

CHAPTER V

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IMPACT OF MUNICIPAL LANDFILLS ON QUALITY OF GROUND AND SURFACE WATERS

Introduction

Any human activity generates waste, which can be a serious threat to the natural environment. Comprehensive waste management is one of these aspects of environmental protection which, as the amount of waste is growing, have become a problem awaiting an urgent solution. The current model of waste management in Poland needs to be termed as a typically extensive one, with nearly 97% of the generated waste ending up on dumping sites. The result is the progressing degradation of all components of the natural environment, which have an important influence on man's comfort of life (DRZAŁ et al. 1995, SZYSZKOWSKI 1995, BŁASZCZYK, GÓRSKI 1996, DOBRZYŃSKA et al. 1998, GRUSZKA, PLEWNIAK 1999, BARTOSEWICZ 2002, ROSIK-DULEWSKA 2007).

Before selecting an adequate method of waste management, one should become acquainted with the characteristics of all methods, many of which involve modern technologies that incur high investment expenses. When waste is deposited on a landfill, high outlays go to the selection of a right site as well as construction and maintenance of this object. A waste dump that has been properly designed will produce less negative impact on people, animals, plants and other elements of nature such as water, soil and air (AVERESCH 1995, JURKIEWICZ et al. 1998, SZYMAŃSKA – PULIKOWSKA 2001b, ŻYGADŁO 2001, KULIG 2002, AL-YAGOUT, HAMODA 2003, SLACK et al. 2005).

Regarding the lithosphere, degradation of the environment caused by presence of landfills includes penetration and accumulation of various substances in the ground. With respect to the hydrosphere, the immediate risk is caused by emissions of polluted leachate to lakes, rivers or groundwater (BELEVI, BACCINI 1989a,b, ALISTAIR 2000, BOZKURT et al. 2000, SZYMAŃSKA-PULIKOWSKA 2001a, AL-YAGOUT, HAMODA 2003; WÓJCIK et al. 2005).

Permeation of pollutants in leachate to the hydrosphere can occur both while a landfill is used and after it has been closed down. Therefore, an important aspect of waste management consists of proper reclamation of the surface of a waste dumping site after its exploitation has been terminated.

This paper present an analysis of the impact of leachate from the currently operating municipal landfill in Brodnica on some properties of ground and surface

water. A detailed analysis was performed to test values of physical, oxygen-related and salinity indices.

Conditions of the research

The study has been conducted at the municipal waste landfill in Brodnica, which is run by the Municipal Management Company, Ltd. The landfill, which was opened in 1997, is situated about 3 km south-west of the town centre. It lies 350 m away from the Drwęca River and 900 m from the border of the zone of indirect protection of the town's water intake. To the north, the landfill is adjacent to the municipal wastewater treatment plant, whereas to the west it borders with a municipal animal asylum (Fig. 1).



Fig. 1. Location of Brodnica Landfill

The landfill basin was designed and constructed as an earthen tank, which is surrounded by an earthen dyke raising about 2.5 – 4.0 m above the land. The superstructure of the basin's subsoil was constructed from the silts originating from the trenches dug out during the macro-levelling of the south-western slope. The landfill was prevented from producing negative impact on the environment with a screen isolating the landfill basin from the groundwater and limiting migration of pollutants into the ground. It was particularly important to provide the sealing with maximum efficiency as the Drwęca River, flowing near the landfill, supplies potable water to the municipality of Torun.

Considering the required resistance to the expected load of waste and the pressure generated by waste compactors as well as the required resistance to

aggressive effects produced by waste, a leachate drainage system was installed at the bottom of the basin. At the ends of drainage pipes as well as at the sites where drainage pipes were fitted into a collector, control wells made of Ø 1,000 mm concrete rings were installed. The drainage system collector ends with a well made of Ø 1,200 mm concrete rings, from which a PE Ø 250 mm pressure pipe transports leachate, by the gravitational force, to a prefabricated Ø 1,400 mm pumping station. From the pumping station, leachate is transported by a piston pipeline to a concrete ring well located near the entrance gate to the landfill (PRZEGLĄD EKOLOGICZNY, 2002).

Regarding the climate, Brodnica and its environs lie between the mild climate of the Great Valleys region and a more severe lakeland climate of the Masurian Lake District. Typical features of this area are quite chilly, snowy and long winters, generally cool summers and low rainfall. The average annual air temperature is 7.5°C, while the average annual precipitation is 556 mm. The average monthly relative air humidity varies from 70% in May to 88% in November and December (KULIG et al. 2003).

In order to establish the effect of leachate on quality of subsurface (ground and deep groundwater) and surface water, measurements of the water table were taken and physicochemical properties of leachate and water samples were tested. Water samples for analyses were collected according to the Polish norms: PN-ISO 5667-11:2004; PN-76/C-04620 and PN-88/C-04632, once every three months, at six different locations.

The following were determined in the samples of subsurface and surface water: reaction (pH), proper electrolytic conductivity, dissolved substances, sulphates (SO_4^{+2}), chlorides (Cl⁻) and content of calcium (Ca^{+2}) and magnesium (Mg^{+}) ions. The laboratory tests were performed according to the analytical recommendations contained in the Polish Norms: [PN-90/C-04540/01; PN-78/C-04541; PN-74/C-04578/03; PN-ISO 9297/1994; PN-79/C-04566/10; PN-ISO 6058/1999 and PN-ISO 6059/1999].

Samples of leachate were collected from the pumping station situated behind the landfill basin. Samples of subsurface water were taken from four piezometers located around the landfill basin. Deep groundwater was sampled from piezometer P1 (a model observation borehole for determination of the hydrochemical background), drilled to test inflowing groundwater, and from piezometer P2, located where water flows away from the landfill. Samples of groundwater were taken from piezometer P3, situated on a bank of a narrow-gauge railway track, and from piezometer P4, drilled around 8 meters from the leachate pumping station. Both piezometers capture water flowing away from the landfill.

The localization of the leachate pumping station, the piezometers for measurements of the quality of subsurface water and the water pond is illustrated in Fig. 2.

