Methodology approaches for geoecological assessment of pollution migration in the "historical waste landfill-environment" system

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Abstract. The assessment of pollution migration in the "historical waste landfill-environment" system requires a comprehensive methodology that integrates various geoecological approaches. This involves understanding the interactions between landfills and their surrounding environments, utilizing advanced modeling techniques, and assessing the risks posed by leachates. The studies outline key methodologies and integrated approaches for effective geoecological assessment: geobotanical survey, lithogeochemical survey, biogeochemical survey, soil-geochemical studies, and mathematical modeling. The importance of integrating biological indicators into the geoecological assessment of historical landfill sites is emphasized. The article presents the results of research conducted between 2014 and 2024, and characterizes migration flows of pollutants and potential for self-restoration of ecosystems. The results demonstrate that a comprehensive approach, which integrates data on flora and soil biota, enhances the accuracy of forecasting long-term environmental consequences. This research provides an important basis for developing effective bioremediation and phytoremediation strategies and for rising awareness of the ecological risks associated with historical landfills.

1 Introduction

The Sortavala district in the Republic of Karelia has unique natural and recreational potential, but it faces serious problems with municipal solid waste (MSW) management [1-3]. The lack of a proper waste management system threatens the region's ecosystem, especially since the district is located near the water bodies of Lake Ladoga basin, a UNESCO World Heritage site. There are many landfills and dumps for MSW, which are at different stages of their life cycle and vary in terms of morphological composition, volume of waste, area, height, and tightness [4]. These facilities are widespread and take up a significant amount of space. The disposal of MSW leads to long-term emissions of pollutants and the irreversible loss of valuable resources [5]. In 2014 and 2024, the main goal of the research was to conduct an ecological and geochemical assessment of the territories adjacent to the waste storage zones. The study focused on the secondary

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geochemical and biogeochemical halos of heavy metals such as Zn, Cu, Pb, Mn, Cr, Ni, and Co. The study focused on the ecological system of a municipal solid waste landfill in Sortavala, Republic of Karelia (Figure 1).

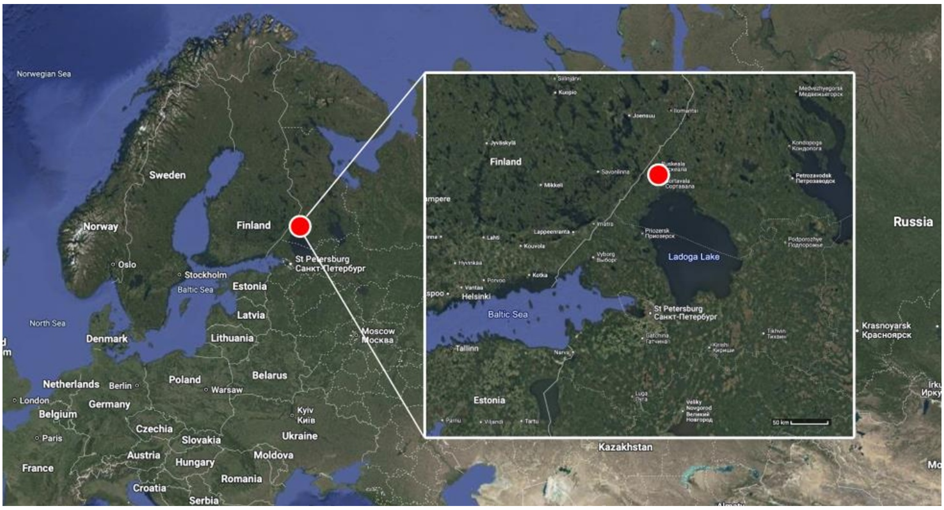

Fig. 1. Location of the research object - solid municipal waste landfill in Sortavala, Republic of Karelia, Russia.

The generally accepted approach to assessing the state of the natural environment involves collecting and analyzing information on the content of pollutants in its components, followed by comparing the analytically determined concentrations of these compounds to the regulated levels of maximum allowable concentrations (MAC) and/or estimated permissible concentration (EPC) [6]. However, due to the incompleteness of regulatory frameworks and the insufficient study of the overall impact of heavy metal complexes on biotic and abiotic environmental components, a promising methodology appears to be the combined use of geochemical and biogeochemical techniques for determining pollutant concentrations in environmental components.

To implement the described approach, the municipal solid waste landfill was considered as an ecological-geological system [6]: "storage zone (landfill body) - environment (adjacent territories) ". This system consists of abiotic elements of the lithogenic sphere, such as rocks and minerals, and biotic elements, including humans and other living organisms. These system components are interconnected and interact with each other to form a certain unity and integrity [7]. In such systems, the most important component is the natural-technogenic geological body, which is composed of technogenic soil that is biogeochemically active. The transformation of this soil leads to environmental pollution due to the release of liquid, gaseous, and solid waste products from the landfill site.

2 Materials and methods

The studied object is located approximately 15 kilometers from the city of Sortavala, in the Republic of Karelia. According to the city administration, this is an unauthorized waste facility that is not registered in the State Register of Waste Facilities (Figure 2). It is an unorganized dump site where various types of waste, mostly MSW, are deposited within a forested area. No waterproofing measures are in place for the storage areas, and the area covered by the dump is approximately 8 hectares. The depth of the waste ranges from 2.5 to 4.5 meters.

