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LOCATION OF WASTE LANDFILLS IN THE ASPECT OF HYDROGEOLOGICAL CONDITIONS

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ABSTRACT: Selecting a site for a landfill should minimise the inevitable ecological effects. The Regulation of the Minister of the Environment (2013) on waste landfills specifies, among others, that it is best to locate a landfill in a place with a natural geological barrier. For landfills other than hazardous and neutral waste, the minimum thickness of the barrier should be ≥1.0 m, and the value of its filtration coefficient $k \leq 1.0 \times 10^{-9}$ m/s. Another criterion for the location of landfills is the expected piezometric table of groundwater, at least 1 m below the level of the planned excavation. In the paper, the last criterion is subjected to a critical analysis based on the results of my own research. It analyses what the piezometric table of groundwater is and what impact it has on the possible penetration of potential pollutants. The considerations are carried out on the example of the ground predicted for a waste landfill, for which tests necessary to determine the hydrogeological conditions were carried out.

KEYWORDS: landfill, hydrogeological conditions, piezometric water table

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Introduction

For many years in Poland, landfills were located, built and operated without clear guidelines and legal regulations. Their role was most often played by excavations, which were the remains of mining, mainly sand and gravel, most often without natural barriers made of cohesive soils that would have a sealing effect (Łuczak-Wilamowska, 2013; Wysocka, 2015). It was only in the 1990s that specific actions were started to improve the condition of waste management. The first legal act regarding the principles of waste removal, use and neutralisation was the Regulation of the Minister of Economy of October 21, 1998 (Rozporządzenie, 1998). It only concerned hazardous waste landfills. Earlier, i.e. in 1993, the guidelines of the Minister of Spatial Management and Construction, "A set of recommendations for programming, design and operation of municipal waste landfills", were issued (Piotrowska et al., 1993). However, it was only the regulation (Rozporządzenie, 2003), which was amended in 2009 (Rozporządzenie, 2009), that regulated the legal status in this respect. Currently, the legal document that regulates landfill waste management is the Regulation of the Minister of the Environment of April 30, 2013, on landfills (Rozporządzenie, 2013) and the Notice of the Minister of Climate and Environment of August 6, 2022, on the announcement of the uniform text of the regulation of the Minister of the Environment on waste landfills (Obwieszczenie, 2022).

The work aims to indicate the elements that should be taken into account when preparing a project for the construction or expansion of non-hazardous and neutral waste landfills. Particular attention was paid to soil and water conditions, i.e. the geological structure of the substrate and, above all, hydrogeological conditions.

An overview of the literature

Waste deposited at a storage site, depending on its chemical and mineral composition, is subject to various transformations as a result of reactions with environmental elements, which results in the formation of further secondary pollutants (Sobik-Szołtysek et al., 2013). The resulting hazardous substances migrate outside the landfill area, penetrating the soil lining the landfill and then entering the aquifers. The decomposition processes of municipal waste can take up to even hundreds of years. It should be remembered that leachate is a highly polluted liquid as a result of the seepage of rainwater, runoff water and water contained in waste through the masses of stored waste, containing, among others, sulfates, chlorides, hydrocarbons, pesticides and heavy metals (Wychowaniak, 2013; Koda et al., 2015).

The rational selection of a landfill location is quite a complex process and should follow specific procedures that take into account all elements of the environment and land development. The geological environment should be particu-

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larly taken into account in these processes, as waste is located directly on it as the substrate (Drągowski, 2002). Selecting potential areas within which waste landfills can be located in terms of geological structure and hydrogeological conditions should always be considered individually (Wysocka, 2015, 2018).

The Regulation of the Minister of the Environment of April 30, 2013 on waste landfills (Rozporządzenie, 2013) and the Notice of the Minister of Climate and Environment of August 6, 2022 on the announcement of the uniform text of the regulation of the Minister of the Environment on waste landfills (Obwieszczenie, 2022) specify currently, detailed requirements regarding the location, construction and operation of waste landfills, which correspond to individual types of waste landfills, also specify the scope, time and frequency as well as the method and conditions of monitoring the waste landfill, how geological research should be carried out and the conditions allowing the construction of a landfill in given place. The scope of geological research that should be performed is also imposed, i.e.:

- identification of the geological structure of the planned waste landfill area and its surroundings based on at least five research holes with a depth sufficient to examine the aquifer and insulating layer; however, the minimum number of cored research holes should be one hole per 1 ha of the examined area,
- taking samples and performing a grain size analysis and laboratory determination of the filtration coefficient k from each layer constituting the lithological precipitate,
- conducting hydrogeological observations and field measurements of the filtration coefficient k in each research well,
- examining the spatial structure of the rock mass in the area of the planned waste landfill and its surroundings using geophysical methods, in particular, the electrical resistivity method or the seismic method,
- determining the sorption capacity of the soil.