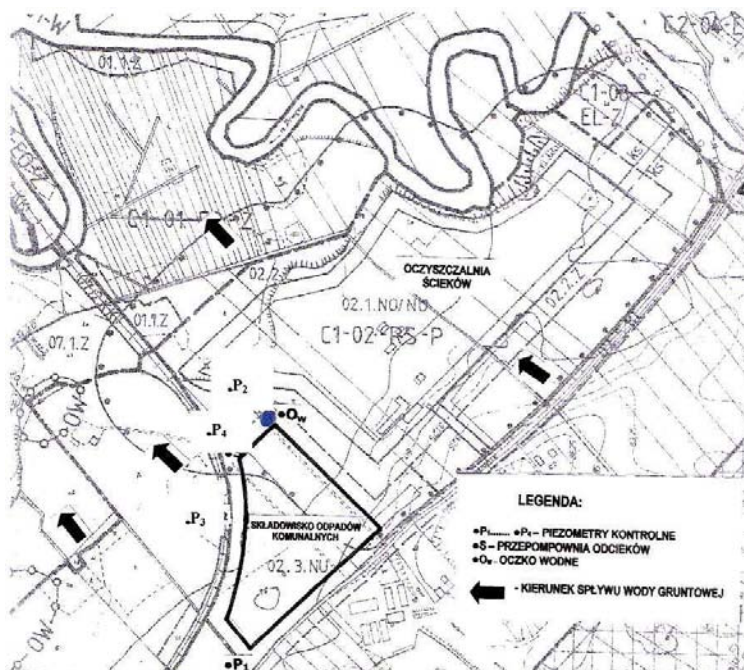


Fig. 2. Location of the pumping station, piezometers for monitoring quality of subsurface water and the water pond

The results of the tests were processed statistically using the software Statistica ver. 6, by StatSoft, Inc. (2001). The least significant differences (LSD) were determined at the level of significance $p=0.05$.

The quality of waters was assessed according to the criteria expressed in the legal regulations contained in the Ordinance of the Minister of the Environment of 11 February 2004 on classification of surface and subsurface water, monitoring methods, interpretation of the results and presentation of the quality of water (Journal of Law, No 32, item 284) and Ordinance of the Minister of the Environment of 14th July 2006 on execution of duties laid on industrial sewage suppliers and conditions for disposal of sewage to sewage facilities (Journal of Law, No 136, items 963 and 964).

Production and amounts of landfill leachate

With the variety of disposed waste, changeable atmospheric conditions and microorganisms present in the bed, landfills are referred to as a certain type of bioreactors, in which complex processes of degradation and biotransformation occur. These processes, both aerobic and anaerobic ones, lead to the formation of highly mineralized substances characterized by various toxicity to live organisms (AVERESCH 1995, COSSU et al. 2000, LEDAKOWICZ, KACZOREK 2004).

The intensity of processes taking place in the deposited mass of waste is affected by many factors, mainly water content and oxygen availability. Some precipitation water falling on the surface of a landfill evaporates, some flows over the surface and some, alongside the water supplied with the waste and originating from decomposition of organic waste, migrates through the bed, where it is enriched with soluble compounds. As a result, a by-product of landfills, called leachate, appears. Most researchers (ROSIK- DULEWSKA, KARWACZYŃSKA 1998, GRUSZKA, PLEWNIAK 1999, ŻYGADŁO 1998, 2001, BARTOSEWICZ 2002) claim that leachate appears primarily due to the penetration of precipitation water to the landfill reservoir and, to a much lesser extent, via decomposition of the organic fraction found in the waste mass. Increased production of leachate can be also caused by surface and subsurface water reaching the landfill which lacks a proper system for draining such water (BELLEVI, BACCINI 1989A,B, LO 1996, ŻYGADŁO 1998, OLESZKIEWICZ 1999, BOZKURT et al. 2000).

Because of its content of chemical substances and compounds that alter the natural composition of water, leachate is considered to be wastewater. Moreover, because it contains elevated amounts of halogen derivative compounds, it is classified as dangerous wastewater (SURMACZ – GÓRSKA et al. 2000).

The composition and amount of leachate can be highly varied, depending on the type of waste, its fragmentation and density, amount of water trickling through the bed, age of the landfill, technology for storing waste, physicochemical transformations occurring in the landfill body and the way the landfill is reclaimed (OBRZUT 1997, RUBACHA, ROGOWSKA 1997, BERGIER, WÓJCIK 2001, KLOJZY – KARCZMARCZYK et al. 2003, ROBINSON et al. 2005).

The amount of generated leachate depends primarily on the volume of atmospheric precipitation as well as on the evaporation and insulation. When the annual precipitation reaches 700 mm, the density of deposited waste is $600 \text{ kg}\cdot\text{m}^{-3}$ and its water content is 30%, the amount of generated leachate per 1 ha of the landfill surface area is ca $450 \text{ mm}\cdot\text{year}^{-1}$, i.e. 4.500 m^3 . Loss of water through evaporation and surface runoff is 250 mm. However, this is a simplified calculation as it does not take into consideration all possible factors. Nonetheless, it gives very close approximation of the volume of generated leachate (SUCHY et al. 1998, OLESZKIEWICZ 1999, BARTOSEWICZ 2002, GÓRSKI 2002). Moreover, amounts of leachate change seasonally. Most leachate will appear between September and April, while in the late spring and summer only minimal amounts of leachate are produced. There are also possible daily peaks caused by rapidly melting snow or heavy rains. When this happens, amounts of leachate can be up to ten-fold higher than observed under natural conditions (KODA 2001).

With respect to the waste deposited on the landfill in Brodnica, the amount of leachate discharged to the municipal wastewater treatment plant was steadily increasing (Fig. 3).

The highest amount of leachate was recorded in December, and the smallest one occurred in September 2004, which confirms the results of studies completed by other authors. From October 2004 to March 2005, the quantity of leachate was observed to have increased considerably relative to the summer season. This was caused by a very high volume of precipitation which occurred in the autumn and

winter of that year. Another reason was the fact that a draining system was installed in Section II of the landfill.

