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Original article

Risk assessment for groundwater in the region of municipal landfill systems in Tychy-Urbanowice (Southern Poland)

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ABSTRACT

An Environmental Risk Assessment is an efficient technical and analytical method for analyzing environmental impacts and it supports the decision-making process connected with projects variants by using historical data collection, identification of regional risk sources, probability and impact estimation of signal risk type. In this article, an Environmental Risk Assessment was performed for groundwater quality in the region of municipal landfills in Tychy-Urbanowice (Southern Poland) to assess the impact of various factors on the quality of groundwater in the region. The assessment used qualitative and quantitative risk analysis methods, including cause and consequence analysis, completion of an effect/probability matrix and utilization of the SWOT analysis method. The results of the assessment indicate that use of the SWOT analysis was the best method for groundwater risk assessment in the examined area. The analysis included an assessment of the spatial and temporal variability of leachate and groundwater quality (using data from a groundwater monitoring system), simulation of the longevity of both the top and bottom security system, spatial planning and an assessment of the impact of other parameters on groundwater, terrain and climatic conditions. The overall result for this analysis for the likely potential groundwater hazard was a score of -4. For the purposes of further risk analyses, it is possible to consider additional factors that are likely to affect the water quality of the area under investigation or to use other methods that will be based on a time series analysis.

KEY WORDS: risk assessment, landfill, groundwater, leachates, Tychy

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1. Introduction

Landfill is the most popular method of waste disposal (SOBIK, 2007). However, the real problem, which also affects smart and sustainable towns, is the waste generation process itself (ESMAEILIAN ET AL., 2018). Despite the fact that economic development exerts a significant effect on the level of waste generation (MINELGAITĖ & LIOBIKIENĖ, 2019), a large percentage of waste will be collected in landfill. In this context, the technical design of landfill sites and the existence of a security system for the ground are of crucial importance (DĄBROWSKA ET AL., 2018a). Old closed landfill sites generally have no security for the ground, which means that these represent a major source of groundwater pollution (MOR ET AL., 2018). Landfill sites with liner systems can also become potential groundwater pollution centres due to their degradation (SUN ET AL., 2019). A numerical model is under development to analyze the earthquake-induced deformation of the liner system which use a geomembrane and a geosynthetic clay liner within a composite liner (FENG ET AL., 2019).

Pollutants leached from waste migrate into groundwater and jeopardize the quality of the groundwater in terms of both physicochemical and bacteriological parameters (TAYLOR ET AL., 2004). The size and chemical composition of leachates are dependent on the extent to which the waste has access to oxygen during storage (Freyssinet et al., 2002). Determination of the amount and composition of leachates is necessary for the development of the drainage system (Dąbrowska et al., 2018b) and should be subject to permanent determination during the operation of the landfill and after its closure. The groundwater and leachate monitoring should take into account, among others, the following parameters: electrical conductivity (EC) and Cl^-, SO_4^{2-}, nitrogen, B^+, Cr^{6+}, Cu^{2+}, Zn^{2+}, Pb^{2+}, Hg^{2+}, Co^{3+} and Ni^{2+} (Bojakowska, 1994; Slack et al., 2005) which are treated as significant indicators of groundwater pollution (Dąbrowska et al., 2018a; Sołtysiak et al., 2018).

Determination of the landfill security system and the physicochemical parameters of the leachate are important for the protection of groundwater in the area of potential contaminants, but they are not sufficient for a complete risk analysis. The Environmental Risk Assessment is an efficient technical and analytical method for analyzing unfavorable environmental impacts and it supports the decision-making process (Wu & Zhang, 2013).

Risk management can be described as a risk estimation process that aims to reduce the risk to an acceptable level. The correct system should include the following phases: planning, acquisition, development, testing and proper deployment of information systems (Pritchard, 2013). However, risk analysis is a process of risk recognition and an understanding of its size and the identification of areas that require security. In terms of hazards, we most often mean sudden, very likely events that have negative consequences with their impact. Risk analysis is an important tool to deal with an indefinite future and the onset of a crisis. It can also be described as a way to control uncertainty and the resulting risk in a given area for a given entity (Pritchard, 2013). Risk analysis and risk management are the most basic elements of crisis management in an organization that are aimed at minimizing losses related to the occurrence of a crisis situation and operational risk.

