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Determination of the sanitary protection zone of municipal waste landfill based on evaluation of the environmental hazards: Case study of the Zhytomyr territorial community, Ukraine

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ABSTRACT

Today, Ukraine is far from European standards, and the country's waste management system remains confronted with environmental and technogenic problems, with 7 % of the territory occupied by landfills. Most settlements in Ukraine do not have solid waste management programs or sanitation schemes. Landfills, and especially municipal solid waste dumps, are significant contributors to air, water, and soil pollution. The objective of this research is to develop a comprehensive understanding of the environmental impact of landfills, to translate them from a descriptive and abstract plane to a mathematical plane, and to identify the sanitary protection zones currently utilized for landfills. The subject of this study is the municipal waste landfill of the Zhytomyr territorial community (Ukraine), a typical Ukrainian landfill operated with minimal environmental protection measures.

The authors used an original approach to assess the environmental hazard of a municipal waste landfill, taking into consideration the values of absolute indicators of water pollution for specific physicochemical characteristics; maximum permissible concentrations of the studied indicators; distance from the landfill boundary; the amount of excess of the absolute indicator of pollution compared to the MPC; and the intensity of odor in the landfill. The calculated pollution indicators served as the basis for an integrated assessment of the environmental hazards posed by the municipal waste landfill.

The study revealed that the O_t indicator (evaluation of the environmental hazards of municipal waste landfills) depends exponentially on the landfill boundary. Based on the value of O_t, environmental zoning was carried out: according to the calculations and taking into account the monitoring of the environmental condition in the landfill's impact zone, the authors recommended the parameters of environmental zoning on the basis of the O_t value.

The purpose of this study is to clarify the sanitary protection zones that are currently used for landfills and solid household waste disposals.

The research materials can also be used to create databases on landfills, enabling the development of a plan to manage them as sources of heightened environmental risk.

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1. Introduction

The world generates 2 billion tons of household waste annually, and this number is increasing every year. The World Bank estimates that the amount of waste could increase to 2.58 billion tons by 2030, and to 3.77 billion tons by 2050. Municipal landfills accumulate thousands of tons of waste annually, even in medium-sized cities. The findings of the Waste Atlas report on The World's 50 Largest Landfills indicate that 64 million people are affected daily by the world's 50 largest landfills (the study used 59,000 files from 25 countries collected through crowdsourcing) [1].

Despite the fact that one of the most significant environmental technogenic challenges of our time is the incorporation of industrial and household waste into the recycling process, the Ukraine's current waste management system is distinguished by the following tendencies.

- substantial amounts of industrial and household waste generation and accumulation;
- disposing of household waste without taking into account any potential risks and focusing on landfill disposal of waste;
- disposing waste in dumps (which are mostly documented as landfills), the majority of which fail to meet environmental safety standards;
- low utilization of waste as recyclable materials;
- inadequate use of efficient waste management strategies and technologies;
- the use of both volumetric and weight categories in statistical reporting and regulations on the management of various types of waste, thus converting one unit to another, leads to significant errors in evaluations, forecasts, etc.;
- improper utilization and disposal of hazardous waste [2].

Every year, Ukraine generates more than 470 million tons of industrial and household waste. Even though the population is decreasing, the amount of waste is only growing: on average, one person produces 250–300 kg per year. 93 % of waste is taken to waste dumps and landfills, more than 2 % is incinerated, and 4.5 % is recycled. The problems associated with household waste are relevant for all regions of Ukraine without exception. According to the Ministry of Development of Communities and Territories of Ukraine, more than 51 million m^3, or more than 10 million tons, of household waste were produced in Ukraine in 2021 and disposed of in 6000 landfills and waste dumps that cover a combined area of nearly 9000 ha.

Due to the implementation of separate household waste collection in 1725 settlements, the operation of 34 waste sorting lines, one waste incineration plant, and three waste incineration units, approximately 7.64 % of household waste was recycled and utilized, of which 1.14 % was incinerated and 6.5 % was sent to recycling centers and waste processing lines. However, this is an extremely low figure compared to European requirements. The situation with waste disposal in Ukraine is strikingly different from what is happening in the European Union: 47 % of EU household waste is sent for recycling (this percentage is constantly growing), 28 % is destroyed by incineration (generating energy), and only 23 % goes to landfills.

The number of overloaded landfills reached 230 (3.8 %), and 824 (13.8 %) did not meet environmental safety standards. The certification and recultivation of landfills are not being done properly. 1489 landfills require certification. There is a demand for 288 new landfills.

In addition to legal landfills and dumps, our country is covered by a number of illegal dumps. One of the reasons is that 21 % of the population does not have access to a centralized system for waste collection.

Given the insufficient system of household solid waste management in settlements, primarily in the private sector, 26.8 thousand unauthorized dumpsites covering 0.6 thousand hectares were identified, of which 25.5 thousand unauthorized dumpsites covering 0.38 thousand hectares were eliminated in 2021 [3]. Despite specialized laws, the National Waste Management Strategy (which aims to have half of our waste recycled by 2030) and the National Waste Management Plan until 2030 (which outlines general tasks and measures to improve the legislative regulation, institutional structure, and information support of the waste management sector), Ukraine is far from European standards, and the technogenic environmental problems of the country's waste management system remain relevant, with 7 % of the country's territory occupied by landfills [4,5,6,7].

The majority of Ukrainian settlements lack solid waste management programs, sanitation schemes, and records of waste generation, disposal, and disposal sites, which leads to the development of dumps, deterioration of settlement health, and an increase in environmental risks in the area. The research findings indicate that the current structure of Ukraine's solid waste management system at the regional level is inefficient [8,9].