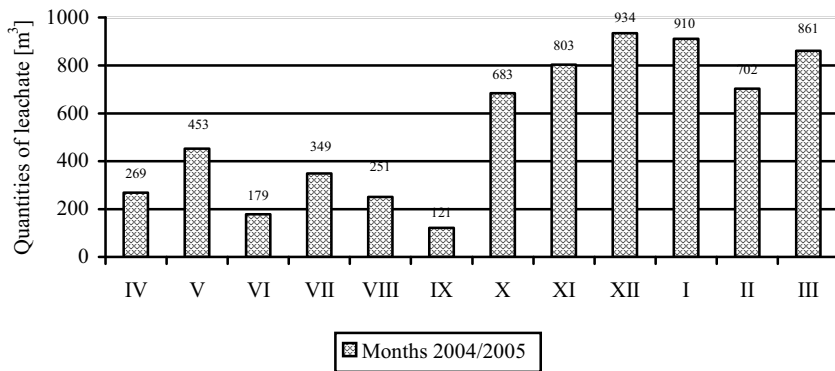


Fig. 3. Quantities of leachate in 2004-2005

Chemical composition of leachate

The precipitation water trickling through the landfill as well as subsurface and surface water cause leaching of water soluble substances. These three sources of water largely affect the qualitative (chemical) composition of generated leachate. It is assumed that the chemism of leachate depends mainly on the content of organic substance in waste, the stage of waste transformation and technology of waste deposition. Another important factor is the chemical composition of deposited waste as well as decomposability and leachability of particular waste components (CLÈMENT et al. 1997, ALLEN 1999, DĄBROWSKA et al. 1999, KANG et al. 2002, KODA et al. 2006).

The main process which takes place on a landfill is the microbial decomposition of organic matter, followed by the reaction of decomposition products with other components. As a result, substances found in leachate are a mixture of compounds originating from solid components dissolved in water and liquid components as well as intermediate products occurring during the fermentation processes. The final composition of leachate, as the above implies, is a resultant of processes occurring in a mixture of old and fresh waste.

The load of pollutants in leachate produced during the early stage of waste deposition is much higher than in leachate produced during later stages. This dependence holds particularly true for organic pollutants, as can be demonstrated with an aid of oxygen indices, i.e. BOD₅, COD, as well as TOC (total organic carbon). The value of leachate reaction reveals a reverse regularity. In the initial years after opening a landfill (up to five years), landfill leachate is acidic (pH 3.7 to 6.4), which is directly caused by the processes occurring in the waste bed. During this phase of the landfill exploitation, the decomposition of waste generates short-chain volatile acids, which make up 70-90% of organic components, as well as hydrogen and carbon dioxide. These chemicals are directly responsible for

acidification of leachate. In the later years of exploitation, leachate becomes neutral or slightly alkaline (7.0-7.6) and after about ten years it is alkaline in reaction (8.0-8.5) (SZUBSKA 1997, SUCHY in. 1998, VADILLO et al. 1999, PRZYWARSKA 2001, SZYMAŃSKI 2006, ROSIK-DULEWSKA 2007).

The reaction of the leachate produced at the landfill in Brodnica oscillated around 7.5 to 7.8, which is characteristic for stabilized landfills. No significant differences in the value of this parameter were observed between the leachate sampling dates (Fig. 4).

The values of oxygen indices reported by different authors (SURMACZ-GÓRSKA et al. 1997, SZUBSKA 1997, VADILLO et al. 1999, SZPADT 2006, SZYDŁOWSKI 2007) oscillate within broad ranges and depend mainly on the age of a landfill. In leachate from young landfills, the values of these indices are much higher than from older ones. In leachate from landfills exploited for three years, the values of BOD₅ vary between 1,500 and 45,000 mg O₂ m⁻³ and the values of COD – between 3,600 and 62,000 mg O₂ m⁻³. In leachate from landfills used for over 3 years, BOD₅ equals 250 to 16,000 mg O₂ m⁻³ and COD reaches 2,800 to 19,000 mg O₂ m⁻³.

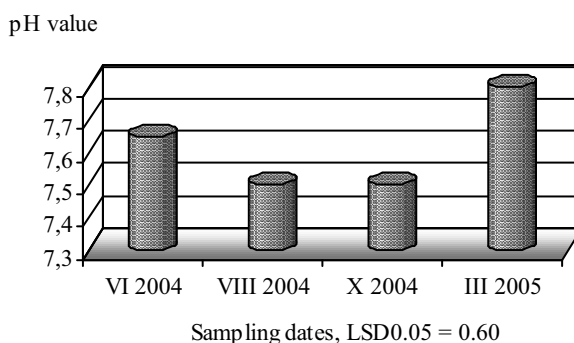


Fig. 4. Value of reaction (pH) of leachate

Higher content of organic compounds in leachate from younger landfills is caused by the fact that during the initial years of waste deposition on a landfill, processes of organic substance decomposition are the most intensive. At that time, during the acidogenic phase, the highest amount of easily soluble organic bonds are created. At landfills older than 3 years, organic matter decomposition processes slow down, which is clearly reflected by numerical values of oxygen indices. During that time, due to the progressing stabilisation processes (waste methane fermentation phase), small quantities of hardly decomposable organic compounds, mainly humic and fulvic acids, appear in leachate (VADILLO et al. 1999, ALISTAIR 2000, COSSU et al. 2000, LEDAKOWICZ-KACZOREK 2004).

Among the oxygen indices characterising properties of leachate from the waste landfill in Brodnica, the following were determined: BOD₅, COD_{Cr} and total organic carbon. During our study, fluctuations in BOD₅ in leachate were within 45.00 to 100.00 mg O₂ dm⁻³ (on average 65.00 mg O₂ dm⁻³) whereas COD_{Cr} varied from 170.00 to 682.00 mg O₂ dm⁻³ (on average 373.90 mg O₂ dm⁻³). Differences in the values of these parameters between the sampling dates were in most cases highly significant (Fig. 5, Tab. 1). The highest values of BOD₅ were recorded in August

2004, and those of COD_{Cr} – in June 2004. The results of quantitative determinations of oxygen (the values of COD and BOD_5) for the analysed samples of leachate suggest that small amounts of organic pollutants were present (Fig. 5). The BOD_5/COD ratio for all the samples reached between 0.03 and 0.38, which proves that the landfill is stabilized.

The total carbon content in leachate ranges from 195.0 to 12,060.0 mg dm^{-3} . In the leachate from the municipal waste landfill in Brodnica this ratio was very low, at 39.66 mg C dm^{-3} . Although there was a large variation in the content of organic carbon during our study (3.54 – 64.81), in none of the cases the determined values were higher than the monthly values within the ranges quoted by various authors (SZUBSKA 1997, KULIG 2002, KLOJZY-KARCZMARCZYK et al. 2003, ROSIK-DULEWSKA 2007). The highest total carbon content was recorded in October, and the lowest – in August 2004. The differences between the values of TOC obtained in June 2004 and March 2005 were not significant, while these between the other months were highly significant (Fig. 6).