An important issue in risk analysis is also securing the process in terms of personnel, equipment or information. Moreover, risk assessment also requires a list of threats to be drawn up. The overall objective of risk assessment is to prepare the longest possible list of risks, whilst bearing in mind the domino effect which has an impact on the emergence of subsequent risks. The priority of risk identification is the grouping of risks resulting from probable events that may lead to, limit or prevent, the achievement of a goal. The basic identification factor is information that must be reliable, complete and timely (Wróblewski, 2015).

In the case of landfill, the risk assessment should take into consideration the spatial and temporal variability of leachate quality, simulation of the longevity of both the top and bottom security systems, but should also be an assessment of the impact of external factors, such as spatial planning and the impact of other objects on groundwater, terrain or climatic conditions in the studied area. The commonest approaches are historical data collection, regional risk sources identification, probability and impact estimation of signal risk type and comprehensive risk assessment (Calamari & Zhang, 2002).

In this article an Environmental Risk Assessment was performed for groundwater in the region of a municipal landfill system in Tychy-Urbanowice (Southern Poland). The aim of the study was to determine the impact of various factors on the quality of groundwater in this region using qualitative risk analysis methods, including the SWOT method.

2. Study area

An Environmental Risk Assessment was performed for the municipal landfill complex in the eastern part of the town Tychy-Urbanowice (Southern Poland). The landfill site is divided into two parts: (I) a closed and reclaimed landfill and (II), (III) a currently active landfill with the surrounding infrastructure. The total area of the described complex is 12.7 ha (Fig. 1).

The inactive landfill with a size of 3.5 ha was used before 1988 as a landfill for construction materials. Then, in 1988, the landfill was transformed into a municipal waste storage facility for Tychy. The landfill was closed due to a lack of an adequate liner system preventing infiltration of pollutants into the groundwater, which resulted in the lack of ground sealing (Dąbrowska et al., 2018a). The active part of the landfill consists of two adjacent quarters which were built between 1994 and 2004. They were equipped with a modern security system and seals preventing entry of pollutants into the environment (Dąbrowska et al., 2018b). These systems include, among others, a triple drainage system: inter-soil drainage, drainage (overfoliage) and sub-layer drainage; as well as a sealing system consisting of two PEHD films.

The modern plant with an area of 3.5 ha (Fig. 2) receives waste from 200 thousand inhabitants from 8 communities. During the year, the plant recovers 10 tons of recyclable raw materials, 10 tons of energy resources and 10 tons of construction waste (https://www.master.tychy.pl/).

