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MODELLING THE MIGRATION OF ANTHROPOGENIC POLLUTION FROM ACTIVE MUNICIPAL LANDFILL IN GROUNDWATERS

Józef CIUŁA *

* PhD Eng.; State University of Applied Sciences Nowy Sącz, Institute of Engineering, Zamenhofa 1A, 33–300 Nowy Sącz, Poland
E-mail address: *jciula@pwsz-ns.edu.pl*

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Abstract

Landfill requires a systematic monitoring of its impact on groundwater and surface waters. The paper presents the modeling of pollution migration for cases when leachate penetrates the aquifer layer. For this purpose, a conceptual hydrodynamic model of the aquifer was developed in the program Visual ModFlow Pro, which is a spatial two-layer model. Chloride ion was used as an indicator defining the rate of pollution migration. The results of calculations and modeling of pollution migration in soil-water conditions demonstrated that it is practically impossible for pollutants to penetrate the aquifer, since a sufficient protection is provided by artificial insulation and a layer of sandy clays. A potential pollution migration to groundwater can only occur after a rupture – damage to the insulation layer. In such a case, vertical infiltration will be taking place in the 4aeration zone for a relatively long period, while the migration of pollutants already in the saturation zone (hydrated) will be taking place at a relatively high speed.

Keywords: **Landfill site; Leachate; Environmental monitoring; Modeling; Pollution migration.**

1. INTRODUCTION

The storage of wastes in a landfill site is one of the methods of their disposal. The necessity of waste management is enforced by the need to save environmental resources, limit the space indispensable for their neutralization, processing and storage. The selection of an optimal disposal technology, including storage, guarantees their safe neutralization, especially in the future. In order to reduce the amount of landfilled waste, an appropriate waste management strategy must be selected for a particular region, which includes technological, environmental and economic aspects [1]. The use of multi-criteria analysis to estimate and select the most optimal waste management system should include ecological, economic and social aspects. A solution adopted as part of the system must ensure: the reduction of waste stream, social acceptance and profitability of the economic efficiency index. Each applicable strategy should include wastes segregation and the maximum level of their recycling [2, 3]. If wastes require landfilling, it is the landfill site which should serve as a facility to collect wastes for the purpose of their disposal. Proper location, construction and operation of municipal waste landfills reduce the negative impact of the landfill on individual components of the natural environment (soil, groundwater, surface water or air) [4, 5]. Within the boundaries of a single waste treatment plant, mechanical and biological waste treatment installations are located in the vicinity of landfills, which may additionally pose a potential threat to the atmosphere and groundwater [6, 7]. Landfill leachates are characterized by a diversified composition, and they contain, e.g. polycyclic aromatic hydrocarbons, heavy metals and toxic compounds which are particularly dangerous for living organisms. Research studies on the composition of leachate as part of the environmental monitoring often indicate raised levels of such compounds in groundwater in the vicinity of landfills [8, 9, 10].

In order to enhance the reliability of landfill sealing, it is recommended to differentiate the selection of layers to be applied, depending on the identified geological conditions of the substrate and the dimensions of the landfill. Such protective measures are necessary due to frequently occurring damage to geomembranes as a result of pressure, friction and stretching of the sealing layer [11, 12,]. An audit monitoring the condition of the sealing liner of landfill base should be carried out during its operation, during its reclamation as well as after its closure. The basic factors determining sealing tightness are groundwater quality tests in the landfill area [13, 14]. The landfilled wastes containing organic fractions are the source of methane and carbon dioxide emissions to the atmosphere, which are referred to as so-called greenhouse gases. One of the solutions aiming to reduce such fugitive emissions is the construction of degassing installations, biogas intake facilities and its thermal neutralization in engines powered by landfill biogas in the combined electricity and heat generation system [15, 16] Additionally, it is also possible to convert biogas to biomethane and use it to drive motor vehicles [17, 18]. Having in mind the adverse impact of landfills, the key issue at the operational stage and after the closure of the landfill is to ensure environmental monitoring conducted by the operator. The scope of monitoring specified in relevant legal acts is the basis for settlements with control authorities. The conducted research also demonstrated that apart from heavy metals, also inorganic and organic substances were found in the leachate [19, 20]. In order to effectively predict and estimate the transport of pollutants in groundwater, in the event of damage to the sealing liner, progressively more frequently IT tools integrated with GIS systems (Geographic Information System) are applied to support the mathematical modeling process [21].