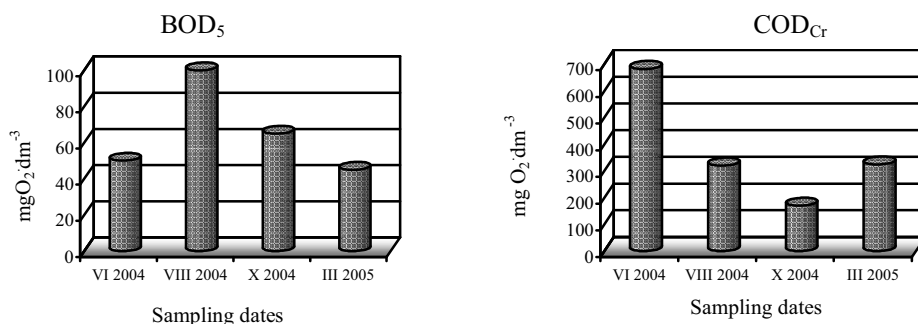


Fig. 5. Values of BOD_5 and COD_{Cr} in leachate from the landfill

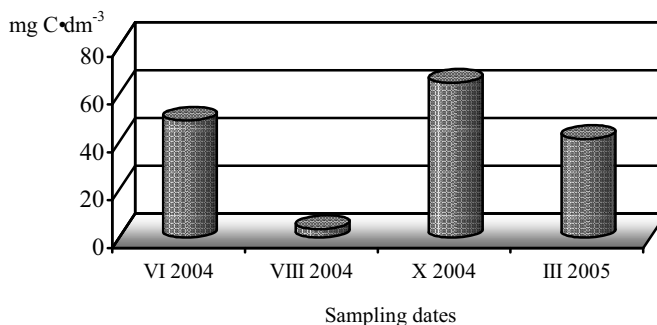


Fig. 6. Content of total organic carbon in leachate

Among the indices characterising salinity of leachate are proper electrolytic conductivity and content of soluble substances such as sulphates, chlorides and calcium and magnesium ions. Many authors report that values of these

parameters in leachate can be highly varied (BELLEVI, BACCINI 1989a,b, DĄBROWSKA et al. 1999, KULIG 2002, KŁOJZY-KARCZMARCZYK et al. 2003, MOCZULSKA 2006A,B, KŁACZKO, ROSIK-DULEWSKA 2007, SZYMAŃSKI et al. 2007). The highest concentrations of soluble substance appear in the first 2-3 years of the exploitation of a new landfill.

In the leachate from Brodnica Landfill, the values of indices expressing the salinity of effluents were also highly varied. The value of proper electrolytic conductivity was within 1,115.1 – 7744.30 $\mu\text{S cm}$ (on average, 4,675.00 $\mu\text{S cm}$). High values of this parameters in leachate from municipal waste dumping sites have been recorded at other locations (VADILLO et al. 1999, SZYMAŃSKI et al. 2007). The value of proper electrolytic conductivity at Brodnica Landfill demonstrably declined during our study, which may have been a result of fitting a draining system to Section II of the landfill. Consequently, the wastewater discharged to the WTP was more strongly diluted. Similar tendencies appeared with respect to the values characterising the content of soluble substances in leachate (Fig. 7).

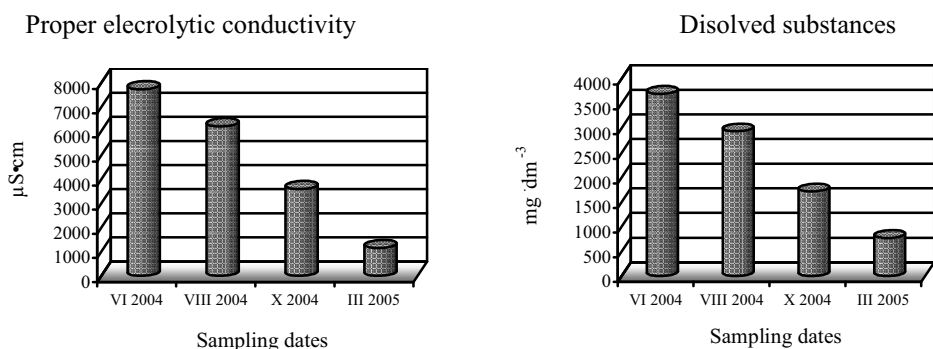


Fig. 7. Value of proper electrolytic conductivity and content of dissolved substances in leachate

Values of salinity indices expressed as the content of sulphates and chlorides were much lower compared to the composition of leachate from other landfills similar in age (KŁOJZY-KARCZMARCZYK et al. 2003, MOTYKA et al. 2005, KODA et al. 2007, SZYMAŃSKI et al. 2007) (Fig. 8). Noteworthy is the elevated value of sulphate ions versus chloride ions, which indicates that the hydrochemical type of leachate had been shaped as a result of leaching sulphate minerals, which are a product of sulphate weathering. During our study, the concentration of sulphates in leachate grew demonstrably – from 28.00 to 101.00 $\text{mg SO}_4^{-2} \text{ dm}^{-3}$. Reverse dependencies occurred in regard to the content of chlorides, whose ions fell from 897.75 $\text{mg Cl}^{-} \text{ dm}^{-3}$ to 106.50 $\text{mg Cl}^{-} \text{ dm}^{-3}$.

SURMACZ-GÓRSKA et al. (2000), who analysed composition of leachate from three municipal waste landfills, different in age and exploitation technology, demonstrated that high salinity in leachate, mainly the content of chlorine ions, is caused largely by depositing street waste collected during winter season as well as the release of chlorine during mineralization of organic substance in fermentation processes that take place in masses of deposited waste. This, however, has found no

confirmation in the authors' own study, as shown by much lower values of this ion in leachate sampled in spring than in summer or autumn.