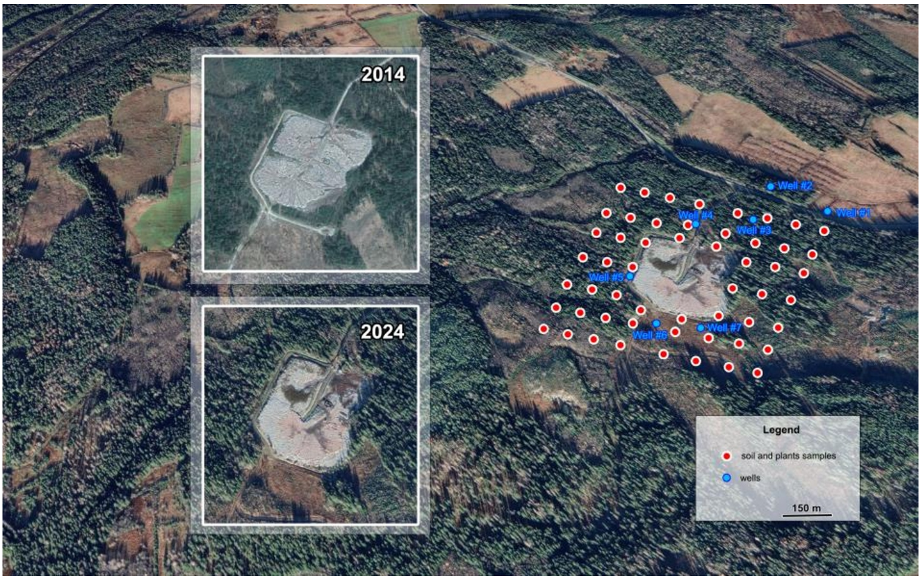

Fig. 2. Satellite images of the study area. Soil/plant sampling points and location of research wells for 2014-2024.

The area adjacent to the landfill site is partially marshy. In the southeast, there is a swamp with a shallow open water surface (maximum depth 0.5 m). There is also a flooded area in the north and northeast of the storage area. From the west, the landfill bordered directly on a stretch of coniferous forest. To assess the condition of this area, a 100 x 100 m grid was laid out and geochemical and bio-geo chemical surveys were carried out along it (Figure 2). Soil samples were taken and prepared in accordance with GOST R 58595-2019 government standard.

To conduct a comprehensive assessment of the geochemical conditions of the territory, we laid 6 soil sections and drilled 10 wells to a depth of up to 4 meters (7 wells in 2014 and 3 wells in 2024). We collected samples from the wells, layer by layer, every meter (0-1 meter, 1-2 meters, etc.) and from soil sections from identified horizons (Figure 3). We analyzed the samples for heavy metals (Zn, Cu, Pb) using a portable X-ray fluorescence (XRF) analyzer, Delta S1 TITAN^{SP}.

To assess the degree of polyelement pollution in the territories adjacent to storage zones, the Zc indicator was calculated using the following formula: $c = \sum \text{Kc}_i - (n-1)$, where Kci is the concentration coefficient of each element, and n is the total number of elements whose concentration coefficients are greater than 1. According to existing regulations, soil with a Zc value of less than 16 is classified as "permissible" pollution, between 16 and 32 as "moderately hazardous", between 32 and 128 as "hazardous", and more than 128 as "extremely hazardous".

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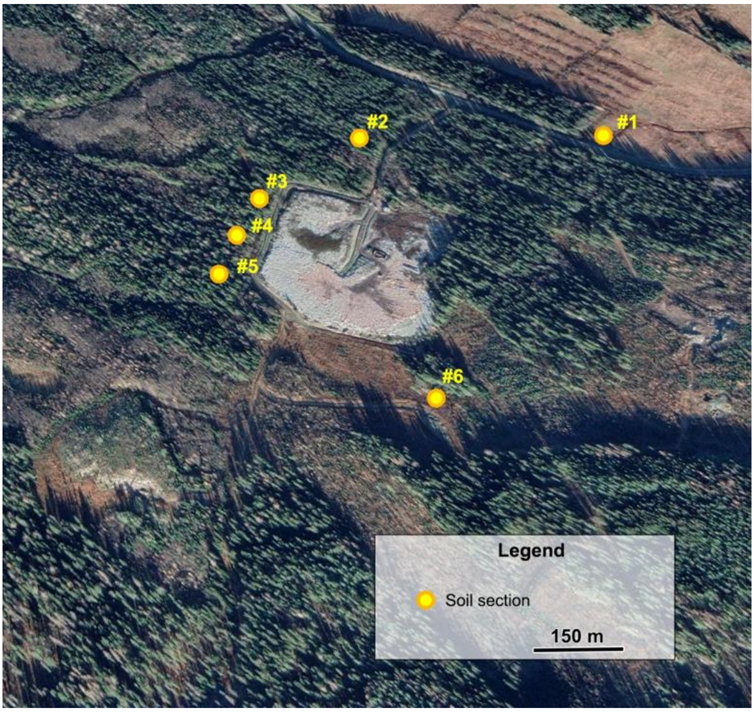

Fig. 3. Scheme of the location of soil sections.

This indicator is used in its modernized form (Vodyanitsky, 2009), classified according to the hazard classes of the elements used in the calculation. The toxicity (and hazard) degree of heavy elements varies, depending on their chemical properties. In accordance with GOST R 70281-2022, heavy metals and metalloids are divided into three hazard classes:

Class I (toxicity coefficients Ct=1.5) - As, Cd, Hg, Se, Pb, Zn, Cr;
Class II - (toxicity coefficients Ct = 1.0) - Co, Ni, Mo, Cu, Sb;
Class III - (toxicity coefficients Ct = 0.5) - Ba, V, W, Mn, Sr.

Using toxicity correction factors in calculating the total pollution index (Zct), it was calculated using the formula: $Z_{CT} = \sum(\mathrm{Cc}_i \times \mathrm{C}_{\mathrm{C}i}) - (n-1)$, where Cci is the concentration coefficient of the i-th element.