With respect to landfill leachate management and the management of possible hazards of landfill sealing damage, it is recommended to perform numerical modeling of anthropogenic pollutants migration in groundwater, using hydrodynamic models to estimate the distribution accuracy of potential pollutants [22]. Based on hydrogeological maps and the actual measurement data, mathematical models of filtration and mass transport are developed. Such models are mainly used to assess the impact of waste management on soil and groundwater [23]. The support of scientific research through the use of dedicated computer programs is now becoming a standard involving the impact of waste management facilities on the natural environment, in terms of management, forecasting and preparation of research results.

2. MATERIALS AND METHODS

2.1. Research object and hydrogeological conditions

The research object involves the above-ground landfill site which has one separate storage area. The area of the landfill site is approximately 2.25 ha, and its capacity is approximately 480,000 m^3. The landfill contains residual waste after mechanical treatment and other waste released for storage. The landfill has active degassing, made with the use of vertical individual degassing wells, from which the biogas is sucked into biogas conditioning stations and then used for energy production in a cogeneration unit. The natural sealing of the landfill is made of a layer of loam and clay stabilizing the natural substrate, a layer of gravel and a layer of mineral soil. The artificial sealing is made of bentomat, PEHD foil and geotextile. The landfill is drained by means of two systems:

- sub-foil drainage,
- over-foil drainage.

The sub-foil drainage is intended to drain the locally occurring seepage and groundwater from under the landfill cover to the watercourse. The over-foil drainage is designed to capture and discharge leachate generated in the landfill from the waste deposited in the cell. The landfill site operator follows specific procedures involving the monitoring of environmental impact of the landfill site within its confines. The tests of groundwater quality in piezometers and those of surface waters in the stream to which waters from the sub-foil drainage are discharged, carried out as part of environmental monitoring in 2013–2019, did not exceed the permissible quality parameters for these waters. The said situation bespeaks of the fact that the landfill site sealing was tight and the leachates were wholly contained by the over-foil drainage system and discharged to the treatment plant. It should be noted that the artificial sealing of the landfill fulfills its function, effectively preventing the migration of pollutants produced in the landfill into watercourses and soil.

An additional sealing layer is made up by the geological structure of the area in which the Quaternary and Tertiary formations are found. The Quaternary is represented by river accumulation formations and diluvial-weathered formations. The Quaternary lies on the Tertiary sandstones and shales of the Magura series, whereof roof was identified at a depth of 1.6–7.5 m below ground surface. The thickness of sandstone shoals ranges from 0.5 m to ≥ 2 m [24]. The landfill site is located in an area where medium and low erosion and accumulation terraces dominate in the morphology, while the remaining part consists of wide floodplain terraces, flood terraces and river quarries. The facies zone is represented by sandstones, shales and marls [25]. In the area of the landfill site, the Quaternary (Pleistocene) formations developed in the form of gravels and river boulders, sands and clays of erosion and accumulation terraces. Generally, the lithological profile – from the ground surface – is made up by clays constituting an sealing layer, then sands and gravels, which are the main aquifer in the area, lying on the Miocene clay and sandstone formations [26].

2.2. Modeling of pollution migration in groundwater of the landfill

The use of models of the migration of anthropogenic pollutants in groundwater in the area of landfills based on the available computer programs is aimed at estimating the potential negative impact of a landfill [27]. The numerical model of aquifers developed as part of this work comprises the hydrodynamic field described by the filtration equations and convective-dispersive transport equations on the migration route of pollutants from the core to the point of water intake (drainage) or from the observation point. The model of pollution migration in groundwater in the area of an active landfill was developed in the program Visual ModFlow Pro ver. 4.2. The model comprises the piezometers made around the landfill. The modeling area was extended to minimize the impact of the extrapolation of hydraulic pressures in the aquifer on the subsequent modeling of pollution migration processes. The total modeled area was approximately 2.5 km^2. The soil and water conditions in the model were adopted on the basis of archival materials and documentation, in particular:

- networks of hydrogeological monitoring,
- hydrodynamic conditions specified on the hydrogeological map,
- reports on the monitoring of landfill for wastes other than hazardous or inert,
- information contained in literature data,
- profiles of geotechnical boreholes.