The content of the above legal acts also states that:

- the landfill is located so that it has a natural geological barrier that seals the bottom and side walls,
- the minimum thickness and value of the filtration coefficient k of the natural geological barrier for a waste landfill is:
  - hazardous – thickness not less than 5 m, filtration coefficient $k \leq 1.0 \cdot 10^{-9}$ m/s,
  - other than hazardous and neutral – thickness not less than 1 m, filtration coefficient $k \leq 1.0 \cdot 10^{-9}$ m/s,
  - neutral – thickness not less than 1 m, filtration coefficient $k \leq 1.0 \cdot 10^{-7}$ m/s.
- the geological barrier should have a horizontal extension exceeding the area of the planned waste landfill,

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- the expected highest piezometric level of groundwater at the bottom of the landfill should be at least 1 m below the level of the planned excavation.

Additionally, the regulations to the Geological and Mining Law Act (Act, 2011) regarding geological works projects (Rozporządzenie, 2011) and the preparation of hydrogeological and geological-engineering documentation (Rozporządzenie, 2016) impose the type of geological research and work that should be performed in the area of land where the waste landfill is to be built. The basis is to perform drilling (their number depends on the size of the waste landfill), which is intended to approximate the geological structure of the area. Their depth should be sufficient to examine the aquifer and the isolating layer. For a thorough analysis of the research area, it is also important to use archival wells near the planned investment, as well as topographic, geological and hydrogeological maps. When drilling holes, soil samples should be taken for grain size analysis and laboratory determination of the filtration coefficient k from each layer constituting the lithological precipitate. The sorption capacity of the soil is also tested. Hydrogeological observations should also be carried out, and field measurements of the filtration coefficient for aquifers should be made. In case of complicated geological conditions, the structure of the rock mass is additionally identified using geophysical methods, in particular, the electrical resistivity or seismic method.

Taking into account geological criteria, it is possible to distinguish areas where landfills can be constructed (Drągowski, 2002):

- I – not recommended and unacceptable for hazardous waste landfills,
- II – possible with restrictions, except for hazardous waste landfills,
- III – beneficial for all types of landfills.

Conditions in group I are influenced by:

- water intake,
- lake bowl areas,
- river valleys,
- shallow groundwater table,
- soils of valuation class I–IV,
- areas of active geodynamic processes (landslides, active karst),
- mining exploitation areas where discontinuous deformations of the land surface occur.

Areas where waste storage is possible for geological reasons but with limitations requiring the use of appropriate technical solutions and extensive research:

- zones where the location of the landfill poses a threat to GZWP (Main Ground Water Reservoirs) and UZWP (Utility Ground Water Reservoirs),
- mining exploitation areas where continuous deformations of the land surface occur,
- areas with slope inclination > 15^{o},
- glacio-tectonically disturbed areas.

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Favourable areas should be considered those that allow optimal use of the subsoil's insulating properties and its load-bearing capacity. Within areas II and III, efforts should be made to locate the landfill:

- in degraded areas,
- areas adjacent to existing landfills,
- use existing post-mining workings.

Under natural conditions, it is difficult to find an area that would meet all recommendations regarding geological structure. However, it can certainly be said that there are regions with better or worse conditions. The most important thing is to choose a location that will minimise the inevitable ecological effects, as well as the amount of financial outlays incurred for arranging landfills so that their impact on the environment is as small as possible (Wiater, 2011; Wysocka & Zabielska-Adamska, 2017).

Sealing municipal and industrial waste landfills, whose task is to reduce the negative impact of waste on the natural environment, is the most important element of landfill construction. Sealing of landfills (Daniel, 1997) is achieved through a system of independently operating protective barriers in the form of geological barriers, seals of the bottom (liner), as well the upper surface of landfills (cover) and vertical barriers. Sealing the landfill surface is mainly intended to protect the landfill surface against atmospheric and biological influences, as well as to protect the surrounding environment against accumulated waste (odours, dust and pieces of deposited materials). This seal limits the infiltration of rainwater into the mass of stored waste and prevents the formation of an increased amount of leachate. The purpose of sealing the base and slopes is to create an impermeable sealing barrier that protects the subsoil against the penetration of leachate and landfill gases into the lower layers of the subgrade and groundwater, as well as to discharge the resulting leachate into the treatment system. Side sealing, in the form of vertical barriers reaching the impermeable ground, eliminates the horizontal migration of leachates outside the landfill and allows for maintaining a lower groundwater level inside the closed barrier (Zabielska-Adamska, 2006). The method of selecting and implementing the seal depends primarily on the type of landfill, the geological and hydrogeological structure of the substrate and the type of waste stored (Górecka & Koda, 2010).