The concentrations in zonal soils located outside the area of local human impact were used as background values for calculating the concentration ratios of the studied elements. To describe the geochemical characteristics of the soils and grounds in the study area, we calculated a radial differentiation index, which shows the ratio of the concentration of a chemical element in a soil horizon to its concentration in the parent rock. This index is used to analyze vertical heterogeneity in chemical composition, by comparing the concentrations in soil horizons with the concentration in the horizon of the parent rock.

2.1 Bioindication assessment

Bioindicator assessment of the condition of the territories adjacent to the storage areas was conducted using an accumulative phytoindicator method. Silver birch (Betula peudula) and Norway spruce (Pícea ábies) were selected as indicators, taking into account their availability and sampling possibilities. Samples were taken from birch leaves from at least 10 trees in the extrapolation area, and annual spruce shoots were collected simultaneously with soil samples. The analysis of the concentration of heavy metals (Zn, Cu, Pb, Mn, Cr, Co, Ni) in the soil was conducted using the Delta S1 TITAN^{SP} XRF analyzer. An important criterion for assessing the significance of plants participating in biogeochemical processes in contaminated areas is the biological accumulation coefficient (BAC) for metals in the soil-plant system [8]. This coefficient is calculated using the formula: BAC = A/B, where A represents the metal content in plant biomass and B represents the total metal concentration in the soil.

Both selected plant species were represented by approximately the same number of observation points in 2014 (34) and 2024 (38). As a result of this work, a total of 56 samples were collected from the surface soil layer and 78 plant samples were obtained.

3 Results and decisions

3.1 Geobotanical survey

Geobotanical descriptions of environmental factors were carried out in June-August 2014 and 2024 in accordance with generally accepted methods [6] at 54 points in the territory. Several communities were identified, and a diagram of their distribution across the study area was constructed (Figure 4):

1. A fresh blueberry spruce forest with birches on thin sandy soils with granite-gneiss outcrops. The parent rock is moraine sand. The forest is a fresh blueberry-spruce forest with a birch tree. The age of the forest is between 80 and 250 years old.

The forest stand formula is "8 spruce trees + 2 birch trees". In addition to Norway spruce (*Picea abies*), the forest stand also contains silver birch (Betula pendula) (12%), Scots pine (*Pinus sylvestris*) (4%), and trembling poplar (*Populus tremula*) (3%). The undergrowth includes mountain ash and prickly roses. The crown density is 0.7-0.8, with an average tree height of 21 meters and a diameter of 26 centimeters. There are 400 trunks per hectare, and the projective cover of trees is around 32%. The grass-shrub and moss-lichen layers are well-developed, accounting for about 60% and 35%, respectively. Above ground, sinuous meadow grass, common bilberries, wood reeds, and common forest sorrell (*Equisetum sylvaticum*) dominate, as well as true bedstraw (*Galium verum*) and club-shaped club moss (*Lycopodium clavatum*).

Above ground, sinuous meadow grass, common bilberries, wood reeds, and common wood sorrell, forest horsetail (*Equisetum sylvaticum*), true bedstraw (*Galium verum*) and club-shaped club moss (*Lycopodium clavatum*) dominate. The soil is superficially podzol.

2. A severely disturbed spruce forest, dominated by bilberry, on thin morainic loam represents a remnant of a spruce forest near the foot of a granite-gneiss dome. The underlying parent rock is morainic soil. At a depth of 1.2 - 1.5 meters, morainic deposits underlie granite-gneiss rock. This forest can be classified as a young spruce-bilberry forest. The stand composition is “8 spruce trees + 1 birch tree”, and the age of spruce trees (*Picea abies*) varies from 100 to 120 years. Understory vegetation is abundant and includes mountain ash (*Sorbus aucuparia*), silver birch (*Betula pendula*) and common juniper (*Juniperus communis*). Ground cover is almost entirely green moss, with some bilberry (*Vaccinium myrtillus*) and lingonberry (*Vaccinium vitis-idaea*), may lily (*Maianthemum bifolium*) and meadowgrass (*Deschampsia flexuosa*). Within the test plots, ground vegetation is uniform and has been heavily disturbed by intensive trampling.. The area is heavily littered with soils that are sandy loams, podzols, and illuvial iron-humus gleyed.

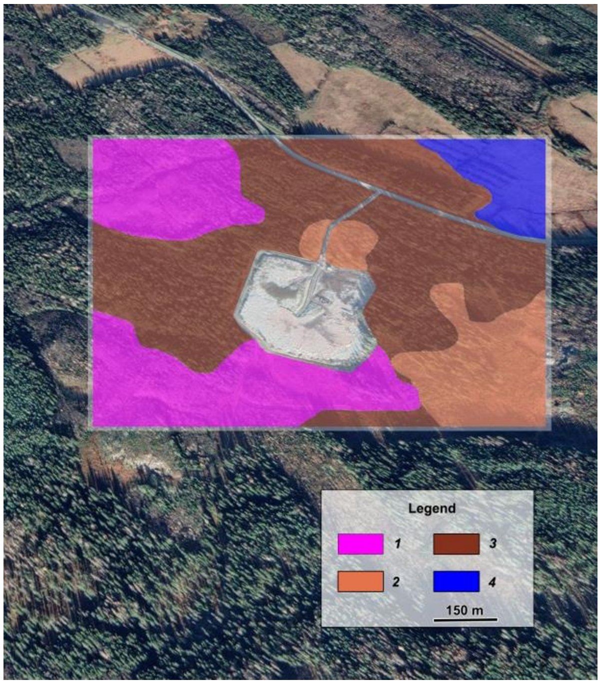

Fig. 4. Distribution pattern of plant communities in the study area: 1 – fresh blueberry spruce forest with birch on thin sandy loam; 2 – fresh blueberry spruce forest with birch on thin sandy loam, heavily disturbed; 3 – fresh blueberry spruce forest with pine on thin boulder moraine; 4 – secondary meadow-forest phytocenoses.