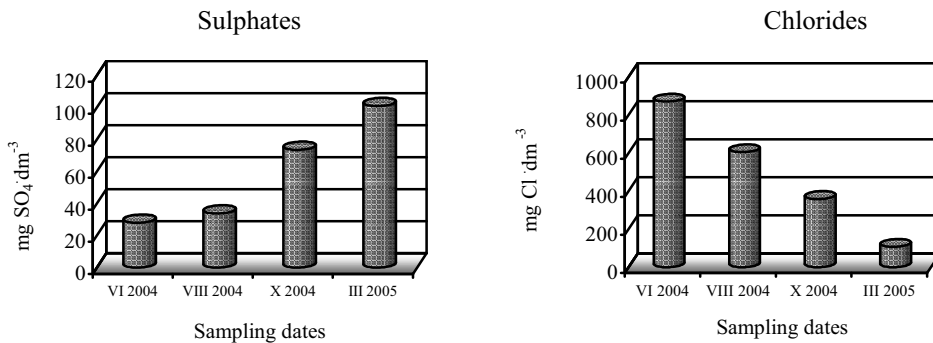


Fig. 8. Content of sulphates and chlorides in leachate from the landfill

The average content of calcium ions was 72.64 mg Ca⁺² dm⁻³, with values of this parameter being significantly higher in leachate samples collected in autumn than in spring (Fig. 9, Tab. 1). During our study, the level of magnesium fell demonstrably, from 226.18 to 22.97 Mg⁺² dm⁻³, which was obviously caused by the dilution of leachate when a draining system was installed in Section II of the landfill. High levels of magnesium ions in leachate from municipal waste landfills have been noticed by other authors (VADILLO et al. 1999, MOTYKA et al. 2005).

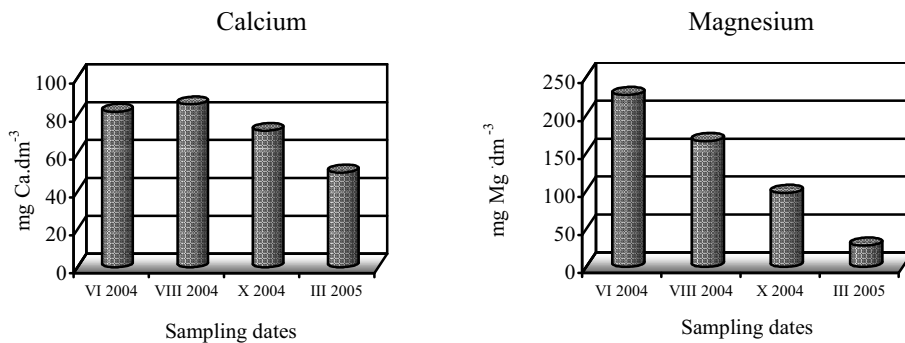


Fig. 9. Content of calcium and magnesium cations in leachate from the landfill

Elements classified as heavy metals, whose salts are mostly toxic substances, are particularly noxious pollutants in leachate. Leachate from landfills tend to contain most of Fe ions, but other elements such as Cr, Ni, Cu, Cd and Pb appear as well, albeit in lower concentrations. Heavy metals undergo more intense leaching during the early years of operating a landfill than in later years. This is a consequence of processes occurring in a young landfill which lead to acidification of leachate (ROSIK-DULEWSKA, KARWACZYŃSKA 1998, SUCHY et al. 1998, BUDEK et al. 2000, ROSIK-DULEWSKA 2003, KOZAKIEWICZ, MIKOŁAJCZYK 2003, SZYMAŃSKI et al. 2007). The presence of this group of elements in leachate is mainly caused by

disposal of batteries, fluorescent bulbs, accumulators and empty paint, varnish or solvent containers, etc. In countries where waste recycling is well-developed, the content of heavy metals in landfill leachate is much lower (WARGAN 2002, WARD et al. 2005, SZYMAŃSKI 2006).

Table 1

Statistical calculations for values of physical, oxygen and salinity indices in landfill leachate

Index	LSD _{0,05}	Standard deviation	Standard error
Reaction	0.60	0.14	0.07
BOD ₅	7.93	24.83	12.42
COD _{Cr}	23.47	217.50	108.75
Total organic carbon	8.11	25.99	13.00
Proper electrolytic conductivity	85.75	2903.90	1451.95
Dissolved substances	57.25	1294.60	647.30
Sulphates	9.35	34.51	17.25
Chlorides	28.80	327.47	163.74
Calcium	6.39	16.15	8.07
Magnesium	14.72	85.60	42.80

In the early years of operating a landfill, the leachate also contains bacteriological contaminants. OLESZKIEWICZ (1999), KAŻMIERCZUK, KALISZ (2001) and NIEMIEC and ZAMORSKA (2002) report that landfill leachate is several-fold more loaded with bacteria than municipal wastewater and sewage. In addition, it also demonstrates a much larger variation of the bacterial fauna. Landfill leachate contains numerous pathogenic microorganisms, including the ones responsible for intestinal infections (typhoid fever, dysentery, diarrhoea in children), tuberculosis, tetanus, gas gangrene, anthrax, diphtheria and viruses of jaundice or Heine-Medina as well as enteroviruses and adenoviruses. The most common bacteria are rods of *Salmonella typhi* and *Salmonella paratyphi*. These bacteria are claimed to be a potential source of pathogenic microorganisms, which can considerably affect the level of pollution of ground and surface waters.

The effect of municipal waste landfill leachate on quality of ground and surface waters

Landfills are typically situated on the surface or near the surface of the ground, which means that they are within the natural circulation of water in the environment. Atmospheric precipitation rinses trickles through a whole landfill, carrying leached pollutants to subsurface, surface and even deep groundwater. Migration of pollutants in leachate to the hydrosphere is certainly one of the gravest problems caused by the presence and exploitation of landfills (AVERESCH 1995, BŁASZCZYK, GÓRSKI 1996, BARTOSIEWICZ 2002, KŁOJZY-KACZMARCZYK, MAZUREK 2003, KRYZA, CHUDY 2003, KŁACZKO-SZYMAŃSKI 2007). The pollutants found in leachate, due to their toxicity, lead to persistent contamination of surface waters, disrupting their natural

balance and inhibiting their self-purification. Pollutants can also enter groundwater, mainly in the first aquifer, causing contamination (SZYSZKOWSKI 1995, KODA 2001, MORYL, MORGA 2001a, b, KLOJZY – KARCZMARCZYK et al. 2003).

The extent of the influence of a landfill on the quality of water is measured as a distance from the edge of the landfill cap to the line surrounding the landfill along which the values of pollutants equal the values of the hydrogeochemical background. As SZYMAŃSKA – PULIKOWSKA (2001) reports, leachate infiltrating from the landfill to the ground can be partly purified in the aeration zone and further purification takes place in the zone of saturation of the aquifer. Under favourable hydrogeochemical conditions, pollutants from leachate can migrate with groundwater over large distances, exceeding 1,000 m.