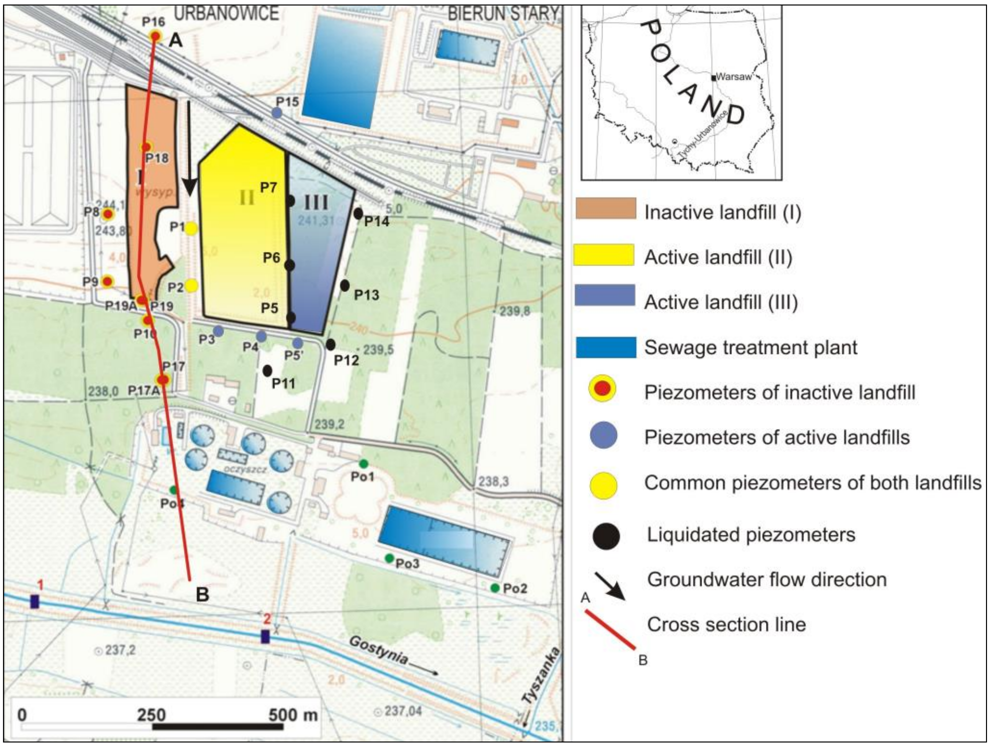

Fig. 1. Study area

Fig. 2. MASTER company (https://www.master.tychy.pl/)

3. Geological and hydrogeological conditions

The municipal landfill site described above is located within the Fore-Carpathian depression in the central part of the Upper Silesian Coal Basin. The upper part of the Upper Carboniferous (productive) in this region contains layers from the Upper Silesian sandstone series. Locally, on the Upper Carboniferous, there are eroded patches of Triassic sediments (WITKOWSKI, 2019). The Quaternary sediments (Pleistocene fluvial formations) in the form of sand of various grain sizes, rarely with gravel or clay formations, which have a thickness in the range of 12.5 to 17.0 m (WITKOWSKI & ŻUREK, 2007).

There are three aquifers in the region of the monitored landfill sites – Quaternary (Pleistocene), Triassic (locally) and Carboniferous. Locally, groundwater exists in the interbeddings of sands or the sandstones of the clays of the Miocene. The Quaternary aquifer, locally separated by poorly permeable sediments, is considered to be the most important. The lower aquifers are protected by very poorly permeable sediments with a thickness of 80 m (gray Miocene clays) in the Quaternary aquifer base (CZERMIŃSKI, 1993). The groundwater flows south in the research area (Fig. 1 and the River Gostynia is the basis for the drainage of 95% of the groundwater volume (SITEK ET AL., 2010).

4. Methodology

Each risk consists of the following elements: sources of risk or threats, events or incidents that are sources of risk, consequences for the organization and the environment, causes of current threats or occurrences, effectiveness of the monitoring and detection systems, place and time of the occurrence of each risk (PALTRINIERI ET AL., 2019). All these components are identified in every situation that could separately pose a threat. The possible methods of identification include, but are not limited to: simulations, measurements, expert assessments, forecasts, modeling, or threat analysis (CHARTRES ET AL., 2019).

Risk management is certainly not limited to preparing a list of threats and undertaking actions. A comprehensive approach to risk assessment consists of several activities: identification, analysis, or risk evaluation. The assumption underlying such a model is that the activities carried out with the help of the plan are effective and performed in a continuous and systematic manner.

The most important stages of risk management involve (Łuczak, 2009): planning the risk management; risk identification; estimation of the impact on operations; estimation of weaknesses and threats; implementation of a risk management plan; compliance measurements, and review and monitoring.

The Environmental Risk Assessment for the described complex of landfill sites was performed using all these stages. The risk analysis was designed to understand each individual threat and made it possible to determine the consequences of the risks and their likelihood, which in turn provided input for the risk evaluation. The results of the risk analysis showed which particular risks require appropriate methods of action. An important factor is to concentrate on bringing the risk down to an acceptable level. Risk management is divided into two levels: the first consists of monitoring the risks and the second in carrying out immediate actions.

The environmental risk assessment is typically understood as a process where the possibility and probability of negative environmental impacts are assessed. It focuses on factors which are dangerous to the environment, the quantity, intensity, or the extent of contamination and likely duration. Many risk assessment methods and tools have been developed (Krogulec et al., 2018) and they may be divided into:

1) quantitative methods – based on measurable quantitative data (e.g. concentrations of contaminants, migration time), related to mathematical statistical methods and probability theory. They are in general very useful methods, but require a large amount of precise input;
2) qualitative methods (descriptive methods) – do not include the numerical creation of risk values. These are very subjective methods related to expert knowledge, good practice and experience. They are usually performed as threat lists (matrices, graphs) along with an appropriate risk ranking, e.g. PHA method;
3) mixed quantitative-qualitative methods – combining probability and descriptive methods, including, for instance, matrix methods, Fault Tree Analysis (FTA) and neural networks (Połap, 2018; Blachnik et al., 2019);
4) simulation methods using computer models of groundwater flow (MODFLOW), hydrogeochemical models (e.g. PHREEQC, DownHole SAT), which are used to predict environmental changes and analyze event scenarios.