Landfills, particularly municipal solid waste dumps, are major polluters of the atmosphere, hydrosphere, and soil [10,11].

The uncontrolled emission of landfill gas into the atmosphere has several adverse effects, which include the pollution of the surrounding environment with toxic substances that not only pose health risks but also create an unpleasant odor [12,13,14].

Research indicates that the primary malodorous compounds emitted from landfills include styrene, toluene, xylene, acetone, methanol, n-butanone, n-butylaldehyde, acetic acid, dimethyl sulfide, dimethyl disulfide, and ammonia [15,16].

Over 50 NMVOCs (Non-Methane Volatile Organic Compounds) have been detected in raw landfill gas, with sulfur compounds contributing the most to the heightened odor intensity [17,18,19,20,21].

This results in grievances from nearby residents who raise concerns about the noxious odor and its potential health implications. The scent can be bothersome, even if the malodorous elements are not inherently harmful to health. The gases and unpleasant odors emanating from landfills can extend over a distance of up to 300–400 m. When landfills are situated close to residential areas, it frequently leads to disputes as the landfill's odor significantly diminishes the quality of life for the residents [22,23].

Another consequence of waste disposal in Ukraine is the problem of leachate contamination of groundwater (through penetration of contaminated water into underground water bodies), as well as contamination migration alongside underground, ground and surface flows [11]. Leachate discharge into surface and groundwater contaminates them with heavy metals [24], ammonium ions [25], and causes eutrophication of water bodies [26]. Thus, waste disposal at landfills involves a variety of ecological risks [13], affecting both the environment and people's health [27,12].

Numerous studies have been conducted to assess the environmental impact of landfills, which only emphasizes the urgency of this problem. Such works usually provide a detailed analysis of the effects of solid household waste landfills on particular environmental components. The studies focus on a particular area of environmental pollution (emissions of harmful gases, soil and water pollution, etc.). However, the drawback of such studies is the lack of a evaluation of the environmental hazards of landfills, which would allow for a quantitative description of the relationship between individual aspects and provide an opportunity to formulate an aggregate indicator of environmental impact. In the authors' opinion, absolutely all components of the impact - surface runoff, groundwater, and harmful gases - should be taken into account when evaluating the environmental impact of landfills and municipal waste sites.

The objective of the study is to develop a comprehensive understanding of the environmental impact of landfills, to translate them from the descriptive and abstract to the mathematical plane, and to specify the SPZs that are currently used for landfills.

2. Materials and methods

This study focuses on a landfill for solid household waste in Zhytomyr, Ukraine, which is representative of Ukrainian landfills with minimal environmental protection measures. All of the city's household waste is dumped at the landfill without prior sorting (see Fig. 1), resulting in significant air and groundwater pollution, posing an epidemic-level threat, and necessitating an improvement in waste disposal procedures. Since 1957, the 21.6-ha landfill for municipal solid household waste has been in operation. The landfill was constructed without a specific plan. At the time of its installation, there were no environmental protection measures required by legislation. Regrettably, this is typical of the majority of Ukrainian cities.

The Zhytomyr solid household waste landfill's geographical location is quite specific (see Fig. 2), allowing for a variety of exhaustive studies. The landfill is surrounded by summer cottages without major highways or industrial enterprises, which could distort the research picture and further affect the anthropogenic load of the surrounding areas.

The following aquifers and complexes are present within the landfill area.

- an aquifer in modern alluvial deposits (aH). Static levels lie at depths of 0.2–1.0 m, and the aquifer is exposed to contamination from the ground surface;
- aquifer of Middle Quaternary water-glacial sediments (f PH dn). At the waste disposal site, static groundwater levels lie at depths of 0.5–2.6 m. This indicates that there is no water stop in the described sediments, and the aquifer is subject to contamination from the ground surface;
- variegated clays with low-powered interlayers of Sarmatian sands, which serve as a water stop between groundwater of Middle Quaternary sandy deposits and water in the zone of weathering and fracturing of Proterozoic crystalline rocks;
- the aquifer of the fracture zone of Proterozoic crystalline rocks and their destruction products is developed everywhere. It is represented by fractured granites and gneisses, as well as their weathering crust.

The water supply of the rocks is directly dependent on the degree of fracturing and varies from 0.3 to 80 m^3/day, the waters are fresh and transparent. By chemical composition, they are sulfate, bicarbonate-sulfate, calcium-sodium with mineralization of 0.3–0.6 g/dm3, slightly pressurized. The nearest watercourse is 1200 m away: the Kroshenka River (a left tributary of the Kamianka River, which is a left tributary of the Teteriv River, the main waterway of the area under study and drains all aquifers and complexes in the landfill area). The closest water intake from the Teteriv River is the Zhytomyr Reservoir (a backup water intake), which is about 7.7 km away; the Vidsichne Reservoir (the main water intake that supplies the city of Zhytomyr) is 13 km away.

Fig. 1. Image of the municipal landfill for the disposal of solid waste (source: https://www.google.com/maps; coordinates: 50.30316 latitude, 28.64262 longitude).

Fig. 2. Location of the solid waste landfill in Zhytomyr (Ukraine) (source: https://www.google.com/maps; Coordinates: latitude – 50.30316, longitude – 28.64262, 1–5 – direction of location and distance from the landfill: 1 – city boundary (0.65 km); 2 – residential and public buildings (0.514 km); 3 – agricultural land (0.05 km); 4 – forest area (0.05 km); 5 – Kroshenka River (1.0–1.20 km); 6 – Kroshnia Brick Plant quarry (0 km). Scale 1:5000.