In the area of the landfill, there are practically impermeable formations – tertiary sandy clays [28]. The aquifer layer is made up by thick-shoal sandstone complexes with clay-marl shale inserts. The average thickness of the aquifer was estimated at 15 m, and the average filtration coefficient was assumed to be 1.0 m·d^{-1}. The layers to a small extent, within the map sheet limits, were examined by hydrogeological boreholes. The computational models available on the commercial market, applicable for the analysis of groundwater migration, are developed on the basis of appropriate algorithms, and they make use of various mathematical equations [29]. The most important parameters of convective transfer are: filtration coefficient, effective porosity coefficient, average filtration rate, average actual filtration rate and average migration time. In a non-homogeneous -in terms of permeability – porous medium under steady conditions, the spatial (three-dimensional) flow of the thrust filtration stream is described by the second-order partial differential equation (1) (Fourier's equation) in the form (1):

$$\frac{\partial}{\partial x}\left[T\,\frac{\partial H}{\partial x}\right]+\frac{\partial}{\partial y}\left[T\,\frac{\partial H}{\partial y}\right]+\frac{\partial}{\partial z}\left[T\,\frac{\partial H}{\partial z}\right]+W=\mu_s\,\frac{\partial H}{\partial t}=0 \tag{1}$$

where:

μ_s – elastic drainage coefficient,

H – height of hydrostatic pressure (piezometric pressure), m

t – time, d (day)

x, y, z – spatial coordinates,

T – transmissivity of the aquifer ,

where: $T = k\cdot m$, $m^2\cdot d^{-1}$

k – filtration coefficient, $m\cdot d^{-1}$

m – thickness of aquifer, m

W – infiltration rate, $m^3\cdot d^{-1}$

The migration of pollutants is modeled on the basis of the real mapping (or as close to the real one as possible) using the groundwater flow model.

Due to hydrogeological conditions and morphology of the area, it was assumed that the migration of pollutants may take place in two phases:

- laterally – in the aeration zone – it comprises only the contour of the landfill and it moves only in compliance with the hydraulic gradient,
- horizontally – in the saturation zone – after reaching the aquifer composed of weathered medium-grain sandstones [30].

The duration of lateral migration was calculated using the Bindeman formula (with Macioszczyk's modification). The modification of the Bindeman formula (2) proposed by Macioszczyk consists in replacing the active porosity with volumetric moisture content as probably the closest to the active porosity of the formations present in the aeration zone (in the state of incomplete saturation) [30]:

$$U_a = \frac{1}{w_o} \cdot \sqrt[3]{\omega^2 \cdot k'} \tag{2}$$

$$t_a = \frac{m_a \cdot w_o}{\sqrt[3]{\omega^2 \cdot k'}} \tag{3}$$

where:

t_a – time of vertical filtration through the aeration zone , d (day),

w_o – volumetric moisture content, 1

ω – active infiltration $m{\cdot}d^{-1}$, calculated from the formula $\omega = P{\cdot}w$,

where: P – precipitation rate, $m{\cdot}d^{-1}$

w – precipitation index , 1

k' – vertical filtration coefficient of aeration zone, $m{\cdot}d^{-1}$

m_a – thickness of aeration zone, m

The modified Bindeman formula allows to obtain vertical filtration time which is closer to the real values than those offered by other formulas [31], and hence it was used in the assessment involving the possibility of pollution migration. The values of hydrogeological parameters for the carried out calculations were adopted from the literature data [31, 32] and from the profiles of geotechnical boreholes. For sandy clay, the minimum thickness of the layer was taken from the profiles of geotechnical boreholes, while the remaining parameters were derived from the literature data and field studies, and calculated from the expression (4):

$$t_{a_g} = \frac{m_{a_g} \cdot w_{o_g}}{\sqrt[3]{{\omega_g}^2 \cdot k'_g}} \tag{4}$$

where:

$m_{a_g} = 5.6\ m$,

$w_{o_g} = 0.38$ l,

$\omega_g = 0.000112\ m{\cdot}d^{-1}$,

$k'_g = 865.4{\cdot}10^{-4}\ m{\cdot}d^{-1}$,

$$t_{a_g} = \frac{5.6 \cdot 0.38}{\sqrt[3]{0.000112^2 \cdot 86.4 \cdot 10^{-4}}}$$

$$t_{a_g} = 4463.3\ days, \text{i.e.}\ 12.23\ years$$

For sandstone weathering, the minimum thickness of the sandstone weathered layer (non-waterlogged one – the aeration zone was estimated on the basis of the geological map sheet and the data resulting from the morphology of the terrain) was calculated from the expression (5):

$$t_{a_p} = \frac{m_{a_p} \cdot w_p}{\sqrt[3]{{\omega_p}^2 \cdot {k'}_p}} \tag{5}$$

where:

$m_{a_p} = 35\ m$,

$w_{o_p} = 0.10$ l,

$\omega_p = 0.000229\ m{\cdot}d^{-1}$,

$k'_p = 86.4\ m{\cdot}d^{-1}$,

$$t_{a_p} = \frac{35 \cdot 0.10}{\sqrt[3]{0.000299^2 \cdot 86.4}}$$

$$t_{a_p} = 215.51\ days, \text{i.e.}\ 0.59\ years$$

The calculation results for vertical infiltration in the aeration zone for sandy clays yielded the filtration time of 12.23 years, while for sandstone weathering the said time was 0.59 years. In total, the time of vertical migration of pollutants infiltrating from the landfill through the layer of sandy clays and through sandstone weathering into the aquifer is 12.82 years. Hence, the conclusion is that the first batch of pollutants migrating from the landfill will reach the aquifer in the minimum concentration not earlier than in about 13 years.

Based on the above, we assume that it is possible to map or observe the migration of pollutants migrating under the presently defined soil and water conditions for the cases when pollutants are present immediately in the aquifer (after vertical filtration). For such conditions, a conceptual hydrodynamic model of landfill was developed in the program Visual ModFlow Pro ver. 4.2. Based on the observations of the concentrations of potential pollutants analyzed during the monitoring of the aquifer layer and leachate from the landfill, we did not find any exceedance of permissible concentrations of any of the monitored substances. To observe the nature of pollution migration and the direction of its spread the plug flow model was adopted. As an indicator determining the rate of pollution migration, we adopted chloride ion which does not react with the environment, which allowed for the determination of the maximum rate of migration. For the differential equation, boundary conditions have been adopted, i.e. a set of conditions that the solution must meet at the points located on the edge of the area, so that the solution is unambiguous at all points of the area. The first boundary condition, which takes the value of hydraulic height at certain points along the shore of the modeled area, was adopted on the basis of a hydrogeological map and it was assumed that the directions of groundwater flow in the area were determined by the main drainage watercourses. The second type boundary condition is interpreted as the value of the feed in the direction perpendicular to the edge of the area. In this case, the edge of the area constituties also the boundaries of the impermeable formations, therefore the value of the supply will be zero. The boundary condition of the third type has been interpreted as variable feeding of the aquifer by filtration through poorly permeable formations. In this case, the boundary condition is characterized by the filtration coefficient of the poorly permeable layer and the thickness of the poorly permeable layer.