The seals of the bottom of landfills are most often single or double-mixed (complex) seals. They consist of layers of appropriately incorporated cohesive soils with a permeability coefficient $k < 10^{-9}$m/s, characterised by a long-term ability to bind and retain compounds contained in leachates from stored waste and landfill gases and synthetic geomembranes (Daniel, 1997; Rowe, 2005). Instead of compacted cohesive soils, seals are also used in the form of sealing mats made of industrially combined layers of geotextiles and bentonite, called GCL (Geosynthetic Clay Liner). Since damage to the geomembrane causes the entire structure to leak, leakage through the hole in the geomembrane is minimised by placing a mineral sealing layer below the geomembrane. The flow rate

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of leachate through a mixed seal is much lower than through a geomembrane or mineral layer used separately. The situation is similar to the migration speed of pollutants caused by molecular diffusion. The materials most often used to build mineral sealing layers are clays and boulder clays, sealed with bentonite, hydraulic binders, or silica (Zabielska-Adamska, 2006, 2020).

Wiater (2011) emphasises that none of the currently used technologies for protection and subsequent operation completely protect the environment against the negative impact of stored waste. Waste landfills should, therefore, be located primarily in places where their negative impact on soil and water conditions will be as small as possible. The best areas would be areas where the aquifer lies deep, and above it, there are poorly or practically impermeable formations in the form of suitable cohesive soils. Such a geological situation and an additional artificial barrier would significantly minimise the impact of stored waste on groundwater.

Description of subsoil for a future landfill

The subject of the research is an excavation after the exploitation of a clay deposit. This area has been excluded from mining activities and is planned to be partially reclaimed by filling it with waste permitted for use in the Regulation of the Minister of the Environment of March 21, 2006, on the recovery or disposal of waste outside installations and devices (Rozporządzenie, 2015), and in the remaining part of it is planned to invest in the construction of a landfill for waste other than hazardous and neutral. Therefore, following the Regulation of the Council of Ministers of September 10, 2019, on projects that may have a significant impact on the environment (Rozporządzenie, 2019), the excavation in question, within which waste collection is planned, has been classified as a project that may always have a significant impact on the environment, which dictates the implementation of further activities aimed at determining geological conditions, as well as monitoring groundwater using research wells – piezometers.

The description of the geological structure and hydrogeological conditions of the area under review was presented based on:

- network of research holes made in the studied area (archival holes and holes made to prepare hydrogeological documentation),
- hydrogeological cross-sections prepared based on existing research boreholes and wells made in the area of the area under review,
- hydrogeological map of Poland at a scale of 1:50,000,
- geological and Economic Map at a scale of 1:50,000,
- geological documentation and studies prepared in the research area,
- on-site visit.

Stratigraphically, in terms of lithology, the formations occurring in the study area are classified as Quaternary, the thickness of which is estimated at approx. 100-150 m (according to the Polish Geological Institute). The geological struc-

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ture of the Quaternary formations in the study area was formed during the Central Polish glaciation and is related to denudation, erosion and accumulation activities occurring during subsequent transgressions and regressions of the Scandinavian ice sheet.

In the studied area, the surface is dominated by reservoir formation deposits in the form of clays, varve and silt clays, which were deposited in an extensive pond formed during the Central Polish glaciation. A series of deposited clays reach a depth of several meters below the ground surface. Underneath the layer of clay, there are mainly silty sands, forming the first aquifer, the floor of which occurs at a depth of approx. 35 m. Below, there are cohesive soils in the form of clays and compact dust with a thickness of approx. 8.0 m, below which there is another aquifer in the form of sand and gravel formations of various granulations. This layer ends at a depth of approximately 60-70 m above sea level, below which there is a complex of clays.

Figure 1 shows a hydrogeological cross-section illustrating the succession of layers of geological sediments. The area lies within the boundaries of a hydrogeological unit within which there are two usable aquifers, i.e. minor and main.