Initially, the risk assessment starts with the identification and detailed analysis of the area along with all the objects and installations located on it which may pose a threat to the environment. Its purpose is to identify the origin, extent and type of threat. Then, further research methods are selected and a conceptual risk diagram is prepared.

In this article, the available cartographic materials for the described research area, reports on the monitoring of groundwater quality in the area of the landfill site as well as the available studies on deposited waste were subjected to analysis.

In the course of this analysis, the following elements were taken into account: hazards (pollution sources, phenomena and events that can lead to pollution); stressors (types of pollutants); sources of exposure (medium in which contaminants are contained); routes of exposure (routes of entry of pollutants and the manner in which they affect the environmental elements); receptors (elements of the environment subjected to pressure and degradation as a result of contamination, e.g. plant and animal organisms).

Analysis of the obtained results allowed for carrying out a risk assessment of groundwater using qualitative methods (Korczowski, 2009). Out of all the available methods for environmental risk assessment, the following were selected: analysis of causes - consequences, effect/probability matrix and SWOT analysis (Phadermrod et al., 2019).

The analysis of causes and consequences is a combined method of the fault tree and event tree method; moreover, it offers the possibility of introducing a time delay. The reasons and consequences of the initiating situation are examined – an event that started a series of events. The analysis starts with the marking of the critical event, then the consequences of that situation are analyzed using 'yes/no' logic gates (Bubbico, 2018). They present events that may occur in the created system (intensifying or mitigating the critical moment). The causes of the situation are examined using the fault tree. This method was devised as a tool to ensure the security of critical systems (a direct impact on property, environment and health) and to reveal the occurrence of failures. It also makes it possible to distinguish different development paths at the time of an undesirable situation, depending on some subsystems (Wróblewski, 2015).

The consequence/probability (hazard) matrix is used mainly to classify sources of risk, hierarchy or for dealing with it. It is possible to specify which risks require immediate preventive action and which need further analysis. The assessment of the probability of an unfavourable situation provides the information necessary for determination of the level of risk. It depends on the consequences and probabilities. At the same time, these parameters depend on the accuracy of the information (Haddad et al., 2012).

The consequences, probabilities and levels of risk can be named and interpreted in a different manner. This means that some factor is modified depending on the needs. Once the level of risk is determined and assigned, the next step consists of specifying the factor of engagement (Paltrinieri et al., 2019).

A risk assessed as very serious requires immediate action, a high risk demands attention, monitoring, indication and taking actions that will reduce its level to at least the average medium risk and necessitates increased monitoring, or preparation of procedures for responding, within the chain of responsibility, whereas a low risk does not require any additional action, or response, except following the routine procedures (Table 1).

Table 1. Risk assessment matrix (based on Dominguez et al., 2019)

Potential severity	Probability of occurence	Unlikely	Remote	Occasional	Frequent
Catastrophic		medium risk	high risk	extreme risk	very extreme risk
Critical		low risk	medium risk	high risk	extreme risk
Moderate		low risk	medium risk	high risk	high risk
Minor		low risk	low risk	medium risk	high risk

When compiling safety measures, the risk assessment is determined on the basis of loss and the likelihood of its occurrence and often also takes into account all the benefits (National Research Council, 2005).

A correct analysis should provide answers to the following specific questions (Wróblewski, 2015):

1) To what extent are the risk management personnel notified of the applicable provisions of law and their proper application in practice?
2) What is the nature of existing monitoring: detection and elimination of risk factors, detecting and limiting the risk level?
3) What can be the negative effects of the risk when it occurs on the predicted scale and after the application of the risk reduction measures?
4) What factors can increase, or decrease, the risk and what is their impact?
5) What is the probability of risk?

All the obtained answers allow risk assessment and qualification of the case in the appropriate risk management system.

The SWOT analysis is one of the most common methods used by public entities in strategic management. It is used in the process of defining strategic plans (Hahizadeh, 2019). SWOT is an abbreviation of the first letters of each English word which define the characteristics of the enterprise's environment and resources: strengths; weaknesses; opportunities, and threats.