According to BŁASZYK and GÓRSKI (1996) or MORYL and MORGI (2001a, b), migration of pollutants from a landfill is mainly conditioned by the permeability of rock formations in the substrate directly under the deposited waste. Apart from migrating with the rainfall trickling through the landfill, pollutants can also reach groundwater as a result of leaching the waste in the saturation zone if the water table is high.

The total load of pollutants removed from the landfill depends on the type of deposited waste and biological as well as physicochemical transformations which occur in the landfill body. Reduction of the stream of precipitation trickling deep through landfill has a significant influence on limiting the penetration of leachate to the environment. Considering the variety of hydrogeological conditions, it is extremely important to select a good location for a new landfill and to create appropriate barriers reducing the outflowing infiltration water stream (TWARDY, JAGUŚ 2001A, SIKORSKA-MAYKOWSKA et al. 2002).

The volume of pollutants escaping the landfill leachate to ground and surface waters can be evaluated through by monitoring the quality of water through a network of piezometers or by analysing water quality in nearby homestead wells. In our study, the level of deep groundwater measured in model piezometer P1, situated in front of the landfill basin, where the groundwater was flowing to the landfill, and in piezometer P2, drilled into a water stream flowing away from the landfill, ranged within 1.75 and 3.50 m. In both piezometers, higher levels of water were observed in summer and spring than in autumn (Tab. 2).

Table 2

Values of physical parameters of subsurface and surface water

Parameter	unit	Piezometers				Surface water (water pond)
		1	2	3	4	
		Deep groundwater		Groundwater		
Water level	m	*3.48	1.91	0.95	0.88	-
		**3.44÷3.50	1.75÷2.10	0.65÷1.50	1.15÷0.25	
Reaction	pH	7.46	7.00	7.18	7.36	7.60
		7.30÷7.70	6.80÷7.35	6.95÷7.50	7.05÷7.85	

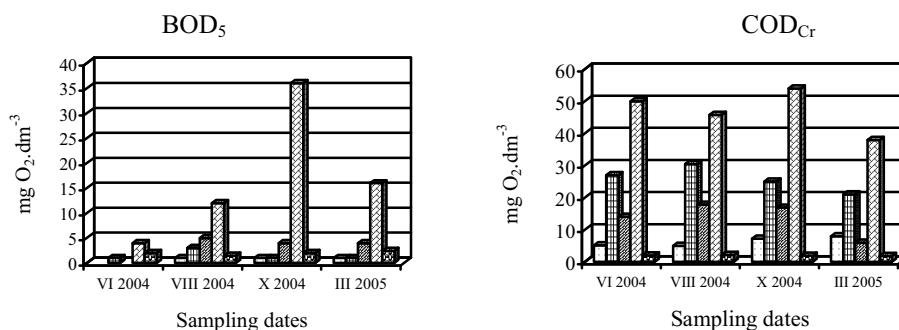
*average
**fluctuations

The average level of groundwater collected from piezometers P3 and P4, drilled into the water flowing away from the landfill, was similar, oscillating between 0.88 and 0.95 m. In the former piezometer, the highest water level occurred in spring, and the lowest one – in autumn; in the latter piezometer, higher values were determined in summer and lower – in spring.

The average value of the reaction (pH) of groundwater was similar in all piezometers, ranging within 7.00 and 7.46 (Tab. 2). Lower pH values were determined in ground than in surface waters, in which the average reaction was 7.50. According to this parameter, all the analysed water samples could be classified as water purity class I.

Waste, next to wastewater, sewage and mineral fertilizers, is one of the major factors responsible for degradation of water supplies, especially resources of groundwater. Threats posed by a landfill to the surface of the earth or to air are just as noxious, but they will appear only as long as a given landfill is operated. The subterranean sphere, however, is threatened not only during the life of a landfill but also when it has been closed, which makes landfills a danger to groundwater for tens or even hundreds of years after their exploitation was terminated (GÓRSKI 2002, KODA 2001, TWARDY, JAGUŚ 2001 b, ZAŁATAJ 2001, KODA et al. 2006, 2007).

Deep groundwater collected from the area adjacent to the municipal waste landfill in Brodnica, which is being exploited, were characterised by small variations in the values of BOD₅. The average value of this parameter in water sampled from both piezometers P1 and P2 varied at a level of 1.50 mg O₂ dm⁻³, which classifies this water as belonging to water purity class I (Fig.10). Several-fold higher values of BOD₅ were determined in groundwater, where the average value of this parameter was 4.33 mg O₂ dm⁻³ in piezometer P3, water purity class III, and 17.00 mg O₂ dm⁻³ in piezometer P4, water purity class V. In the former case, higher values were recorded in water samples collected in summer and lower – in water samples taken in autumn and spring. Regarding piezometer P4, situated behind the landfill cap, near the wastewater pumping station, very high variations in BOD₅ were noticed, oscillating from 4.00 to 36.00 mg O₂ dm⁻³. The highest values were observed in autumn, and the lowest ones in summer.



Key: □ – Piezometer 1; ▤ – Piezometer 2; ▨ – Piezometer 3; ▩ – Piezometer 4; ◆ – Water pond

Fig. 10. Values of BOD₅ and COD_{Cr} in subsurface and surface water

Surface waters sampled from the water pond showed the value of BOD₅ equal 5.87 mg O₂ dm⁻³, which corresponds to water purity class I.

During the whole study, deep water sampled from model piezometer (P1) was characterised by low and only slightly varied values of COD_{Cr} (Fig. 10). The value of this index enabled us to classify the water as belonging to water purity class I. On the other hand, the average value of COD_{Cr}, determined in deep water collected from piezometer P2, located at the animal asylum, was 4-fold higher compared to the average value of this parameter in deep groundwater collected from model piezometer P1. Based on the values of this index, the water should be classified as water purity class IV. Higher values of COD_{Cr} were recorded in August 2004, and lower – in March 2005. High values of COD_{Cr} in deep groundwater collected from piezometer P2 suggest that the contamination of that water was affected by both the landfill and other sources of pollution (the animal asylum). This is confirmed by the lower values of COD_{Cr} found in shallower groundwater collected from piezometer P3, which is 10 m west of the landfill. In that case, higher values of this parameter occurred in summer 2004 than in spring 2005. A noticeable decline in the values of COD_{Cr} was within the range of 17.77 and 6.00 mg O₂ dm⁻³, which classifies these waters as water purity class II. The ground waters sampled from piezometer P4, located behind the landfill basin, about 8 m from the pumping station, were characterised by much higher values of COD_{Cr} than ground waters from piezometer P3. The average value of this parameter was 46.92 mg O₂ dm⁻³, corresponding to water purity class IV.