The existing system for monitoring the impact on the environment of the investigated household waste landfill includes groundwater quality control and water quality control in the landfill's sedimentation tanks. To control the quality of groundwater at the landfill, there are 5 regime monitoring wells on three observation profiles (the location of the wells depends on the direction of the soil flow - to the northeast). However, the assessment of the impact of solid waste landfills on the hydrochemical regime of the adjacent territories (in particular, on the water of wells and surface water bodies in the zone of influence of solid waste landfills) is not carried out. On the territory of the landfill, there are leachate sumps, from which there is a regular outflow towards the surface water bodies that were studied. In order to control the possible leachate contamination of reservoirs that are in the zone of influence of the Zhytomyr solid waste dump and are used for drinking and sanitary-economic purposes, the content of chemicals in the water and the compliance

Fig. 3. Scheme of water sampling from surface water bodies (Distance from the landfill boundary: water body 1–100 m, water body 2–250 m) and wells (Distance from the landfill boundary: well 1–500 m, well 2–750 m, well 3–1000 m) materials from the site https://www.gooogle.com/maps; coordinates: latitude – 50.30316, longitude – 28.64262, Scale 1:5000.

of their values with the permissible values of regulatory requirements for water quality were investigated.

A study was carried out to assess the impact of the landfill on the hydrochemical conditions of the surrounding areas [28]. For the study, 5 sampling points were selected on the site: 2 surface water bodies (lakes) adjacent to the landfill (located 100 and 250 m from the landfill boundary), and 3 wells in a residential area (located 500, 750, 1000 m from the landfill boundary), see Fig. 3.

Water quality was monitored in November (during autumn rains, the period of the most likely water pollution), in December (during snowfall); and in spring (during snowmelt). In the course of analyzing and processing the results, we used regression analysis methods. The validity of the data obtained was checked by Fisher's criterion with a reliability level of 95 %. The methods of variance analysis were utilized to assess the influence of the studied factors on the change in the obtained indicators. A one-factor variance analysis of the research data was conducted depending on: season; type of water environment (water body or well); distance; odor. The following water quality indicators were monitored: odor; color; turbidity; pH; alkalinity; total hardness; ammonium nitrogen; nitrates; nitrites; sulfates; calcium; magnesium. The pH value was determined by the potentiometric method using a pH - 150 MI device. Ammonium nitrogen was determined by the colorimetric method with Nessler's reagent on a photoelectrocolorimeter CFC-2. Nitrite was determined by the Griess method. For the determination of nitrates, a colorimetric method with salicylic acid was used. Sulfates were determined by iodometric titrometric analysis. The total calcium and magnesium content (total hardness) was determined by titrating the sample with Trilon-B solution in the presence of an acid chrome-dark blue indicator, followed by calculating the titration results. Calcium ions were determined in the same way by titration with Trilon-B, but using the murexide indicator. The magnesium ion content was determined as a difference in the total hardness and calcium ion content and expressed in mg/L. All studies were conducted in accordance with the methods of the State Sanitary Rules and Regulations in force in Ukraine "Hygienic requirements for drinking water intended for human consumption", [29].

Additionally, we utilized the facility's research findings to conduct a human sensor-based study of air pollution near the landfill.

The statistical method ASTM E544 [30] to evaluate the odor intensity in the zone of influence of landfills was chosen. It can be used to quantitatively express the smell intensity by comparing it with static scale.

According to this method, the smell of the sample is compared by intensity with the scale of the prepared solutions. During the comparison, the qualitative characteristics of the smell are not taken into account. Intensity is evaluated by 8 independent assessments. The evaluators report a point on the scale where an odor intensity is the similar to the sample smell. Independent evaluations were statistically processed and calculated. The result was reported as the concentration in ppm of 1-butanol in water.

Solutions of 1-butanol in water were prepared using standard laboratory procedures. Each solution had a volume of 200 ml and was placed in 500 ml Erlenmeyer flasks. These solutions were replaced with fresh ones every 2 h. During the intervals between assessments, the flasks were covered with foil to maintain equilibrium between the solutions and the available volume within the flasks. Careful shaking of the flasks was performed prior to odor evaluation to ensure consistency. The experiment was conducted at ambient temperature.

The minimum detectable odor threshold for 1-butanol in water is 2.5 ppm (ppm - parts per million, where 1 ppm equals 1 μL per 1L) at 21 °C. The lower end of the scale started with higher concentrations, while the upper limit did not exceed 70,800 ppm, which represents the solubility limit of butanol in water at 30 °C. The most practical concentration range fell between 10 and 20,000 ppm. This range was covered by using 12 flasks with solutions, where concentrations increased exponentially with a factor of 2. The first flask contained a concentration of 10 ppm, the second had 20 ppm, and so on. The scale numbers (corresponding to the flask numbers) denoted the points of correspondence between the sample odor and the scale.

The results obtained by all assessors were converted from scale points to ppm of 1-butanol. In cases where values were not whole numbers, geometric means were calculated between the concentrations. The geometric mean of the results from all assessors was computed. The standard deviation for the logarithms of the concentrations was calculated.