The described analysis consists of identifying and assessing the four groups of factors listed above, interpreting their impact on further development. The analysis used a uniform scale in the point range from -2 to 2 for individual factors. The creation of the SWOT analysis compels one to think strategically, monitor any changes taking place in the environment, produce reports and analyses which provide information important for the formulation of scenarios. A SWOT analysis was carried out in total for all factors for this research.

5. Results

Several risk components for groundwater can be distinguished in the analyzed area. The potential, or actual, sources of risk, or threats, include a set of municipal waste landfill sites, numerous production plants for car parts, a sewage treatment plant located south of the landfill sites, as well as a sewage treatment plant located at the production plant for car parts and an animal shelter.

With regard to the groundwater risk analysis, it is quite difficult to identify specific events or incidents that are sources of risk. The event that represents a source of risk for the new landfill is the liner system serving as a system for protection from the ground, and for the inactive site, the disruption of the foil on the top of the landfill. Confirmation of the occurrence of such an incident can be obtained by analyzing the results of the groundwater quality monitoring in the area of the landfill sites.

Additional events, relating to the landfill, that could cause a risk for the groundwater include the failure of the leachate drainage system, leakage of the leachate tank and migration of leachate into the aquifer from waste that has not yet been placed into the landfill.

In the case of the migration of pollutants into groundwater, major consequences may follow from the contamination of soils, surface and underground water, deepening of the cloud pollution zone and its migration in the groundwater flow direction, the need for additional groundwater monitoring, the need for remediation, financial sanctions for enterprises, the need to introduce additional protection systems against the migration of pollutants into the aquifer, change in the manner of waste storage, or change in the manner of the temporary storage of waste before its deposition.

The natural threat from floods in this area must also be taken into account. They are caused by pouring rain in the summer period. The River Gostynia poses the biggest danger for this area from the side of Lake Paprocany. In the immediate vicinity of the river there is a sewage treatment plant, which is a potential threat due to flooding and thus contamination of ground and underground water. However, the probability of occurrence of the suggested event is minimal, given that the applicable Water Law accurately defines the conditions for the construction of such facilities and determines the necessity of preparing flood risk maps. The main cause of groundwater pollution in the described area is the lack of protection from the ground in the area containing pollution sources, or the lack of a natural barrier against the migration of pollutants.

Reliable groundwater quality monitoring is necessary in areas where there are sources of groundwater pollution as this allows a proper assessment of the impact of the parameters on the groundwater and the implementation of a threat prevention system (NIELSEN, 2006; DĄBROWSKA ET AL., 2018a). Piezometers P1, P2, P8, P9, P10, P16, P17, P17A, P18, P19 and P19A were sampled for the old landfill. The active landfill is monitored quarterly, currently through the sampling of piezometers P1, P2, P3, P4, P5 and P15 (Fig. 1).

From the initiating event (unsealing of the film under the landfill), we can extract the circumstances that led to that. The basic circumstance was faulty work related to the construction and sealing of a given substrate during the design, or installation, of security measures. In this case, the fault may lie in human error or the defectiveness of a given batch of materials that were used for the project. Material defects can be revealed much later during the long-term operating period of the repository. Another likely circumstance may be unsuitable waste stored in the area. The foil is designed to prevent specific types of contaminants from penetrating deep into the soil. Where undesirable waste, that is not foreseen in the project, such as radioactive waste, is found in the area, the protective barrier may be broken.

In the next phase of the analysis, elementary events for the initiating situation were added. Soil contamination through egress of pollutants into the depths, and hence the contamination of groundwater in the area of the landfill site, would pose a major threat to local residents. Another risk element would be the loss of credibility and safety of the waste disposal facility. Many residents would be dissatisfied with the plant's operations. In a worse case scenario, this might result in the closure of the landfill in that area. This would in turn result in the transportation of the waste to a safer place, problems for the town of Tychy with the collection of sewage from its residents, or leaving the repository in its existing state and subjecting it to monitoring. The final element of the analysis was the determination of action criteria. In this case, it would be a very detailed monitoring of the behaviour of the landfill substrate and the direction of pollution movement. Moreover, measures should be taken to minimize soil and groundwater contamination.