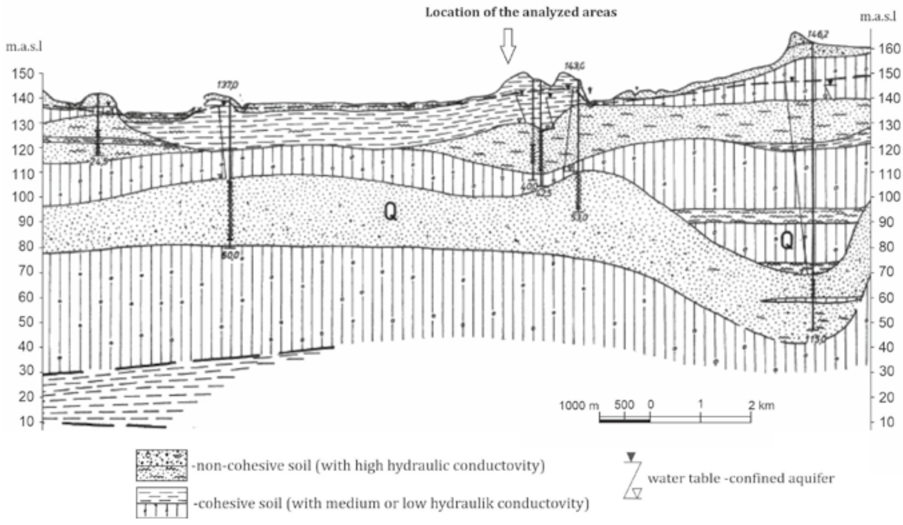

Figure 1. Hydrogeological cross-section of the research area

Source: author's work based on Kleczkowski (1990).

The subordinate level occurs immediately beneath a series of stasis deposits. This level is irregular and discontinuous – in the area of the examined workings, it wedges out and turns into congestive deposits. In the research area, this layer is marginal – it is captured by two deep wells (water used only for plant needs). The water table has a pressure character and stabilises in the research area at an elevation of approximately 139.24–144.79 m above sea level.

The main level, 25 m thick, in the analysed area, occurs at a depth of approximately 45 m. The water table stabilises at an elevation of approximately 143 m above sea level, which indicates that this level may have a hydraulic connection with the higher level, i.e. “subordinate” level. This layer is exploited by water intake wells.

Both layers are supplied mainly by underground-lateral inflow and, to a very small extent, by the seepage of rainwater through the overburden of poorly and practically impermeable formations. According to the hydrogeological map, these levels have a very low-risk level.

The overlying layer of cohesive formations – poorly and practically impermeable – largely protects aquifers against the penetration of potential pollutants.

The analysed area, according to the data included in the study *Map of the areas of the Main Ground Water Reservoirs in Poland requiring special protection on a scale of 1:500,000* (Kleczkowski, 1990), is located outside the boundaries of the designated areas (the landfill area is not within the protection zones of water intakes underground and surface areas as well as areas of special protection – Areas of the Highest Protection and Areas of High Protection of the Main Ground Water Reservoirs in Poland).

Research methods

In the area of the excavation, five research holes were drilled to identify the geological structure and hydrogeological conditions. During drilling, we obtained a macroscopic description of the soil, and samples were taken for laboratory tests. The laboratory tests aimed to determine the filtration coefficient of each layer constituting the lithological precipitate and its sorption capacity and total specific surface area. The analysis focused particularly on the soil that is to seal the base of the landfill. This paper presents the results of laboratory tests for representative soil samples.

Hydraulic conductivity tests can be carried out under either constant or falling head permeability conditions. Falling head methods are linked to hydraulic conductivity tests in the classic oedometer or cylinder, which are equipped with a narrow drain joined with the oedometer (cylinder) bottom designed to supply fluid to the sample. There is no possibility of sample saturation control during the test. In this case, a narrow glass tube with cross-sectional area a was used, connected to the oedometer with a rubber hose, which allows for observing a clear fall of water from the level h_1 to the level h_2 in the tube during the time $t = t_2 - t_1$.

In the case of the oedometer test (with falling head permeability conditions), the filtration coefficient k is calculated according to the formula:

$$k = \frac{a \cdot l}{A \cdot (t_2 - t_1)} \cdot \ln \frac{h_1}{h_2}, \tag{1}$$

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where:
a – the cross-sectional area of the water column filling the glass tube,
l – the soil sample height,
A – the cross-sectional area of the sample,
$(t_2 - t_1)$ – time difference between two subsequent readings of the height of the water column in the glass tube,
h_1 – the height of the water column during the first reading,
h_2 – the height of the water column during the second reading.

The filtration coefficient k is given in m/s. Next, the k values are reduced to k_{10} (at the temperature of 10°C) depending on the measured temperatures T of the flowing water using the formula:

$$k_{10} = \frac{k}{0{,}7+0{,}03\mathrm{T}}, \tag{2}$$

where:
T – the temperature of the flowing water.

Filtration tests with vertical drainage (from bottom to top) were carried out after consolidation of soil samples. The flows were performed at four different stress values σ equal to: 12.5, 50.0, 150.0, and 300.0 kPa.