For a evaluation of the environmental hazard of a solid waste landfill, the author's approach is proposed, which takes into account the value of absolute indicators of water pollution at a particular point according to a separate physicochemical characteristic; maximum permissible concentrations of the studied indicators; the distance from the landfill boundary; the amount of excess of the absolute pollution indicator over the MPC and the odor intensity in the area of landfill impact. The calculated pollution indicators were used as the basis for a evaluation of the environmental hazards of the solid waste landfill.

For a evaluation of the environmental hazard of a solid household waste landfill, it was proposed to use the approach of relative evaluation of pollution indicators. The total relative indicator of water pollution at the selected point W_t was determined by formula *(1)*:

$$W_t = \sum \frac{\Delta C_i}{MPC_i} \tag{1}$$

After that, the relative indicator was calculated at the selected point V_t (*2*):

$$V_t = W_t / n \tag{2}$$

where C_i is an absolute indicator of water pollution at a particular point according to a specific physico-chemical characteristic;

MPC_i is the maximum permissible concentration of this indicator;

t – distance from the landfill boundary;

n – number of parameters for which water quality indicators were measured (in our case, n = 8, but it may vary depending on the conditions of the research, depending on the analyzed parameters);

W_t – total relative indicator of water pollution at the selected point;

V_t – relative indicator of water pollution at a selected point

ΔC_i– value of the excess of the absolute pollution indicator over MPC_i *(3):*

$$\Delta C_i = |C_i - \text{MPC}_i| \tag{3}$$

Thus, an evaluation of the environmental hazards of municipal waste landfills *(4)*

$$\text{Ot} = \text{Vt} \times \text{Ft} \tag{4}$$

Representation of the research process looks as follows (see Fig. 4)

General limitations of the study: the lack of reliable data (due to the variety of waste that enters landfills, it is quite difficult to assess the chemical composition of waste and its impact on the environment), as well as the seasonal dynamics of the composition of waste significantly affects the composition of the leachate. In addition, the evaluation of the degree of ecological danger using the human sensory system is probably the most subjective (depends on the number of participants in the experiment and their perception of the strength of the smell), but the measurement of the smell can allow an objective assessment of the real scale of the problem.

3. Results and discussion

The prevailing wind direction in the examined region is from the west, accounting for 18.5 % (Fig. 5). The most intense odor is experienced on the downwind side, leading to discomfort among the local residents.

Assessing the odor and determining how its intensity varied depending on how close it was to the object of study was the initial step in the study. The first odor evaluation point in the landfill impact zone was located at a distance of 500 m - at the border of the sanitary protection zone (State Construction Norms of Ukraine), and the rest - every 100 m to the landfill border (6 points in total) see Fig. 6. At each of the selected points, eight independent assessors evaluated the odor by intensity (excluding qualitative characteristics) according to the ASTM E544 methodology. A total of 56 odor intensity studies were conducted [12].

At all selected locations, eight independent assessors conducted an evaluation of the odor, focusing solely on its intensity, following the ASTM E544 method. Each expert assessed the odor's strength by utilizing samples contained in labeled flasks numbered 1–12, as per the scale of prepared solutions detailed in Table 1. The findings of the investigation, along with their statistical analysis, are presented in Table 2.

The final results for each point were determined using the odor intensity scale, and these findings are presented in Table 3. To validate the reliability of the results, an assessment of odorous gas odors at the solid waste landfill was conducted, yielding a result of 18766.142 ppm – the equivalent odor concentration in n-butanol, ppm.

According to the calculations, an exponential relationship (Fig. 7, *(5)*) was discovered to represent the connection between the intensity of the odor and the distance from the source of gas generation (the landfill for solid household waste in Zhytomyr).

$$\begin{aligned} y &= 7890,8e - 0,01x \\ R^2 &= 0,9987 \end{aligned} \tag{5}$$

The results obtained confirmed the validity of the applied method. When measured under different weather conditions (humidity, precipitation, and wind speed), the odor from the landfill may disperse over a different distance; consequently, the coefficients in the mathematical relationship will vary, but its shape will remain exponential.

The second stage of the research was to assess the impact of the landfill for solid household waste on the hydrochemical conditions of the adjacent territories.

In some relevant studies it is being researched the influence of landfills and solid household waste disposals on the condition of water bodies and these studies are mostly taking into account the pollution of water bodies in a complex way - from the influence of the urbanized areas [24]. Existing studies mainly analyze the anthropogenic impact on the ecological state of river waters (combined pollution by discharges of insufficiently treated wastewater, as well as unauthorized landfills of household waste and rainwater runoff from urbanized areas and adjacent industrial areas) and emphasize the negative impact of landfills on surface and groundwater (not

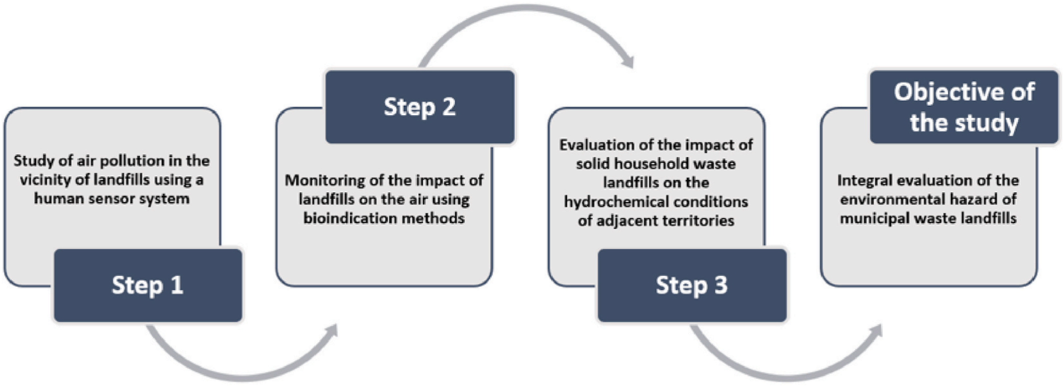

Fig. 4. Representation of the research process.