The following model parameters were adopted:

a. for subsurface layers:

$k_p = 1.0 \cdot 10^{-6}\ m \cdot s^{-1}$ – the adopted value of the filtration coefficient of plastic sandy clays [27],

$m_g = 5.6$ m – average thickness of subsurface layers – sandy clays,

b. for the aquifer layer,

$k_w = 1.16 \cdot 10^{-5}\ m \cdot s^{-1}$ – filtration coefficient of the aquifer layer,

$m_p = 35$ m – average thickness of permeable layers – sandstones,

$\alpha = 10$ m – dispersion constant – it was adopted due to low water flow rates in pore medium (aquifer) and probable occurrence of dispersion processes [33],

$n_e = 0.2$ p – effective porosity,

$n_c = 0.4$ p – total porosity,

$s_s = 100\ mm \cdot m^2 \cdot \text{year}^{-1}$ – infiltration feed through the poorly permeable layer of sandy clays – it was assumed at the level of approx. 15% of the amount of atmospheric precipitation,

H – hydraulic heights (pressure rates) were assumed on the basis of the hydrogeological map, and at the same time it was assumed that due to the presence of aquifer layers having free water table in the profile, the directions of groundwater flow in the area were determined by the main drainage watercourses [25, 34].

The developed hydrodynamic model of the aquifer (weathered sandstone and sandy clay) is a two-layer, dynamic, spatial model [35]. The conditions for pollution migration are based on the distribution of piezometric pressures in the aquifer observed around the landfill. The discretization of the modeled area was made on the basis of a regular grid having the dimensions of a single calculation block 10x10 m (in the vicinity of the landfill) and 200x100 m (at the boundaries of the model). The values of filtration coefficient were adjusted (calibrated) until the hydrostatic pressure distribution was identical to that determined in line with the hydrogeological map. Due to the lack of detailed information on the lithological profile and water conditions (the conditions determined on the basis of archival materials are only of a general nature), the constructed hydrodynamic model has an indicative meaning, i.e. it allows to determine the trend and estimate the speed of pollution propagation in the aquifer.

3. RESULTS AND DISCUSSION

The carried out modeling of leachate migration from the landfill in groundwater layers was aimed at determining the likely directions of pollution migration and its potential rate. The results have demonstrated the direction and speed at which the propagation of pollution already present in the aquifer can be observed (after infiltration in the aeration zone estimated at 12.82 years). The distribution of isohypses shows the general direction of groundwater flow in the area of the landfill towards the south, to the main drainage watercourse, which confirms the region's characteristics presented on the hydrogeological map and in the hydrogeological cross-section of the landfill area. For the obtained piezometric pressure distribution and water flow directions in the aquifer, the modeling of pollution migration was carried out. The migration of a chloride ion was modeled. Chlorides, being conservative ions, will not react with the rock environment, but they will only be subjected to the processes of hydrodynamic dispersion and diffusion. For the purposes of this study it was assumed that 500 $mg \cdot dm^{-3}$ of pollution would be washed out from the landfill body in the form of leachate, and this is the amount of ions which will infiltrate the aquifer. The modeling of pollution migration was analyzed at intervals allowing to determine the start of migration in the aquifer and the moment when the pollution reaches the maximum concentration in the leachate to the main drainage watercourse. The results of pollution migration in the aquifer are presented in

Figs. 1 to 3, where the numerical values on the isohips distribution inform about the concentration of chloride ion, while the arrows in the figures indicate the direction of pollution migration, i.e. to the watercourse.

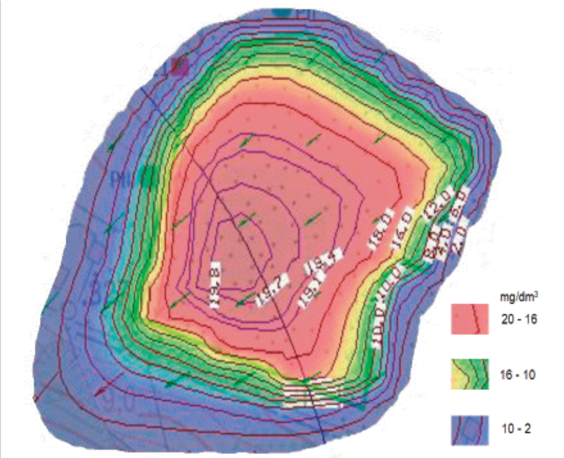

Figure 1.
Migration and concentration value of chloride ion in the aquifer after 16 days since it reach the aquifer. Own study

The image of pollution migration obtained in the modelling demonstrates that after 16 days since reaching the aquifer, the concentration of the chloride ion reaches a maximum of 19.8 mg·dm^{-3} and it starts to move towards the main drainage watercourse. As the pollution approaches the watercourse, the intensity of the ongoing migration increases. This is due to increased hydraulic drops – visible through the condensation of hydroisohypses in the area of the watercourse.