The second method used was the effect/ probability analysis. It is made on the basis of the "Risk assessment matrix" (Table 1). The analysis gives an example of two events that may occur in the described area and have an impact on groundwater. The first described situation is the potential failure and leakage of sewage to the natural environment from a nearby sewage treatment plant located south of the landfill site. It would be a very dangerous situation which, under unfavourable conditions, could have long-term effects. On the basis of the Table, the presented failure was adjusted to the "possible" probability, and hence to extremely "high" consequences. Leaks from similar plants are relatively rare in Poland due to the likely high penalties imposed on enterprises in the event of such situations happening and as a result of the implementation of extensive security and monitoring systems. However, the human error factor and the shortcomings of the factory equipment cannot be ignored. There is at least a small likelihood of the occurrence of risk in every situation which involves human intervention.

The high level of consequences indicates the extreme scale of the problem. The extraction of pollution would have a huge impact on the degradation of the soil and water environment. Over time, the sewage would migrate into the ground ultimately reaching the nearby River Gostynia Adverse weather conditions might cause further difficulties which cannot be ignored. At high risk, it is important to constantly monitor the situation and deploy a person into authority whose task is to undertake actions that will lower the risk to at least the average level. On the whole, the losses in this situation would undoubtedly include contamination of the ground environment and the groundwater in the area of the waste landfill in Tychy, the problem of transporting sewage from the town would impose an enormous cost burden on the company, as well as a reduction in the sense of security of the town.

The second situation analyzed was the potential migration of leachate to the aquifer from waste that has not yet been placed within the landfill. Based on the reference table (Table 1), such an event can be classified with respect to probability as "very possible" and, is consequently, extremely "high" risk. Such situations also present a great danger to the surrounding environment. Monitoring the groundwater in the area of the landfill site and sewage treatment plants would enable the detection of a threat. A number of activities would have to be carried out, which would minimize the threat to the environment and surrounding buildings, and for a long time, also to local residents.

The last method to be adopted is the SWOT risk analysis. These results are presented in Table 2. It presents the positive and negative sides of possible internal and external options of the occurrence of risk and the situation as well as the consequences that may ensue. The positive aspects are divided into "strengths" and "opportunities," whereas the negative ones are divided into "weaknesses" and "threats." Moreover, each identified option is gradually assigned a certain number of positive and negative points. The sum of these points in each group determines the scale of the importance of the situation.

Table 2. SWOT analysis results for groundwater in the region of the municipal landfill complex

	POSITIVE SIDES	NEGATIVE SIDES
INTERNAL	STRENGTHS • Modern research monitoring +2 • Trained employee staff +1 • Modern security system +2 • New jobs +1 • Leveling of land (uncultivated land) +1	WEAKNESSES • Possibility of migration of pollutants into the soil and water environment -2 • Possibility of failure of security systems in a landfill, sewage treatment plant or nearby factories -2 • Possibility of human factor -1 error • Uninhabitable area -1 • Occurrence of undesirable waste at the landfill site -2 • Negative impact of production intensity on the environment -2
EXTERNAL	OPPORTUNITIES • Increase in financial inflow to the city budget +2 • Reducing the amount of municipal waste in own city +2 • Development of waste management technologies +1 • Increasing the popularity of the city's development +1 • Possibility of further development of the nearby area +2 • Increased co-financing from the central office of the city +1	THREATS • Possibility to manage the nearby area only by specific investments -2 • Design defect of security -2 • Destruction of natural animal habitats -1 • Occurrence of a threat to nearby residents of the city -2 • A decline in the attractiveness of the city through investments -1 • Contamination of the area - 2

Following the SWOT analysis, it can be concluded that the groundwater in the described area is exposed to a significant risk. The mere fact of the existence of a landfill site, sewage treatment plant or factory is a weakness for a given analysis. Undoubtedly, the most serious threat is contamination of the water environment. The consequences of such a risk would continue to affect the area and local residents for a long time and would most likely entail huge financial costs. Nonetheless, the positive sides and opportunities in a given analysis cannot be ignored. Increased environmental monitoring would result in the purchase of modern analytical equipment as well as an increase in research in this area. Notably, the town would boost its income from the profits from landfill sites in its area.

6. Summary and conclusions

The study presented the application of three methods of risk assessment to groundwater for the municipal landfill site in Tychy. The claim that the groundwater in the area of the landfill complex in Tychy is exposed to risk is justified. A number of factors such as climate, spatial development, hydrological conditions and human error factor exert a huge impact on the scale of the problem.