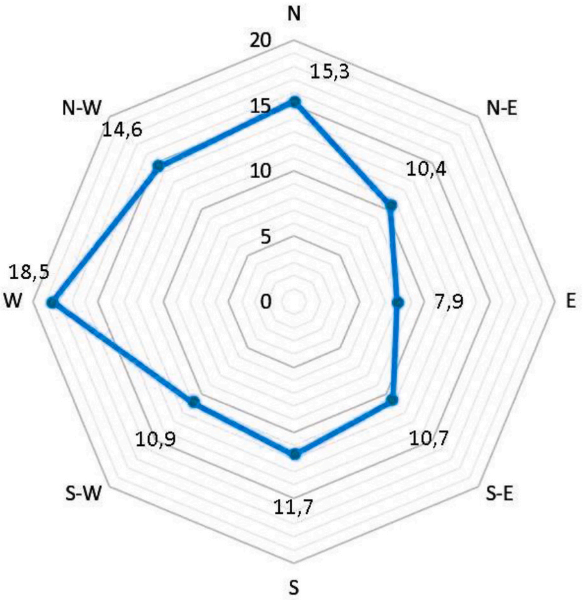

Fig. 5. Wind rose of the research object's location with averaged values (Zhytomyr, Ukraine).

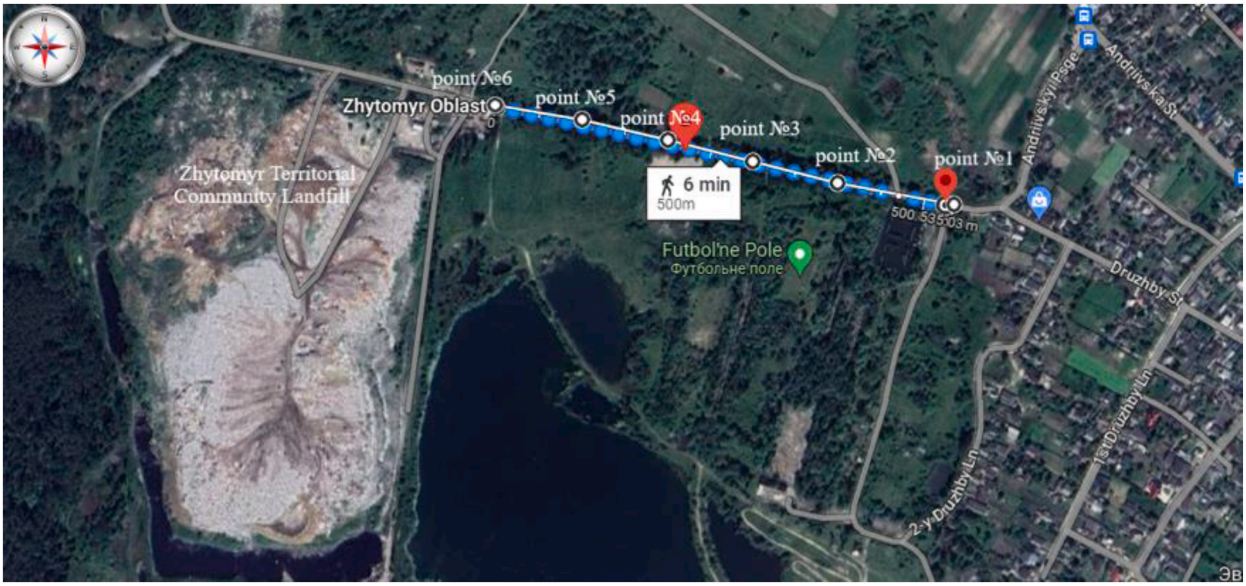

Fig. 6. The direction of movement during the study of odor in the area of influence of the landfill and measurement points (1–6) materials from the site https://www.gooogle.com/maps; coordinates: latitude – 50.30316, longitude – 28.64262, Scale 1:5000.

separating the impact only of landfills and solid household waste disposals). The geographical location of the research place of current study is quite specific and provides a unique opportunity for various comprehensive studies of the impact on the environment (in particular, on the hydrochemical regime of the adjacent territories). The landfill is surrounded by country plots without major highways and industrial enterprises, which could distort the relevance of the study and additionally to affect the hydrochemical regime of the adjacent territories.

As a result of the research, we determined the chemical parameters of water in surface water bodies and wells located at various distances from the landfill boundary (Table 4). It was found that the content of chemicals in the water exceeds the permissible values of regulatory requirements for water quality [29].

In the course of research, an excess of nitrates by almost 4 times was found in three points, namely in water that was taken from wells in the surrounding areas.