3. A fresh bilberry spruce forest with pine is located on a thin boulder moraine. The parent material consists of silty-sandy boulders. The forest itself is defined as a fresh spruce bilberry forest with a pine component. The trees in the forest are 155 to 190 years old and have a stand formula of "8 spruce trees + 2 pines+ 1 birch tree". Norway spruce is the dominant tree species (*Picea abies*), accounting for 76% of the total stand. There are also some deciduous tree species, such as silver birch (*Betula pendula*) and downy birch (*Betula pubescens*), accounting for about 21%. Pines (*Pinus sylvestris*) account for only 3%. Overall, the projective tree cover in this forest is very high, at approximately 80%. Grasses and shrubs make up 29% of the ground cover, while mosses and lichens account for 17%. There are a total of 1,133 tree trunks per hectare, and common bilberries dominate the ground cover. There is also a significant amount of mayflower (*Maianthemum bifolium*) and common wood sorrel (*Oxalis acetosella*), with little wood reed grass (*Calamagrostis arundinacea*) and sinuous meadow grass (*Deschampsia flexuosa*). Of the ferns, the three-part fern (*Gymnocarpium dryopteris*), grows abundantly. The lower tier is exclusively occupied by green mosses, especially *Hylocomium*. The average height of the trees is 17 meters, and the average diameter is 26 centimeters. The soils are podzolic podburs, and there are abundant outcrops of granite-gneiss bedrock.

4. Secondary meadow-forest phytocenoses are characteristic of the middle taiga in Karelia. The study area is an old spruce forest clearing (*Picea abies*), which has been at the stage of restoration for 5-10 years. Dominant species in the grass-dwarf shrub layer include cereals (*Calamagrostis epigejos* (ground reed grass) - 25-40% area coverage), *Deschampsia flexuosa* (sinuous hair grass) - 15-25% area coverage), forbs (*Chamerion angustifolium* (narrow-leaved fireweed) - 10-20% area coverage), *Rubus idaeus* (common raspberry) - 5-15% area coverage), *Trientalis europaea* (European starflower) (3-8% area coverage), moss-lichen cover (*Pleurozium schreberi*) - in patches up to 10% and *Cladonia rangiferina*

(deer cladonia) – locally). According to Ramenskaya's classification (1983), the phytocenosis corresponds to the *Calamagrostis epigeios–Chamaerio angustifolia* association, which is characteristic of freshly cleared areas in Karelia. A transition stage from a ruderal community to a young deciduous spruce forest is observed, and the soils are podolic with signs of initial sod formation.

3.2 Lithogeochemical survey

In the geoecological assessment of the state of the "landfill - adjacent territories" system, the content of heavy metals (Zn, Cu, Pb, Mn, Cr, Ni, Co) in the components of the surrounding natural environment was chosen as the main parameter of pollution (Venkata Ramaiah et al. 2014; Popovych et al. 2020) [4]. The ranges of the contents of these elements in soil established during studies are presented in Table 1.

Data analysis shows that the contents of the main metals in surface layers of soils decreased in 2014 in the following order: Mn > Cu > Cr > Ni > Zn > Pb > Co. According to the variation in content (%): Cu (46) > Zn (45) > Pb (35) > Ni (30) > Co (28) > Mn (27) > Cr (27).

Table 1. Results of the 2014 and 2024 survey of the surface soil layer of adjacent territories of the solid municipal waste landfill storage zone (mg/kg).

Heavy metals	Background	Median	Min	Max	Std. dev.	Coefficient of variation, %
2014						
Zn	40	66.5	24.5	120.5	16.6	45
Cu	18	113	14.5	124.5	26.7	46
Pb	15	50.5	7.5	77	15.4	35
Mn	250	837.5	212	917	47	27
Cr	30	87	59	102	12.9	27
Ni	27	68.5	46.5	83	7.5	30
Co	20	16.5	11.5	24	3.3	28
2024						
Zn	40	89	23	1041	174.1	105
Cu	18	144.2	13	1580	478.6	120
Pb	15	70.1	11.5	293	48.8	77
Mn	250	892	568	2050	398.9	37
Cr	30	93	24	176	53.1	43
Ni	27	84.7	19.5	621	86.3	56
Co	20	37	5	120	22	45

The median values of the content of the elements studied in 2014 were higher than the background levels for zinc by a factor of 1.7, copper by a factor of 6.3, lead by a factor of 3.4, manganese by a factor of 3.4, chromium by a factor of 2.9, and nickel by a factor of 2.5. The background level of cobalt in soil was not exceeded in the median values of our sample. Statistical analysis of the data showed that 75% of the samples for all elements exceeded the background levels by several times (see Table 1), indicating a medium to high level of technogenic pollution near the landfill site. The analysis of variation coefficients revealed relatively low variation among most elements, indicating heterogeneity within the group of samples for Zn, Pb, and Cu. The highest variations were observed for copper and zinc, which may indicate their constant input into the soil.

The 2024 lithogeochemical survey data demonstrate an increase in the intensity of the load due to contributions from all components. The average content of all elements exceeds regional background concentrations and the median values established for the 2014 samples. It is important to note that the distribution according to average content (Mn > Cu > Cr > Zn > Ni > Pb > Co) remains almost the same, indicating that the qualitative composition of the technogenic load has not changed, i.e., the source of impact remains the same.

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The most significant contribution to the system is related to the distribution of certain elements, including Zn, Cu, Pb, and Ni. This can be seen in a diagram illustrating the variation in the concentration of these elements in samples collected in 2014 and 2024 (see Figure 5).It is important to note that the natural "distribution pattern" is traced only for manganese, any other elements and their contents are most likely associated with technogenic activity, such as waste disposal.