1) Risk analysis provides a thoughtful and orderly insight into the problem. Its task is to identify weaknesses in the monitoring system, human work or errors in the procedures. It results in the improvement of the security system and the functioning of the landfill site, while constantly changing the factors. The three methods of risk analysis that were chosen made it possible to examine possible scenarios and situations that may occur in a given area. SWOT analysis was chosen as the best method for describing a simulated situation in the region of the landfill site in Tychy. That analysis enabled the identification of both the strengths and weaknesses of the operation. Furthermore, the SWOT analysis offers a wider perspective of the issue under investigation and also addresses additional aspects such as whether the situation will positively affect the town, whether the financial inflow will increase the town's budget, or whether the area of interest will develop technologically and logistically for the benefit of the town and its inhabitants.

2) Regardless of the applied method, the analysis of risks that may occur in the studied area can improve the crisis management system in a given area, identify the weakest points of the procedures concerning the human factor in the event of an unexpected failure or incident and improve the monitoring system in places that require additional data.

3) The presented analysis provides an indispensable and very useful document, which is often overlooked by investors.

References:

Blachnik M., Sołtysiak M., Dąbrowska D. 2019. Predicting Presence of Amphibian Species Using Features Obtained from GIS and Satellite Images. *ISPRS International Journal of Geo-Information*, 8, 3: 123.

Bojakowska I. 1994. *Wpływ czynnika antropogenicznego na procesy geochemiczne w powierzchniowych warstwach litosfery*. Państwowy Instytut Geologiczny, 53, Warszawa.

Bubbico R. 2018. A statistical analysis of causes and consequences of the release of hazardous materials from pipelines. The influence of layout. *Journal of Loss Prevention in the Process Industries*, 56: 458–466.

Calamari D., Zhang L. 2002. Environmental Risk Assessment of Pesticides on Aquatic Life in Xiamen (China). *Toxicology Letters*, 128, 1–3: 45–53.

Chartres N., Bero L., Norris S. 2019. A review of methods used for hazard identification and risk assessment of environmental hazards. *Environment International*, 123: 231–239.

Czermiński P. 1993. *Instrukcja obsługi systemu monitoringu wód podziemnych składowiska odpadów komunalnych w Tychach*. Zakład Ochrony Środowiska EKO-SON. Tychy.

Dąbrowska D., Witkowski A., Sołtysiak M. 2018a. Application of pollution indices for the spatiotemporal assessment of the negative impact of a municipal landfill on groundwater (Tychy, southern Poland). *Geological Quarterly*, 62, 3: 496–508.

Dąbrowska D., Witkowski A., Sołtysiak M. 2018b. Representativeness of the groundwater monitoring results in the context of its methodology: case study of a municipal landfill complex in Poland. *Environmental Earth Sciences*, 77: 266.

Dominguez C., Martinez I., Pena P., Ochoa A. 2019. Analysis and evaluation of risks in underground mining using the decision matrix risk-assessment (DMRA) technique, in Guanajuato (Mexico). *Journal of Sustainable Mining*, 18, 1: 52–59.

Esmaeilian B., Wang B., Lewis K., Duarte F., Ratti C., Behdad S. 2018. The future of waste management in smart and sustainable cities: A review and concept paper. *Waste Management*, 81: 177–195.

Feng S., Chang J., Chen H., Zhang D. 2019. Numerical analysis of earthquake-induced deformation of liner system of typical canyon landfill. *Soil Dynamics and Earthquake Engineering*, 116: 96–106.

Freyssinet, P., Piantone P., Azaroual M., Itard Y., Clozel-Leloup B., Guyonnet D., Baubron J. 2002. Chemical changes and leachate mass balance of municipal solid waste bottom ash submitted to weathering. *Waste Management*, 22, 2: 159–172.

Haddad A., Galante E., Caldas R., Morgado C. 2012. Hazard Matrix Application in Health, Safety and Environmental Management Risk Evaluation. [in:] J. Emblemsvåg (ed.) *Risk Management for the Future – Theory and Cases*: 29–50.

Hajizadeh Y. 2019. Machine learning in oil and gas; a SWOT analysis approach. *Journal of Petroleum Science and Engineering*, 176: 661–666.