The content of nitrates in well water is significantly higher than the content of nitrates in water from reservoirs, this may be related

Table 1
Alignment of n-butanol concentrations with the scale for determining odor intensity.

scale point	n-butanol concentration, ppm	Lg (ppm)
1	10	1
2	20	1.301
3	40	1.602
4	80	1.903
5	160	2.204
6	320	2.505
7	640	2.806
8	1280	3.107
9	2560	3.408
10	5120	3.709
11	10240	4.01
12	20480	4.311

Table 2
The outcomes of the odor evaluation within the research object's vicinity.

odor assessment results	500 m	400 m	300 m	200 m	100 m	landfill boundary	landfill
1	4	5	6	8	10	12	12
2	3	6	8	8	9	10	11
3	4	5	6	8	9	10	12
4	3	4	4	6	8	10	12
5	4	6	7	9	9	11	12
6	3	5	7	9	9	11	12
7	3	6	8	7	10	10	11
8	4	4	6	8	9	11	12
Arithmetical mean	3.500	5.125	6.500	7.875	9.125	10.625	11.750
Dispersion	0.2857	0.6964	1.7143	0.9821	0.4107	0.5536	0.2143
Arithmetic mean error	0.1890	0.2950	0.4629	0.3504	0.2266	0.2631	0.1637
Accuracy of the experiment, %	5.4	5.8	7.1	4.4	2.5	2.5	1.4

Table 3
The study findings for evaluating the odor intensity in the vicinity influenced by the solid waste landfill (measured in n-butanol concentration, ppm).

№ of point	Distance from the landfill boundary, m	Correspondence to n-butanol concentration, ppm
1	500	56.56
2	400	174.43
3	300	452.376
4	200	1173.208
5	100	2790.134
6	0	7890.872
Control (landfill)	–	18766.142

Regression analysis, which is prevalent in ecology, was chosen as the method for processing the results. According to regression statistics, the coefficient of determination for the obtained regression line was 0.99, indicating its high quality. Due to the fact that the coefficient of determination is greater than 80 %, the model can be considered valid.

to the type of water body and water exchange in it. The highest nitrate content in well water is observed in December, January and February, which may be related to seasonal dynamics and climatic conditions. In the water of reservoirs, the highest indicator of nitrate content was observed during torrential rains. The results of univariate variance analysis show with a reliability level of 95 % that the content of ammonium nitrogen varies depending on the season ($F_{fact} = 120.47 > F(1; 3; 0.95) = 18.51$; $p = 0.058$). In December, the average nitrogen content exceeded the same indicator in November and March by 4.1 times. It should be noted that the content of chemicals also depends on the type of water source, and the seasonal dynamics of the content of ammonium nitrogen is more pronounced in the water of reservoirs. In the spring months, the content of ammonium nitrogen did not change significantly compared to the indicators in November. It was also found that the dependence of sulfate content in water on the season is insignificant. A significant relationship between the sulfate content and the type of water source was found - their amount in well water is much higher than that in reservoirs. Landfill filtrates are a powerful factor of potential threat to the state of surface and underground water resources (in most cases – with a long-term effect). As a result of the conducted research, it was found that the pH in the researched reservoirs and wells is neutral (from 6.5 to 7.5). The relationship between water pH and the distance from the source of pollution allows you to construct a regression model equation that is linear in nature.

The chemical parameters of water in water bodies and wells located at various distances from the landfill boundary confirmed the assumption that the impact of the landfill on the hydrosphere at a distance of more than 750 m (1000 m) is insignificant; therefore, the results of the analysis on the water chemical parameters in "well 3″ were not taken into account in the subsequent evaluation of the

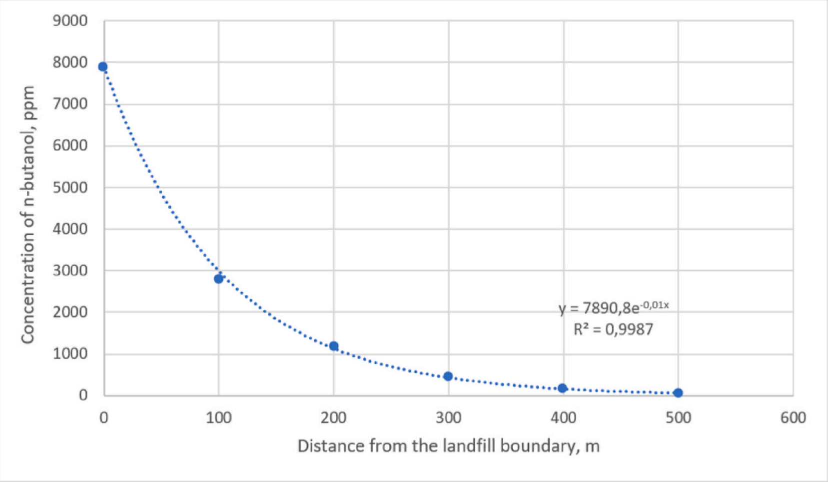

Fig. 7. The research findings to evaluate the intensity of odor in the region impacted by the landfill for solid waste.

Table 4
Chemical parameters of water in water bodies and wells located at different distances from the landfill boundary.

Sampling location	Distance from the landfill boundary, m	Chemical parameters							
		pH	Alkalinity	Total hardness mg-eq/dm^3	Ammonium nitrogen, mg/dm^3	Nitrites, mg/dm^3	Nitrates, mg/dm^3	Sulfates, mg/dm^3	Ca^{2+}, mg/dm^3
water body 1	100	6.53/±0.33	3.85/±0.19	7.60/±0.38	2.23/±0.11	0.01/±0.0005	1.56/±0.08	24.87/±1.24	3.80/±0.19
water body 2	250	6.60/±0.33	3.62/±0.18	14.09/±0.71	2.25/±0.11	0.03/±0.0015	0.95/±0.05	25.78/±1.29	9.15/±0.46
well 1	500	6.89/±0.35	1.94/±0.10	11.69/±0.59	2.09/±0.11	0.01/±0.0005	105.95/±5.3	29.27/±1.46	7.97/±0.4
well 2	750	6.97/±0.35	2.74/±0.14	17.43/±0.87	1.37/±0.07	0.02/±0.001	102.23/±5.11	22.52/±1.13	11.07/±0.55
well 3	1000	7.30/±0.37	4.65/±0.23	9.83/±0.49	0.65 /±0.03	0.01/±0.0005	31.25/±1.56	24.91/±1.25	7.13/±0.36

environmental hazard of the landfill and the creation of the evaluation model. Previous research conducted by the authors also emphasizes that at a distance of 1000 m, the impact of the landfill is not observed (at this study site) [6,7,14].