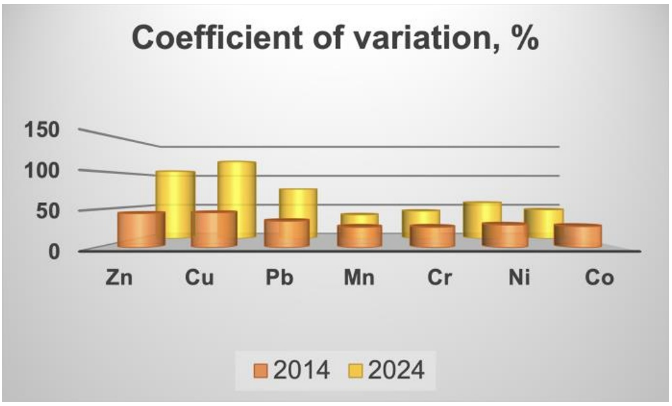

Fig. 5. Variation coefficients for the 2014 and 2024 samples.

The distribution pattern of total pollution index (Zc) on the territory adjacent to MSW storage areas in 2014 (Figure 6) indicates that soil pollution does not exceed moderately hazardous levels (Zc 16-32). Areas with Zc above 16 are located along the perimeter and southeast of the landfill, consistent with the slope and direction of surface and groundwater movement towards Lake Ladoga's water area [9]. Another possible impact direction is northwest, towards an unnamed stream that is part of the Tohmajoki river system, the distance to which exceeds 350 metres.

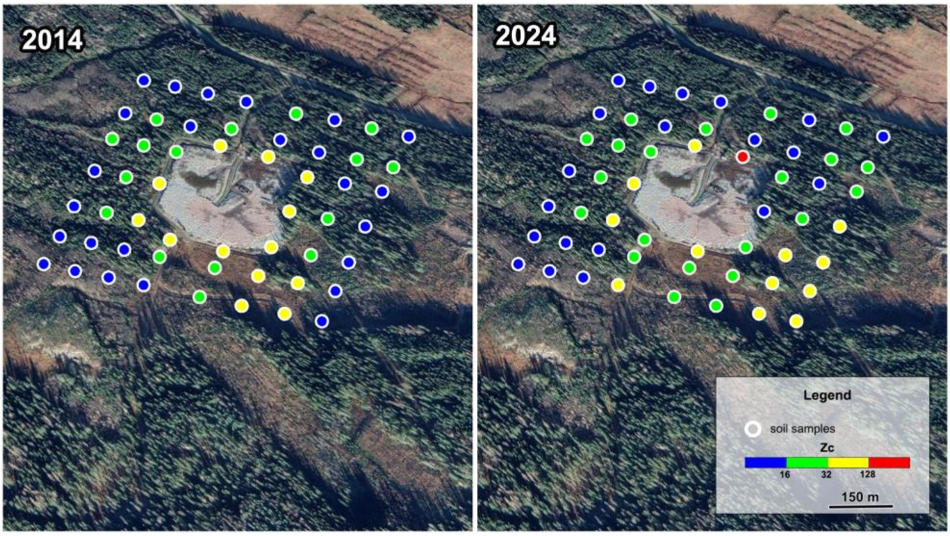

Fig. 6. Distribution diagram of the Zc indicator in the surface soil layer (left – 2014, right – 2024).

According to the calculation of the distribution of values of the total pollution indicator for the 2024 sample, an increase in the total complex load on adjacent territories can be observed. It is worth noting especially the appearance of clear boundaries of dispersion element contents halo in the southeast direction from the storage zone boundaries and the increase in its gradient. No increase in intensity and area pollution in the northwest direction has been recorded, which indicates the formation of a stable, low-gradient, polyelement anomaly that has existed virtually unchanged for 10 years. This may be explained by the presumed time of pollution associated with the initial period of landfill existence.. There is unconfirmed documented information from employees and local residents that, during the initial period of operation, this facility did not have a storm water and thalassic water collection system located along the perimeter of the storage zone. Therefore, surface runoff could spread in any direction associated with the orographic features of the territory. This conclusion confirms the assumption made during the analysis of lithogeochemical and biogeochemical survey data in 2014-2016.

3.3 Biogeochemical survey

To assess the intensity of bioaccumulation of heavy metals in plant tissues, two types of woody vegetation were selected: silver birch (*Betula pendula*) and Norway spruce (*Picea abies*).

The biogeochemical features of Betula pendula in the Republic of Karelia are associated with the accumulation of heavy metals in the organs and tissues of the tree. Leaves accumulate Mn and Zn to the maximum extent (up to 500 and 1500 mg per kg, respectively), which is related to their physiological role in photosynthesis. Cu and Pb accumulate less, at concentrations of 2-15 mg and 0.1-3 mg per kg respectively. The bark accumulates Pb and Cr, which are bound to organic compounds. Roots contain a high concentration of Ni and Co, with concentrations ranging from 5-30 and 0-10 mg per kilogram, respectively [10].

Biogeochemical features of Picea abies: needles, accumulation of Mn (100-300 mg/kg) and Zn (20-80 mg/ kg); low Pb levels (< 1 mg/ kg) – small surface area for deposition; bark concentrates Cu (10–30 mg / kg) – protection from pathogens wood has minimum HM contents (Cr <1 mg /kg) – xylem inertness [10].

Analysis of selected plant species in 2014 showed a positive correlation between elevated concentrations of heavy metals in the soils adjacent to a storage area and their contents in plant organs, such as annual shoots of spruce trees and birch leaves. The correlation was on average about 0.4.

In most tests, the concentration of heavy metals decreased in the order Mn>Cu>Cr>Zn>Ni>Pb>Co for birch and spruce (Table 2). This corresponds to the general trends established for soils (Table 1) [11].