Attention should be paid to the need to perform tests with a hydraulic gradient $i = \Delta h/l$ greater than the so-called initial hydraulic gradient i_0. In cohesive soils, the pores are usually almost filled with film water; therefore, with a hydraulic gradient smaller than the initial, water does not flow through the soil. According to Roza (Wiłun, 2001), the initial hydraulic gradient for cohesive soils is more than 10, but this applies to soils in a semisolid and solid state. In Wiłun's research, such high values of i_0 were not obtained; they did not exceed 5 for consolidated heavy silty clay.

Determination of sorption capacity and total specific surface area were carried out according to Polish standard PN-88/B-04481. Sorption capacity, MBC, determines the adsorption of methylene blue by the soil suspension. To the beaker with the soil suspension, add methylene blue solution in 0.5 or 1.0 cm^3 portions from the burette, and then mix the mixture for 3 minutes each time using a stirrer. Then, pipette 1–2 drops of the suspension onto a filter paper. If the entire amount of the added dye is adsorbed by the soil, a coloured spot with a colourless water shell is created. As more portions of the dye solution are added, the shell will turn blue. This indicates that the soil's sorption capacity has already been exceeded, and free dye has appeared in the solution. The addition of the solution should then be stopped and resumed after approximately 20 hours. If, after adding a certain amount of methylene blue solution, the colour of the shell was observed for the first time, the sorption capacity of MBC was calculated according to the formula:

$$MBC = \frac{100\mathrm{m}}{2m_s}(V_i + V_{i-1}), \qquad (3)$$

where:
m – the mass of methylene blue contained in 1 cm^3 of the solution, expressed as a 3-water substance,
m_s – the mass of soil used for determination per substance dried at a temperature of 105-110°C,
V_i – the volume of the solution at which the sorption capacity was exceeded,
V_{i-1} – volume of solution corresponding to the penultimate portion of the methylene blue solution before exceeding the sorption capacity.

The total specific surface area of soil S_t is equal to the sum of the surface projections of individual methylene blue molecules adsorbed by the soil (in the saturated state) in the form of a single-molecular layer. The specific surface area should be related to 1 g of soil mass, dried to constant mass at a temperature of 105-110°C, as the product of the *MBC* sorption capacity and the k_1 coefficient.

The specific surface area, S_t, should be calculated according to the formula:

$$S_t = k_1\mathrm{MBC}, \qquad (4)$$

where:
k_1 – the coefficient, the value of which should be equal to 20.94 m^2/g,
MBC – sorption capacity of the soil to methylene blue according to the 3-water substance per 1 g of dry soil mass.

Results of the research

Figure 2 and Table 1 present the results obtained from testing the filtration coefficient for three representative soil samples taken from the subsoil that constitutes the base of the landfill.

Table 1. Results of testing the filtration coefficient (varved clay) using the variable-gradient method depending on the load

Normal stress σ [kPa]	Filtration coefficient k_{10} [m/s]		
	Sample 1	Sample 2	Sample 3
12.5	$4.28 \cdot 10^{-11}$	$3.30 \cdot 10^{-10}$	$3.35 \cdot 10^{-11}$
50.0	$3.36 \cdot 10^{-11}$	$1.93 \cdot 10^{-10}$	$2.55 \cdot 10^{-11}$
150.0	$2.45 \cdot 10^{-11}$	$1.48 \cdot 10^{-10}$	$1.71 \cdot 10^{-11}$
300.0	$3.37 \cdot 10^{-11}$	$1.20 \cdot 10^{-10}$	$1.69 \cdot 10^{-11}$