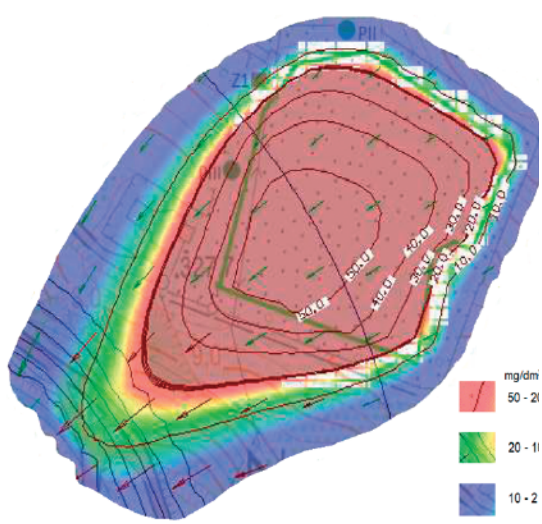

Figure 2.
Migration and concentration value of chloride ion after 50 days since the pollutants reach the aquifer. Own study

After 50 days since reaching the aquifer, the chloride ions reach the main drainage watercourse in the analyzed area. They are very quickly diluted, which results from the adopted concentration of chlorides in groundwater at a very low level of 10 mg·dm^{-3}. The pollutants migrate in a form resembling the body of the landfill and only after reaching the groundwater level they undergo the dilution process as a result of the ongoing dispersion and diffusion. The intensity of this process manifests itself in a gradual increase of pollution concentration in the landfill body to progressively higher concentration level.

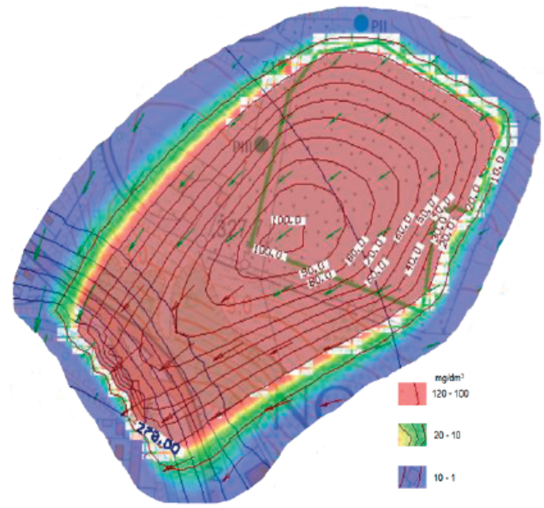

Figure 3.
Migration and concentration value of chloride ion after 160 days since the pollutants reach the aquifer. Own study

A relatively small range of migration is observed, which is mainly due to the location of the landfill, being a short distance from the drainage watercourse and due to rapid washing-away process of the pollutants reaching the aquifer. The maximum observed concentrations of pollutants reaching the groundwater level do not exceed 120 mg·dm^{-3}. Throughout the migration process, the significance of the processes of hydrodynamic dispersion and diffusion can be observed.

The modified Bindeman formula used in the study allowed for the calculation of lateral migration time for values close to the real ones. The said formula was used in the research by Wysowska et al. [36] as a recommended formula for homogeneous rock formations, to which the area of the documented groundwater intake belonged. The results of the authors' work were used to develop a plot demonstrating spatial distribution involving the susceptibility to groundwater contamination in the Dunajec valley. The modeling of leachate impact on the quality of groundwater in a municipal landfill was carried out, among others, by Papadopoulo [37]. The obtained research results demonstrated that the scale of groundwater contamination depends mainly on the hydrogeological conditions of the substrate, the volume of water flowing into the reservoir and the amount of pollutants entering it. Unsealing of the landfill may occur, e.g. during the reclamation works of landfills, during which the artificial sealing liner of the landfill or the drainage of leachate may be damaged. The basic conditions for a properly conducted reclamation process involve, among others, reliability of the carried out works, long-lasting elimination of harmful effects posed to the environment and people triggered by the landfill, including safe management of leachate. By comprehensive collection of leachate and sealing of the landfill, we can provide an effective barrier preventing the migration of pollutants to the soil, groundwater and surface waters [38].