Table 2. Average heavy metal content in plants (2014/2024) (ppm).

Plant species	Zn	Cu	Pb	Mn	Cr	Ni	Co
Betula pendula	33.3 / 363.9	49.9 / 21.9	23.7 / 5.1	412.8 / -	36.1 / -	27.4 / -	6.2 / -
Picea abies	19.6 / 54	33.5 / 31.3	14.1 / 12.5	270.2 / 224	21.8 / -	15.7 / -	3.4 / -

It is easy to see from the table that, for such elements as Cu and Pb, an increase of 1.5 times and 2.5 times in their average content was recorded over a 10-year period.

According to the analysis of data from 2014 and 2024, it has been revealed that in most areas surveyed, the values of the biological absorption coefficient vary within relatively narrow limits (see Table 3). The standard deviation of this coefficient is used as the main indicator for selecting plants for biogeochemical research, as the effectiveness of these studies depends on consistency in the value of this biological parameter.

Table 3. Biological accumulation coefficients (ppm).

Heavy metals	Median	Std. dev.*	Range of variation	Lower quartile 25%	Upper quartile 75%
Picea abies					
Zn	0.31	0.06	0.23	0.27	0.35
Cu	0.3	0.06	0.22	0.26	0.34
Pb	0.28	0.05	0.19	0.24	0.31
Mn	0.33	0.09	0.45	0.31	0.37
Cr	0.26	0.05	0.19	0.22	0.29
Ni	0.24	0.05	0.26	0.21	0.27
Co	0.21	0.04	0.16	0.19	0.24
Betula pendula					
Zn	0.53	0.13	0.72	0.45	0.6
Cu	0.44	0.09	0.38	0.38	0.5
Pb	0.47	0.1	0.4	0.41	0.54
Mn	0.5	0.1	0.37	0.43	0.56
Cr	0.41	0.08	0.32	0.36	0.47
Ni	0.4	0.08	0.29	0.35	0.46
Co	0.38	0.07	0.27	0.33	0.42

* The minimum values of standard deviations of various elements are highlighted.

Based on the analysis of the standard deviation values for indicator elements in MSW landfill sites (specifically, Zn and Cu), we have found that using silver birch (Betula pendula) as a bioindicator is more suitable for monitoring bioindication work in natural areas adjacent to storage zones in order to assess the level of pollution.

3.4 Distribution of Zn, Cu, Pb contents in wells

In the study area, 4 wells were drilled in 2014 and 3 wells were drilled in 2024. No monitoring studies were conducted between those years (i.e., there was not any repeated sampling at the same points).

In all boreholes up to the drilling depth (3.2-4.0 m), light to heavy loams were encountered with interlayers of light sand and medium-sized moist sand. The piezometric level in most wells was not determined. An exception was well #6, where a level of 1.2 m was determined. The aquifer in the area is composed of granite gneiss, which was opened by several wells at depths of 2.5 to 3 m. To characterize the radial distribution of Zn, Cu and Pb in soil, concentration coefficients were calculated according to data from 2014 and graphs were plotted based on sampling depth (Figure 7).

When analyzing the distribution graphs, we can see that in wells #3, #4, and #5, the distribution patterns of metals are clearly visible. This is consistent with the "Goldschmidt enrichment" pattern, which describes an increase in metal content towards the surface due to biological accumulation and adsorption onto organic matter. However, in well 6, which is located on the edge of the local runoff accumulation zone with a stable groundwater level, there is an increase in the concentrations of certain metals associated with municipal solid waste (MSW) placement, such as Zn and Cu (Figure 7).

In 2024, three additional wells were drilled along the northwestern boundary of the storage zone (wells 1 and 2) and at a distance of 50 meters from the boundaries in the southeastern direction (well 7). Well 1 is located near a roadside ditch beyond the boundaries of the storage area. The total depth of well 1 is 2.5 m.

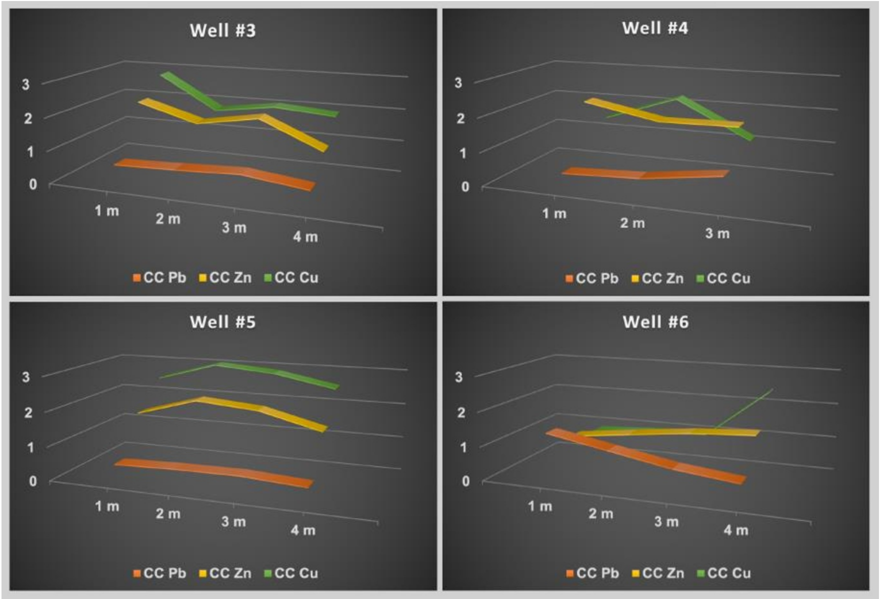

Fig. 7. Distribution of values of the degree of excess of the background level by depth (y-axis – concentration coefficient; x-axis – sampling depth, m).