The average value of COD_{Cr} in surface waters sampled from the water pond was 51.00 mg O₂ dm⁻³, which means that they belonged to water purity class IV.

The total organic carbon content in deep and ground waters was highly varied. The average content of this component in waters sampled from the model piezometer P1 was 24.04 mg C Ca dm⁻³, which classifies them as belonging to water purity class V (Fig. 11). Significant changes in the total organic carbon content were observed between the sampling dates. In waters collected in summer and autumn the organic carbon content was much lower than in the spring samples. A high content of this component in deep waters collected from model piezometer P1 situated over the inflowing waters, is not a measure of the effect of the landfill on the quality of waters but indicates some pollution from other sources in the area where the piezometer is located.

The deep waters collected from piezometer P2 situated over the water flowing away from the landfill, regarding the total organic carbon content, were classified as water purity class IV. However, it was impossible to state firmly that the poor quality of these waters was caused exclusively by the proximity to the landfill. A series of analyses seems to imply that other pollutants, from the area where the piezometer is located, can be involved. Moreover, among the parameters most highly exceeded there were the ones which did not reach high values in ground waters sampled from piezometers P3 and P4, situated in close proximity to the landfill. Pollution of deep waters sampled from piezometer P2 is therefore caused jointly by the landfill and animal asylum.

The average content of organic carbon in ground waters collected from piezometer P3 was 9.94 mg C dm⁻³, which corresponds to water purity class IV; in

ground waters collected from piezometer P4, located behind the landfill cap, it was $20.47 \text{ mg C dm}^{-3}$, which means they belonged to water purity class V. In both cases, the highest values were observable in spring and the lowest ones – in summer.

The total content of organic carbon in surface waters from the water pond equalled $36.44 \text{ mg C dm}^{-3}$, which corresponds to water purity class V (Fig. 11).

The actual threat to ground waters depends not only on the amounts of waste deposited but also on its physicochemical properties, such as water solubility, toxicity, capability of water soluble substances, once they have entered ground waters, to undergo self-purification processes. The extent of threat to ground waters is also dependent on hydrogeological conditions near the landfill. How fast pollutants will spread in ground waters depends on such factors as the volume and quality of leachate, purifying properties of the aeration and saturation spheres, flow properties (hydraulic slope and thickness of strata) which condition the speed and intensity of flow, type of ground in the layer above the water table and in the aquifer (BŁASZYK, BYCZYŃSKI 1986, VADILLO in. 1999, SICIŃSKI, MYŚKÓW 2000, SZYMAŃSKA-PULIKOWSKA 2001a,b, KŁOJZY-KACZMARCZYK et al. 2003).

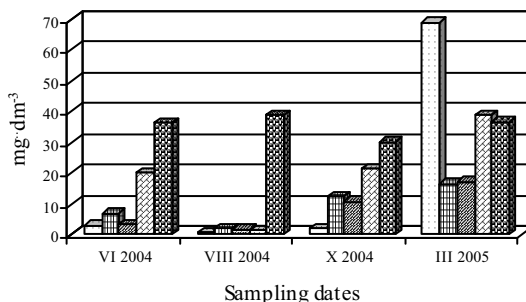


Fig. 11. Content of total organic carbon in subsurface and surface water

Key: – Piezometer 1; – Piezometer 2; – Piezometer 3; – Piezometer 4; – Water pond

In the analysed deep waters sampled near the landfill in Brodnica, the average value of proper electrolytic conductivity was between $730.2 \mu\text{S cm}$ (P1) and $712.3 \mu\text{S cm}$ (P2), which corresponds to water purity class II (Tab. 3). In both cases, significant differences were determined in values of this parameter between particular water sampling dates. The highest value of proper electrolytic conductivity appeared in the first three months and the lowest – in the last three months of a year.

The average value of proper electrolytic conductivity in groundwater was $780.0 \mu\text{S cm}$ (P1) and $1,444.8 \mu\text{S cm}$ (P2), which classifies this water as water purity class II and III, respectively. In both cases, the highest values were recorded in October 2004 and the lowest ones – in March 2005. The differences in the recorded values of proper electrolytic conductivity between the sampling dates were significant (Tab. 3).

The water sampled from the water pond demonstrated proper electrolytic conductivity around $681.00 \mu\text{S cm}$, which means it belonged to water purity class II.

One possible measure of the influence the landfill has on the hydrosphere is the increase in concentration of water soluble substances in ground and surface water. Our analyses of the chemical composition of water samples collected from the four piezometers near the landfill in Brodnica indicate certain pollution of ground water: both deep and subsurface one. This pollution consisted of the increased mineralization of the water and elevated values of such indices as the concentration of chlorides and sulphates. Similarly to the parameters discussed earlier, it is not possible to state firmly whether this situation was an effect produced solely by the landfill. Other factors may have been involved, which is suggested by raised values of many parameters found in deep groundwater collected from model piezometer P1. A possible example is the content of soluble substances, which would enable us to classify the water as water purity class III. Similar levels of soluble substances were found in deep groundwater sampled from piezometer P2, located on the premises of the animal asylum and in groundwater collected from piezometer P3. The groundwater collected from piezometer P4, situated close to the leachate pumping station, contained the highest concentration of soluble substances among all the analysed water samples. Based on the average content of soluble substances, the water from that piezometer belonged to water purity class IV.