The research results on physicochemical parameters, including main ions, conducted by Porowska [39] in the years 1999–2015 demonstrated trends of time-based changes in groundwater around the landfill. The content of many ions in the impact zone of the landfill was high 24 years after the closure of the landfill's operation. In order to minimize the impact of the landfill after the completion of its operation, its reclamation must be properly carried out and the results of water tests must be scrupulously analyzed. The failure to do so may result in the contamination of drinking water intakes located in the vicinity of the landfill. In such a situation, it is of particular importance to conduct rational water and sewage management, including the construction of water supply network ensuring the reliability of water supply and a sewage system. Areas affected by anthropogenic pollution of groundwater should be subject to special protection [40, 41].

The simulation of leachate penetration from landfills to groundwater using fuzzy logic and modeling methods with the use of neural networks was presented in the work of Abunama et al. [42]. The performed models served as tools for forecasting leachate transport and for assessing its environmental impact. The analysis showed that the model that uses two hidden layers achieved the best performance. The ranges and frequency of the relative error expressed as a percentage also show that this model produces more accurate values than other models. The basic condition for limiting the load of pollutants contained in leachate is to limit the storage of waste that has not been segregated and contains a biodegradable fraction. In such cases, the necessary prerequisite is to collect the biogas and to ensure systematic monitoring of the quality of groundwater and surface waters in the landfill area [43]. The three-dimensional model in the ModFlow program was developed by Rolle et al. [44]. The applied equations of the kinetic reaction were used to simulate the movement of leachate along with the aquifer. The demonstrated large organic load of the landfill leachate causes biodegradable processes. The subject model is able to quantify, and provides the possibility of simulating the combined transport processes taking place under the landfill. To ensure that the transport models are reliable, they should be properly calibrated based on actual or experimental data. As the input data for pollution migration models, the results of modeling pollution emissions into the air can be applied, based e.g. on the IPCC model, containing the parameterization of the landfill [45]. According to El Mansouri et al. [46], the main limitation in the development and implementation of these models is the quantification of flow parameters and transport phenomena. In order to minimize such limitations, field studies have to be carried out to reduce errors pertaining to the results obtained during the modeling.

4. CONCLUSION

The modeling results demonstrate that the migration of pollution in natural drainage directions is practically impossible due to a limited possibility of pollution infiltration. Such a situation results from two factors: firstly, the presence of a layer of virtually impermeable formations – sandy clays, which due to the filtration coefficient values, enforce the surface runoff. Secondly, when we collect the leachate from a landfill in the drainage system, it is not possible for pollutants to penetrate surface waters, and in water supply areas to penetrate groundwater. The aquifer is relatively deep, which additionally limits the speed and capability of pollution migration.

The potential ability for pollution migration to groundwater arises only in the event of a breach – damage to the sealing layer of the landfill. In this case, vertical infiltration will be taking place in the aeration zone for a relatively long period – about 13 years. And the migration of pollutants in the saturation (hydrated) zone will be taking place at a relatively high speed, so the released pollutants will reach the main drainage watercourse after 160 days.

The modeling of anthropogenic pollution transport in underground waters in the area of landfills is carried out with the use of mathematical models, which are developed on the basis of available computer programs. The developed and applied models are used to forecast the potential direction and extent of pollution transport and to assess the environmental impact. The authors of the applied models confirm their effectiveness and emphasize the quality of the input parameters constituting the measurement results. To ensure that the results of pollution transport modeling are reliable, high-quality input parameters are required such as measurement results, tests and simulations. The application of the modeling process by landfill managers also allows to optimize the potential anthropogenic impact of the facilities on individual components of the natural environment with some advance notice.

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