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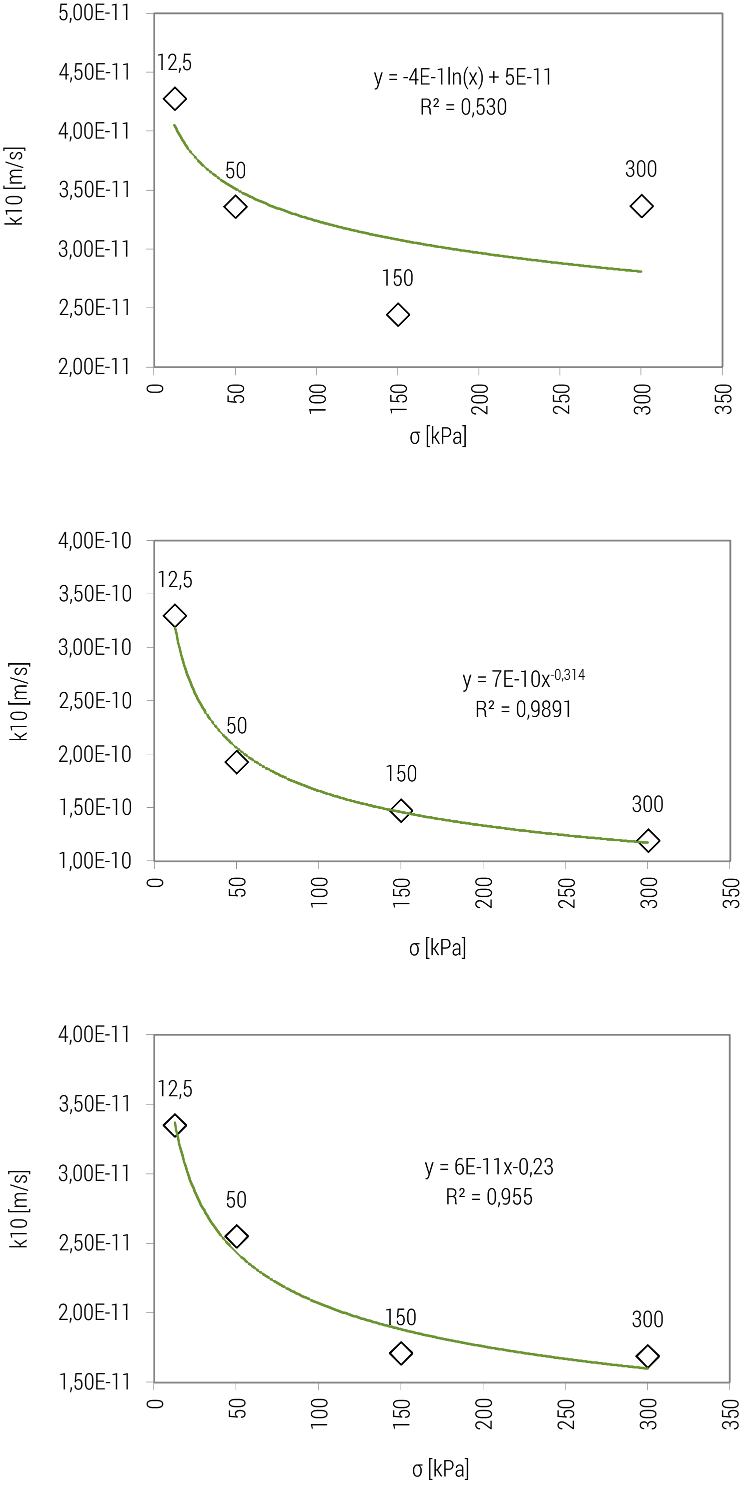

Figure 2. Dependence of the filtration coefficient on the load (varved clay)

The test results for sorption capacity and total specific surface area (varve clay) for three representative samples are presented in Table 2.

Table 2. Test results for sorption capacity and total specific surface area (varve clay)

Sample	Sorption capacity *MBC* of soil [g/100 g]	Specific surface area S_t [m^2/g]
1	6.65	139.19
2	5.49	114.98
3	4.91	102.88

The results of the filtration coefficient tests on soils, which constitute the subsoil for the planned landfill, indicate the sesoils, due to the low value of the filtration coefficient $k < 1\cdot10^{-9}$ m/s, may constitute a natural geological barrier according to legal regulations (Rozporządzenie, 2013; Obwieszczenie, 2022). The filtration coefficient of the subsoil, which is varve clay, ranges from $3.3\cdot10^{-10}$ to $1.71\cdot10^{-11}$ m/s, so the soil can be considered impermeable according to the Pazdro classification (Pazdro & Kozerski, 1990). The value of the filtration coefficient decreases with the loading of the soil, along with sample consolidation.

The value of the sorption capacity also indicates that this soil will be a good seal for the designed landfill because the *MCB* value is 4.91–6.65 g/100 g of soil. The specific surface area of the tested subsoil is 102.88–139.19 m^2/g. According to Wojciechowski (1990), the specific surface area of kaolinites ranges from 0.01 to 30 m^2/g.

It should be added that the subsoil of the considered landfill was assessed as suitable for the construction of mineral insulation barriers for landfills according to the recommendations of the Building Research Institute (Wysokiński, 1995).

Analysis of the piezometric table of groundwater in the light of locating a landfill

An important criterion for the location of landfills, according to legal regulations, is that the expected highest piezometric level of groundwater is located at least 1 m below the level of the planned excavation below the bottom of the landfill.

The piezometric level of the water table, according to the Hydrogeological Dictionary is "The level observed in a piezometer or another hole enabling measurement of the pressure height at a specific point, also in a layer with a free water table" (Kleczkowski & Różkowski, 1997).

