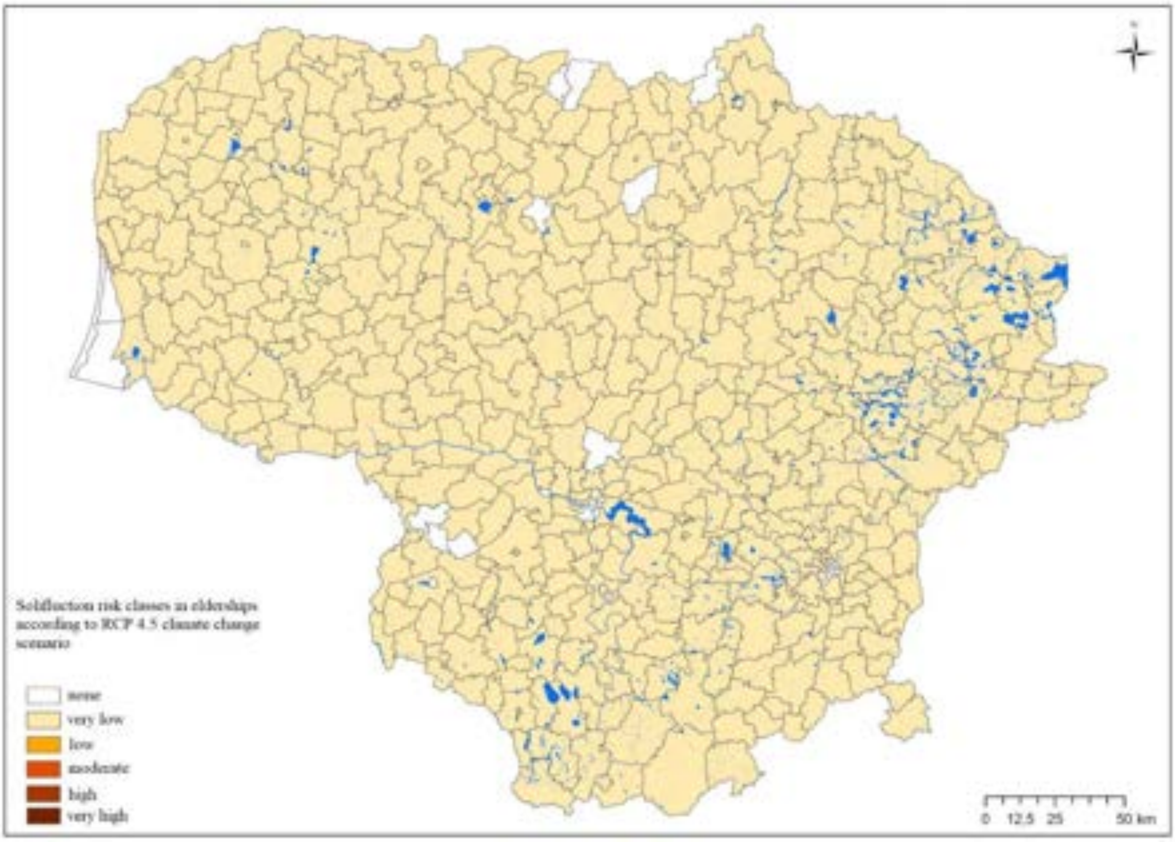


Fig. 21. Solifluction risk classes in elderships under RCP 4.5 climate change scenario

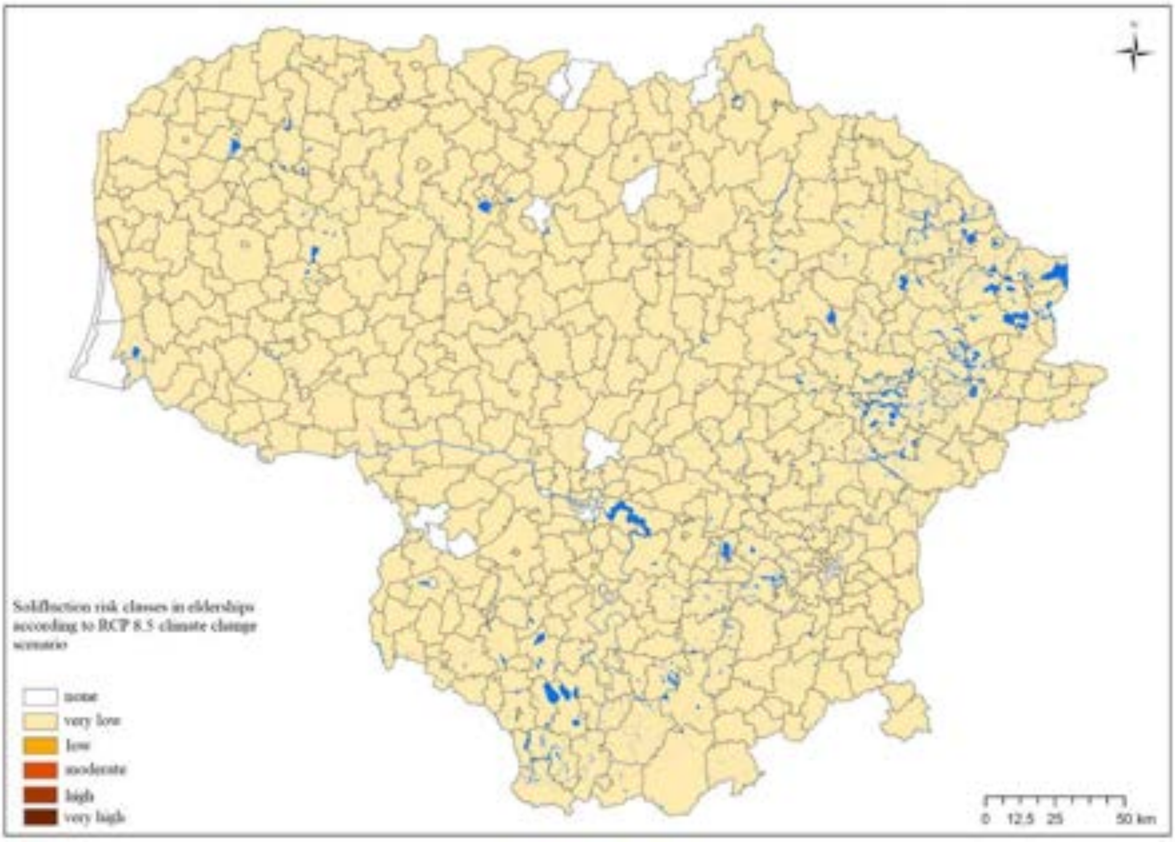


Fig. 22. Solifluction risk classes in elderships under RCP 8.5 climate change scenario