The value of the radial differentiation coefficient for Pb and Cu in the upper layers of well 7 is less than one, indicating an insignificant anthropogenic contribution (biogenic accumulation) in this area, with natural processes dominating. Zinc tends to accumulate in the 1-2 meter horizon, possibly due to illuvial processes, and further accumulation down the profile. Well 1 lies within the boundaries of agricultural land (Figure 8). Similar patterns of Zn and Cu distribution were observed throughout northern Priladozhye on treeless farmlands for various purposes.

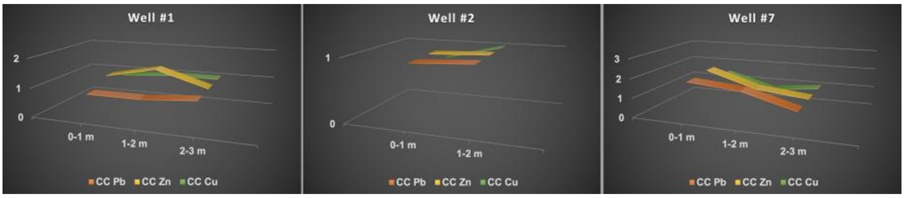

Fig. 8. Radial differentiation coefficients of Zn, Cu and Pb in wells.

In well #2, there is no accumulation of material in the upper layers of the soil, which may be due to favorable conditions for the development of the illuvial process and the absence of a water table (Figure 8).

Well #7 is located approximately 50 meters away from the boundary of the storage zone, in a south-easterly direction. It is situated on the border between the 5-10 year logging zone.

The geochemical conditions, based on the distribution of radial differentiation coefficients, are significantly different from those in boreholes 1 and 2. There is a clear accumulation of Zn, Pb, and Cu in the upper horizons (Figure 7), which can be attributed to the active anthropogenic influence, such as temporary flows of meltwater and rainwater from the municipal solid waste (MSW) storage area, which can be visually identified (Popovych et al. 2020).

Based on the analysis of data obtained from the distribution of zinc, lead, and copper in wells at different depths and from lithogeochemical surveys, it can be concluded that there are several areas where pollutants have accumulated locally (or where pollutants are likely to flow) as a result of activities at the MSW storage site.

3.5 Soil-geochemical studies

Soil profiles were located on the territory as shown in Figure 2. In 2014, profiles #1, #2, and #6 were completed. In 2024, profiles #3, #4, and #5 were also finished. The first profile was located near well #1 on reclaimed agricultural fallow land.

When describing an old arable sod-glei soil profile, four horizons were identified and tested using the standard method (see Figure 8). Concentration coefficients were calculated relative to background values and distribution graphs were created. Conducted distribution analysis revealed a typical situation for reclaimed agricultural land [7], with small accumulation of Zn and Cu in the soil and a uniform distribution of Pb throughout the profile, all within limits that do not exceed background values.

Soil profile 2 was located in an area where blueberry spruce forests grow on low-lying moraine boulders (Figure 3). At the border of a flooded area, characterized by the presence of non-woody vegetation, such as sphagnum mosses, the distribution of Zn, Pb, and Cu is similar to that in profile 1, but with a lower amplitude of difference from the background. Excesses of Zn and Cu in this area are within 1.1-1.3 times the background level, while there are no excesses of Pb throughout the entire profile.

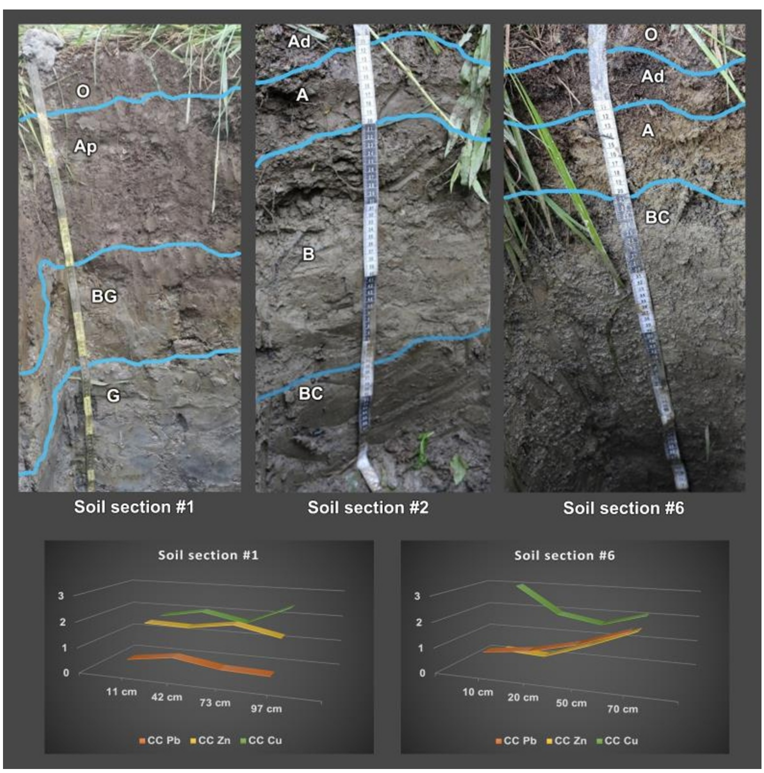

Fig. 9. Features of the distribution of Zn, Cu and Pb across soil horizons (y-axis – concentration coefficient; x-axis – sampling depth, m).

Section #6, located near well 7 on the border of a fresh blueberry spruce forest and birch forest on sandy loam, has a different depth distribution pattern. Clear indications of anthropogenic impacts and accumulation of MSW pollutants are recorded in the groundwater distribution zone. Excess background concentrations of pollutants at a depth of 0.7 m were observed, 2-3 times higher than the background level (Figure 9).