Within the excavation where the waste is to be deposited, three piezometers were made, which indicate that the water from the first aquifer stabilises at an elevation of 139.24-140.79 m above sea level. This layer was drilled at the elevation of 128.34-133.9 m above.

If the above criterion were followed, the bottom of the landfill would have to be designed at an elevation of approximately 142 m above sea level, which is impossible given the current development of the area. The potential area for the landfill is a post-mining excavation, the bottom of which is located at the deepest point of 136.0 m above sea level (the average depth of the excavation is approximately 137-138 m above sea level). The above-described situation is presented in Figure 3.

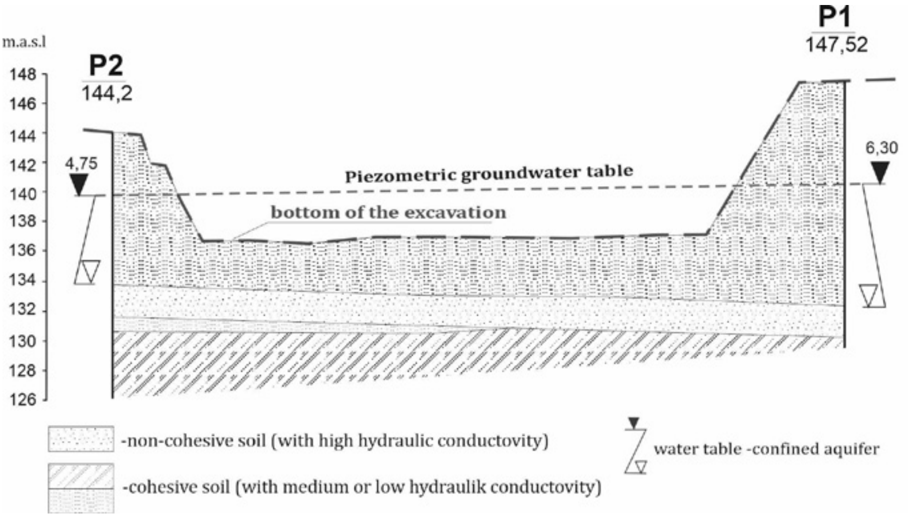

Figure 3. Schematic hydrogeological cross-section through the post-mining excavation – confined aquifer

After analysing the hydrogeological conditions and based on field and laboratory tests, it is concluded that the examined area is favourable in terms of the location of a waste landfill. It is a degraded area (post-mining excavation), has a natural geological barrier in the form of clay soil with a low filtration coefficient of less than $1\cdot10^{-9}$ m/s and a high susceptibility to absorbing pollutants (sorption capacity MCB = 4.91–6,65 g/100 g of soil). The barrier is continuous and also occurs outside the excavation (an extensive basin filled with stagnant formations).

Figure 4 presents a situation where the hydrogeological conditions and geological structure are completely different than those in the above-discussed subsoil.

In the above example (Figure 4), the near-surface formations are non-cohesive – permeable sediments (i.e. sands or gravels), which are associated with their irrigation with a free water table, i.e. one that is not limited from above by

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an impermeable layer and remains under atmospheric pressure. This mirror is located in the drill hole at the depth at which it was drilled. This layer is supplied mainly by the infiltration of rainwater and is directly exposed to the penetration of pollutants from the ground surface. Due to possible contact with possible sources of pollution in the form of stored waste, it requires special protection. In this situation, despite the deep water table, it is believed that the construction of a landfill should never have taken place. The filtration coefficients of the overburdened soils are very high, which causes pollutants to enter the aquifer quickly. The non-cohesive soils found in the subsoil in the form of sand and gravel do not have any sealing properties – these are non-insulating soils according to the classification of soil filtration properties (Witczak & Adamczyk, 1994).