For a evaluation of the environmental hazard of a solid household waste landfill, it was proposed to use the approach of relative evaluation of pollution indicators.

First, the total relative indicator of water pollution at the selected point Wt was determined, after that the relative indicator at the selected point V_t was calculated (according to the formulas given in the research methodology). The data of the calculations are shown in Table 5.

The calculated pollution indicators were used as the basis for a evaluation of the environmental hazards of the solid household waste landfill. No studies were conducted at the landfill boundary (due to the absence of water bodies there, except for leachate reservoirs). If we examine the leachate in the reservoirs, we can assume that the indicator is close to 0, which distorts the research picture (a water body on the border is required for a complete picture). In order to calculate the water pollution indicator (V_t) at the landfill boundary (x = 0), it was decided to study the dependence of the relative water pollution indicator at the selected point on the distance to the landfill boundary (Fig. 8, (6)).

$$\begin{aligned} y &= 0,0002x + 0,6408 \\ R^2 &= 0,7872 \end{aligned} \tag{6}$$

A linear relationship was found with $R^2 = 0.7872$. Indicators of the density of connections in such models can be given a qualitative evaluation (Chaddock scale): (0.1–0.3 - weak; 0.3–0.5 - moderate; 0.5–0.7 – noticeable; 0.7–0.9 - high; 0.9–0.99 - very high) [31]. The variation in the factor characteristics accounts for a smaller share compared to other factors not taken into account in the model that affect the change in the indicator's results. Thus, it is assumed that an increase in measured parameters and their conversion to relative indicators of water pollution can improve the quality of the density of connections in the created model (which will be taken into consideration by the authors in further research). However, on the one hand, to obtain reliable predictions of response values, the model should include as many independent variables as possible (in particular, increase the number of studies of water quality

Table 5
Relative indicators of water pollution.

Point No	Distance from the landfill boundary, m	$\frac{\Delta C_i}{MPC_i}$								W_t	V_t
		pH	Alkalinity	Total hardness	Ammonium nitrogen	Nitrites	Nitrates	Sulfates	Ca^2+		
1	100	0.13	0.41	0.09	0.49	1	0.97	0.95	0.98	5.02	0.6275
2	250	0.12	0.44	1	0.5	0.99	0.98	0.95	0.95	5.93	0.74125
3	500	0.081	0.7	0.67	0.39	1	1.35	0.94	0.96	6.09	0.76125
4	750	0.07	0.58	1.49	0.086	0.99	1.27	0.95	0.94	6.38	0.7975

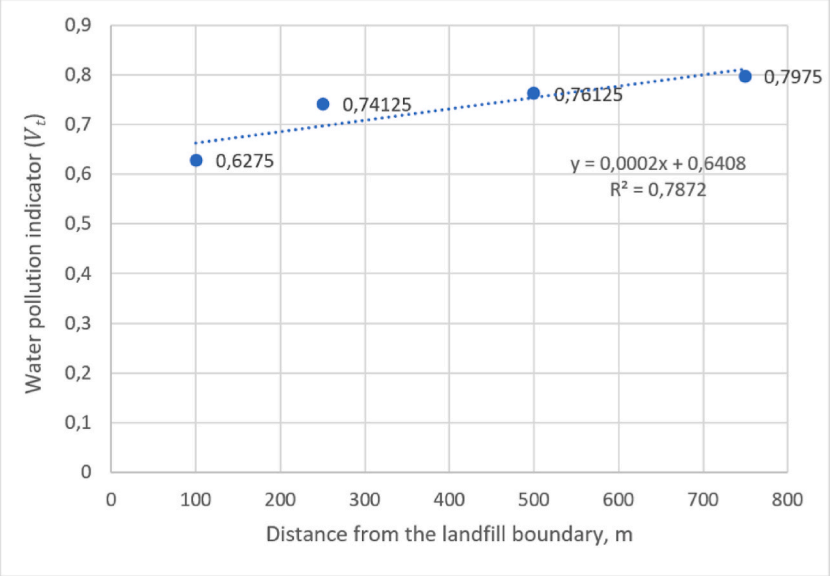

Fig. 8. Dependence of the water pollution indicator (V_t) on the distance to the landfill boundary (m).

parameters, i.e. indicator n), but on the other hand, as their number increases, the cost of research increases.

The correlation may vary for each dump and landfill and depends on many factors, but we assume that it will be linear. We can calculate an approximate indicator of water pollution at the landfill boundary x = 0. Thus, the relative water contamination indicator at the landfill boundary is 0.6408.

The assumption was made that soil surface contamination is determined by the level of water contamination as an indicator that evaluates both soil and water quality.

Thus, a evaluation of the environmental hazards of municipal waste landfills (Table 6)

$$O_t = V_t \times \mathrm{F_t} \tag{7}$$

$$\mathrm{y} = 5069,5\mathrm{e}^{-0,01\mathrm{x}}\mathrm{R}^2 = 1 \tag{8}$$

The exponential dependence of the O_t indicator (evaluation of the environmental hazard of municipal waste landfills) on the landfill boundary was revealed (Fig. 9, (8)).