Fig. 10. Radial differentiation coefficients of heavy metals in sod-gley soils.

Based on the analysis of data on zinc (Zn), lead (Pb), and copper (Cu) distribution in boreholes and soil samples, it can be concluded that there is a zone of accumulation (or flow dispersion) located in the southeastern direction from the storage area boundary. This confirms the assumptions made during the initial lithogeochemical and biogeochemical surveys conducted in 2014-2016.

In 2024, three soil pits were dug along the northwest boundary of the storage area to further investigate the environmental conditions. (Figure 2). To determine the depth distribution of zinc, copper, and lead, sampling was conducted at ten centimeter intervals from the surface to the bottom of the pit (0-10 cm, 10-20 cm, and 20-30 cm). Minor excesses above background levels were found for zinc and copper in all sampling intervals, but no excesses were found for lead, allowing these results to be compared to those from 2014 (Table 2, Figure 9). Additionally, radial differentiation coefficients were calculated and diagrams created to identify the depth distribution of these metals in the soil of the study area (Figure 10).

Section #4 is located in an area with previously existing surface water overflows from the storm system and waste waters (filtrates) that exceed the storage area's boundaries. This is clearly reflected in the increased concentration of metals in the surface layers and their gradual decrease with depth.

This distribution pattern is typical of areas with acute and subacute pollution loads, where assimilative processes (self-cleaning) are active. Considering the established dynamics over the past 10 years, we can conclude that the overall recovery time is at least 20-25 years.

Sections 3 and 5 show similar patterns in the distribution of Zn and Pb by depth: there is a slight increase in the upper sampling horizons (up to 1.7) followed by a gradual decrease, with individual peaks towards the bottom of the sections. These features are probably associated with previous impacts and the modern assimilation of these contaminants.

An interesting pattern has emerged for the distribution of Cu in sections 3, 5 of 2024 and 6, 2014. This suggests that the form of entry of this metal into the environment is highly soluble and mobile in both natural and man-made environments in the northern Priladzhye region.

4 Conclusions

While the technogenic conditions of MSW dumps are critical for their operation, they also pose significant risks to water quality and aquatic ecosystems. The intricate nature of these systems necessitates continuous monitoring and the development of more robust regulatory frameworks in order to mitigate their ecological footprint. The existing approaches, such as the "dry tomb" method, may not offer adequate long-term safeguards, underscoring the need for revising regulations and implementing innovative solutions to protect water resources [12, 13]. Conversely, some ecosystems may exhibit resilience, demonstrating self-purification capabilities despite pollution pressures, highlighting the complexity of these interactions [14].

Based on the analysis of the data obtained on the distribution of Zn, Pb and Cu in wells and soil samples by depth and a lithogeochemical survey, we can conclude that there is an accumulation zone (or dispersion flow) in the south-east direction from the boundaries of storage area (items 2 and 3, Figure 11).

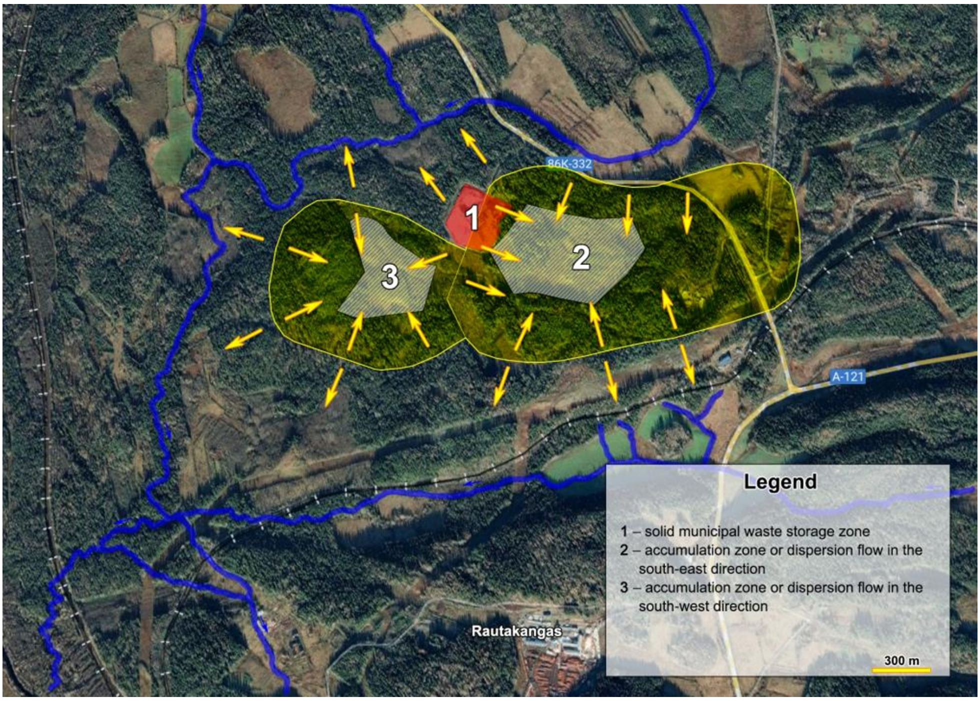

Fig. 11. Functional zoning of the ecological and geological system of the Sortavala solid municipal waste landfill – "storage zone – adjacent territories" (dotted line – expected watershed; arrows – direction of movement of surface and groundwater): *1 – solid municipal waste storage zone; 2 – accumulation zone or dispersion flow in the south-east direction; 3 – accumulation zone or dispersion flow in the south-west direction.*

Therefore, it can be assumed that HM complex will continue to accumulate in zones 2 and 3. If the technogenic conditions for the operation of MSW dump remain the same, there will be no negative impact on watercourses in the work area. These findings validate our hypotheses formulated in the period between 2014 and 2016.

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