Table 3

Values of salinity indices for subsurface and surface water

Parameter	unit	Piezometers				Surface water (water pond)
		1	2	3	4	
		Deep groundwater		Groundwater		
Proper electrolytic conductivity	$\mu\text{S}\cdot\text{cm}$	*730.20	712.30	780.00	1445.05	681.00
		** 677.4-789.0	602.00 - 805.70	755.80 - 817.00	1019.60 - 1828.00	
		LSD _{0,05}	19.98	15.70	15.23	
Dissolved substances	$\text{mg}\cdot\text{dm}^{-3}$	498.00	557.00	588.70	897.00	463.00
		448.00 - 594.00	466.00- 680.00	511.00 - 690.00	760.00 - 1032.00	
		LSD _{0,05}	24.34	16.06	25.58	
Sulphates	$\text{mg SO}_4^{-2}\cdot\text{dm}^{-3}$	70.45	58.36	89.79	40.12	48.00
		61.45 - 77.91	38.00 - 94.00	73.55 - 119.00	21.79 - 58.00	
		LSD _{0,05}	7.71	7.88	13.44	
Chlorides	$\text{mg Cl}^{-}\cdot\text{dm}^{-3}$	44.32	39.01	14.55	118.48	49.70
		39.05 - 53.96	26.63 - 53.96	12.42 - 17.04	85.20 - 170.40	
		LSD _{0,05}	7.72	5.37	4.07	
Calcium	$\text{mg Ca}^{+2}\cdot\text{dm}^{-3}$	122.24	82.16	137.61	137.78	106.21
		120.24 - 124.25	68.14 - 96.19	132.26 - 148.30	94.19-158.32 -	
		LSD _{0,05}	3.78	5.97	8.12	
Magnesium	$\text{mg K}^{+}\cdot\text{dm}^{-3}$	17.63	15.50	29.39	49.55	17.02
		13.98 - 24.32	12.16 - 17.02	22.50 - 34.05	27.97 - 70.53	
		LSD _{0,05}	6.43	2.41	6.59	

*average

**fluctuations

The average content of soluble substances in water samples obtained from the water pond was $463.00 \text{ mg dm}^{-1}$, which corresponds to water purity class I.

Migration of pollutants to groundwater becomes a health hazard when it is used as a source of potable water. The rate and direction of the migration of pollutants to groundwater are mainly conditioned by geological factors. In sedimentary rocks (e.g. limestone, sandstone, dolomite), groundwater tend to flow along bedding planes. The channels created by flowing water in such rocks enable water to travel over relatively big distances without any changes in the concentration of pollutants. Metamorphic rock, on the other hand, such as slate, enable polluted groundwater to travel fast along fracture zones (BŁASZCZYK, GÓRSKI 1996, ALLEN 1999, VADILLO et al. 1999, GOLIMOWSKI, KODA 2001, KRYZA-CHUDY 2003, MOCZULSKA 2006a,b, KŁACZKO, SZYMAŃSKI 2007).

The content of sulphides and chlorides in deep groundwater sampled from the model piezometer and the piezometer at the animal asylum was within the range that would classify it as belonging to water purity class I. The quality of groundwater collected from piezometer 3 and of surface water from the water pond was similar with this respect. The values of these parameters determined in the groundwater sampled from the piezometer located near the leachate pumping station were higher, suggesting that the water belonged to water purity class II. Variations in the content of sulphides and chlorides in water samples from each of the piezometer were relatively large and highly significant differences were noticed at most of the sampling collections. Higher values of these ions were recorded in spring than in summer and autumn.

The content of calcium and magnesium in groundwater samples collected from the piezometers were typical of water representing water purity class I and II. The content of calcium ions in deep groundwater oscillated around 68.14 and $124.25 \text{ mg Ca}^{+2} \text{ dm}^{-3}$, whereas that of magnesium ions ranged between 12.16 and $24.32 \text{ mg Mg}^{+2} \text{ dm}^{-3}$. The average content of calcium in this water was higher by 9.52 to $49.52 \text{ mg Ca}^{+2} \text{ dm}^{-3}$ than in leachate. Thus, it can be assumed that the concentration of calcium ions in deep groundwater was conditioned not only by the influence produced by the landfill but also by other sources of pollution nearby. In the groundwater collected from piezometers P3 and P4, there were evident oscillations in the concentrations of both ions, reaching an amplitude of tens of mg dm^{-3} , with a clear decreasing tendency for the content of calcium in water samples collected in spring versus samples obtained in summer and winter.

In the surface water, the average content of calcium corresponded to the level assigned to water purity class III, while that of magnesium would classify the water to water purity class I.

Our study has demonstrated that the negative influence of well designed and properly maintained landfills on the hydrosphere can be greatly reduced by using adequate barriers (seals). However, groundwater and surface water need to be constantly monitored, in order to prevent potential contamination, which landfills can cause due to uncontrollable migration of leachate.

Summary

Municipal waste landfills are among the objects claimed to exert adverse influence on the natural environment, mainly on the aquatic-terrestrial environment. Landfills can cause very strong pollution of the hydrosphere with a variety of components, more often than not toxic ones. Under favourable hydrogeological conditions, leachate, produced by an operating landfill, can travel over large distances and pose a threat to subsurface water, and consequently local sources of potable water. Thus, constant monitoring of pollutants which can escape to the hydrosphere both while a landfill is operated and after it has been closed down, is necessary. It is also necessary to control the efficiency of the applied sealing systems and potential faults of the used insulation. With such constant monitoring of the effect produced by the landfill on the natural environment the risk of leachate permeating to the aquifer is much lower. This is confirmed by the results of the authors' own studies, which demonstrated that although the examined landfill had insulation barriers, it could be a certain risk to the aquatic and terrestrial environment, as was made evident by the differences in the physical, oxygen and salinity indices determined in leachate, subsurface and surface water. Based on the results of our determinations, it was not possible to state firmly that the quality of groundwater from a given piezometer (including the model one) corresponded to one class of water purity. In some cases, the values of the physical, oxygen and salinity indices exceeded the permissible values of water purity class IV or V. However, it is not possible to state firmly if this situation was a result of the migration of pollutants from the landfill. Identification of sources of components degrading the quality of subsurface water is rather difficult due to the fact that there are several potential points of pollution, e.g. the animal asylum, arable fields. The effect of the landfill on the water physical, oxygen and salinity indices depended on the sampling site. Samples collected from the cross-section above the landfill were characterised by a lower content of chemical substances than the ones sampled at the same time from the cross-section below the landfill. This tendency held true for nearly all of the analysed components (pH, Ca, Mg, Cl⁻, SO₄²⁻). The reaction of the analysed water samples was in most cases alkaline, with small variation.

Comparing the water samples taken from the piezometers drilled along the direction of groundwater flow (behind the landfill basin and at the animal asylum), it was found out that the further away from the landfill, the lower the values of the parameters. There was only one exception to this rule, namely sulphates, whose concentration was not correlated with the distance to the landfill.

The results of our study prove that rational management and exploitation of a landfill, proper sealing to the substrate bed and regular monitoring, one can limit the negative influence of a landfill on the environment.

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