The next task is zoning the state of the environment on the value of O_t. On the basis of the performed calculations and taking into

Table 6
Evaluation of the environmental hazard of municipal waste landfills (O_t), *(7)*.

t distance	V_t According to the study	V_t Calculated y = 0,0002x + 0,6408	$\mathrm{F_t}$ Odor intensity	O_t Evaluation of the environmental hazards of municipal waste landfills t
0		0.6408	7890.872	5056.4707776
100	0.6275	0.6608	2902.86309	1918.211929872
250	0.74125	0.6908	647.716307	447.4424248756
500	0.76125	0.7408	53.1677922	39.38670046176
750	0.7975	0.7908	4.36427815	3.45127116102

account the environmental monitoring in the region of impact of the landfill, the following environmental zoning parameters are recommended based on the O_t value (Table 7).

Prior studies of the authors' research on the research object (bioindication, sensory, impact on the hydrochemical conditions of adjacent territories) [6,7,14] determined the impact zone of the Zhytomyr City Landfill to be approximately 600 m from its boundary. As a result, regulations must be revised, and stricter environmental controls must be put in place in the vicinity of such facilities. These controls must include air monitoring, surface and groundwater inspection, instrumental analysis of soil conditions, and research into the species composition and diversity of flora and fauna in the impacted areas. The findings of these studies can be used to create databases of landfills, allowing for the development of a strategy to manage them as a source of heightened environmental risk.

4. Conclusions

As a result of the conducted research, the chemical indicators of water in surface reservoirs and wells located at different distances from the border of the landfill were determined. The impact of the landfill on the hydrochemical regime of the adjacent territories was assessed. With the help of the human sensory system, the smell was evaluated and the dependence of its intensity on the distance to the research object was established, which allows analyzing the state of the atmospheric air in the area of the landfill.

It is proposed to use the author's approach for a assessment of the ecological hazard of a solid waste landfill, taking into consideration the values of absolute indicators of water pollution for specific physicochemical characteristics; maximum permissible concentrations of the studied indicators; distance from the landfill boundary; the amount of excess of the absolute indicator of pollution compared to the MPC; and the intensity of odor in the landfill. The calculated pollution indicators served as the basis for an assessment of the environmental hazards posed by the municipal waste landfill.

Based on the value of evaluation of the environmental hazards of municipal waste landfills, environmental zoning was carried out: according to the calculations and taking into account the monitoring of the environmental condition in the landfill's impact zone, the authors recommended the parameters of environmental zoning on the basis of the evaluation of the environmental hazards of municipal waste landfills value.

Thus, considering the indicators of the state of water resources (hydrochemical indicators of the quality of water), the degree of stench (which characterizes the degree of environmental pollution), we can obtain a evaluation of the environmental hazard of a municipal waste landfill at any point of its impact and characterize the state of the environment according to the recommended parameters. It will also allow specifying the parameters of sanitary protection zones for any solid waste landfill using the calculation method. This can become an important link in the monitoring of landfills' environmental impact, leading to the implementation of new (or enhanced) engineering solutions for environmental protection.

Data availability statement

Has data associated with your study been deposited into a publicly available repository? Response: no.

Has data associated with your study been deposited into a publicly available repository? Response: data will be made available on request.

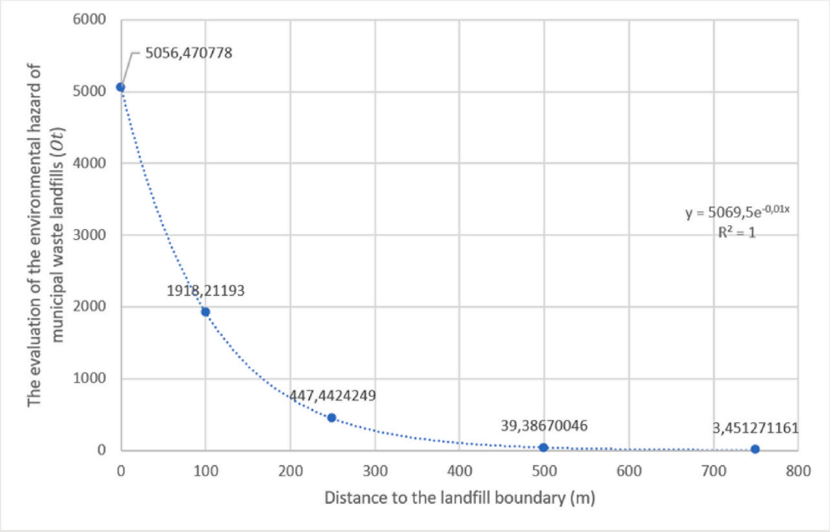

Fig. 9. Dependence of the evaluation of the environmental hazard of municipal waste landfills (*Ot*) on the distance to the landfill boundary (m).

Table 7
Recommended zoning of the environment based on the ecological hazard evaluation of municipal waste landfills.

The value of the environmental indicator (O_t)	State of the environment
0–10	Relatively clean
10–100	Polluted
100–1000	Heavily polluted
More than 1000	Too heavily polluted

CRediT authorship contribution statement

Mariia Korbut: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Myroslav Malovanyy:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Ruslan Boyko:** Software, Resources, Methodology, Investigation, Formal analysis. **Andrew Masikevych:** Supervision, Software, Resources, Methodology, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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