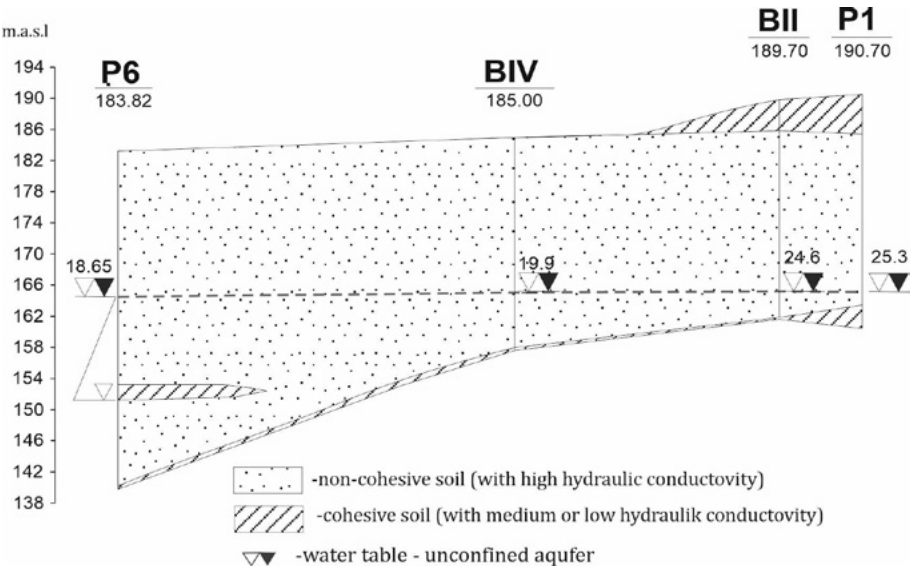

Figure 4. Schematic hydrogeological cross-section – unconfined aquifer

Based on the above data, it is considered that the criterion indicated in the regulation (Rozporządzenie, 2013; Obwieszczenie, 2022) regarding the piezometric level of groundwater raises serious concerns. It should be clarified. The kind of aquifer we are dealing with should be taken into account, i.e., whether it is an aquifer with a free water table or a layer with a pressure table.

The piezometric water level in the layer (the excavation in question) arises only as a result of its mechanical disturbance, e.g. by drilling a drill hole. Given such hydrogeological conditions, it is believed that locating the landfill 1 m above the piezometric water level seems too cautious. It would be reasonable to place the waste above the level of the aquifer ceiling, especially since there are areas where the aquifer occurs only at a depth of approximately 60 m below the ground

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surface and is isolated from the ground surface by poorly and practically impermeable formations, and the water table stabilises in drill holes close to or even above the ground surface. Taking into account such an area, the criterion of locating the bottom of the landfill above the piezometric water table is inadequate for the hydrogeological conditions prevailing here.

Conclusions

- The examined area, as required by legal regulations regarding the location of landfills, has a natural geological barrier in the form of clay soil with a low filtration coefficient of less than $1 \cdot 10^{-9}$ m/s and with a high susceptibility to immobilisation pollutants (*MCB* sorption capacity 4.91–6.65 g/100g of soil). The barrier is continuous and also occurs outside the excavation (an extensive basin filled with stagnant formations). The assessed area is degraded. It is a post-mining excavation. Due to the above, this is a potentially suitable area for locating the proposed landfill, even though the piezometric level of the water table is higher than the bottom of the excavation.
- The legal regulations regarding the piezometric water table are imprecise. The fact is that it is impossible to capture all the conditions prepared by nature and man in the regulations. However, it is believed that an important criterion that should be taken into account is whether the aquifer is confined or unconfined.
- In the case of a confined aquifer, the depth of the aquifer must also be taken into account, and not only the depth of the piezometric water table.
- In the case of a free surface, locating the repository only 1 m above its location seems too risky, even with the use of an artificial barrier.
- Selecting potential areas within which landfills can be located in terms of geological structure and hydrogeological conditions should always be considered individually. Unfortunately, legal regulations have made this aspect very schematic.

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LOKALIZACJA SKŁADOWISK ODPADÓW W ASPEKCIE WARUNKÓW HYDROGEOLOGICZNYCH

STRESZCZENIE: Wytypowanie terenu pod składowisko odpadów jest trudnym zadaniem i powinno ograniczyć do minimum nieuniknione skutki ekologiczne. Rozporządzenie Ministra Środowiska z dnia 30 kwietnia 2013 r. w sprawie składowisk odpadów określa między innymi, iż składowisko najlepiej jest sytuować tak, aby miało naturalną barierę geologiczną. Dla składowisk odpadów innych niż niebezpieczne i obojętne minimalna miąższość bariery powinna być ≥1,0 m, a wartość jej współczynnika filtracji $k \leq 1{,}0 \times 10^{-9}$ m/s. Innym kryterium lokalizacji składowisk jest położenie przewidywanego najwyższego piezometrycznego poziomu wód podziemnych, co najmniej 1 m poniżej poziomu projektowanego wykopu dna składowiska. W pracy ostatnie kryterium poddaje się krytycznej analizie, której podstawą są wyniki badań własnych. Analizuje się, czym jest piezometryczny poziom wód podziemnych i jaki on ma wpływ na możliwe przenikanie potencjalnych zanieczyszczeń do wód podziemnych. Rozważania są przeprowadzone na przykładzie podłoża terenu, planowanego pod składowisko odpadów, dla którego wykonano badania niezbędne do określenia warunków hydrogeologicznych.

SŁOWA KLUCZOWE: składowisko odpadów, warunki hydrogeologiczne, piezometryczny poziom zwierciadła wody

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