Korczowski A. 2009. *Zarządzanie ryzykiem w projektach informatycznych. Teoria i praktyka*, Helion, Warszawa, 224.

Krogulec E., Sawicka K., Zabłocki S., Falkowska E. 2018. Ocena ryzyka środowiskowego w zakresie zanieczyszczenia wód podziemnych i gruntów w rejonie robót górniczych. *Górnictwo Odkrywkowe*, 59, 2: 50–56.

Łuczak J. 2009. Metody szacowania ryzyka – kluczowy element systemu zarządzania bezpieczeństwem informacji ISO/IEC27001. *Zeszyty Naukowe*, Akademia Morska w Szczecinie, 19, 91: 63–70.

Minelgaitė A., Liobikienė G. 2019. Waste problem in European Union and its influence on waste management behaviours. *Science of the Total Environment*, 667, 1: 86–93.

Mor S., Negi P., Ravindra K. 2018. Assessment of groundwater pollution by landfills in India using leachate pollution index and estimation of error. *Environmental Nanotechnology, Monitoring & Management*, 10: 467–476.

National Research Council. 2005. The Owner's Role in Project Risk Management. Washington, DC: The National Academies Press.

Nielsen D. 2006. *Practical Handbook of Environmental Site Characterization and Ground-water Monitoring*. 2nd ed. CRC Press Taylor & Francis Group.

Paltrinieri N., Comfort L., Reniers G. 2019. Learning about risk: Machine learning for risk assessment. *Safety Science*, 118: 475–486.

Phadermrod B., Crowder R., Wills G. 2019. Importance-Performance Analysis based SWOT analysis. International *Journal of Information Management*, 44: 194–203.

Pritchard C. 2013. *Zarządzanie ryzykiem w projektach*. WIG-Press, Łódź.

Połap D. 2018. Human-machine interaction in intelligent technologies using the augmented reality. *Information Technology and Control*, 47, 4: 691–703.

Sitek S., Witkowski A., Kowalczyk A., Żurek-Pucek A. 2010. Ocena oddziaływania składowiska odpadów komunalnych w Tychach na środowisko wód podziemnych w świetle badań modelowych. *Biuletyn Państwowego Instytutu Geologicznego*, 442: 147–152.

Slack R., Gronow J., Voulvoulis N. 2005. Household hazardous waste in municipal landfills: contaminants in leachate. *Science of the Total Environment*, 33: 119–137.

Sobik K. 2007. *Badanie wpływu składowisk odpadów na środowisko gruntowo-wodne na przykładzie wybranych obiektów zlokalizowanych w obrębie zlewni Dunajca*. PhD Thesis, AGH, Kraków.

Sołtysiak M., Dąbrowska D., Jałowiecki K., Nourani V. 2018. A multi-method approach to groundwater risk assessment: A case study of a landfill in southern Poland. *Geological Quarterly,* 62, 2: 361–374.

Sun X., Xu Y., Liu Y., Nai Ch., Dong L., Liu J., Huang Q. 2019. Evolution of geomembrane degradation and defects in a landfill: Impacts on long-term leachate leakage and groundwater quality. *Journal of Cleaner Production*, 224: 335–345.

Taylor R., Cronin A., Pedley S., Barker J., Atkinson T. 2004. The implications of groundwater velocity variations on microbial transport and wellhead protection – review of field evidence. *FEMS Microbiology Ecology*, 49, 1: 17–26.

Witkowski A.J. 2019. Monitoring wód podziemnych w rejonie składowiska odpadów komunalnych w Tychach-Urbanowicach – Raporty 2018. Uniwersytet Śląski, Sosnowiec.

Witkowski A.J., Żurek A. 2007. Wpływ starych, zrekultywowanych składowisk odpadów komunalnych na wody podziemne. [in:] A. Szczepański, E. Kmiecik, A. Żurek (ed.) *Współczesne problemy hydrogeologii*, Wydział Geologii, Geofizyki i Ochrony Środowiska AGH, Kraków, 13: 625–633.

Wróblewski D. 2015. Zarządzanie ryzykiem – przegląd wybranych metodyk. CNBOP - PIB, Józefów.

Wu K., Zhang L. 2013. Progress in the Development of Environmental Risk Assessment as a Tool for the Decision-Making Process. *Journal of Service Science and Management*, 7, 2: 131–143.

Internet sources

https://www.master.tychy.pl/