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Impact of Protective Barriers on Groundwater Quality

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Abstract. The storage yard's leak-proof protection should be achieved by means of independent protective barriers in the form of geological barriers, artificial sealing layers, mineral soil liners and covers, as well as sidewall sealing. Some years ago, construction and exploitation of landfill sites in Poland took place without any guidelines and legal regulations. Landfills, especially situated in rural areas, were quite often constructed directly on the grounds, e.g. in former aggregate excavations, without any protection. Examples of the municipal landfills, located in the sites of adverse geological conditions were presented in this paper. The effect of existence or absence of geological barriers on the groundwater quality was carried out. In tested landfills, higher concentrations of groundwater pollution indicators were found in landfill monitoring wells located on the outlet of these waters, in comparison to the landfill monitoring wells located on their supply. In the case of the landfills situated directly on the soils of high hydraulic conductivity, the indicators of negative influence of deposited landfills increased even after the closing of the landfill sites. Subsurface water-bearing layer is a kind of "indicator" giving information about the harmful effect of landfills on the environment, and the need to take remedial actions.

Keywords: landfill of municipal waste, protective barriers, geological barrier, groundwater quality.

Conference topic: Environmental protection.

Introduction

Depositing waste on the surface of the land is in Poland the dominant way of waste disposal. Introduction of steps towards the improvement of waste management in Poland has begun only several years ago. For many years landfills were localised, built and operated without guidelines and regulations. Until recently, landfills were located randomly in wasteland or areas that could not be used in other ways, also because of the presence of shallow groundwater. Most frequently, defunct, unprotected excavation sites were used as landfills (Łuczak-Wilamowska 2013; Wysocka 2015).

Incorrect location and operation of landfills result in negative impact on the environment, including soil, groundwater, surface water and air. Waste deposited in the storage site, depending on its chemical composition and mineralogy, is subject to various transformations due to reaction with environmental elements, which results in a subsequent, secondary contamination (Hellweg *et al.* 2005; Sobik-Szołtysek *et al.* 2013; Koda *et al.* 2015). The resulting hazardous substances migrate outside the landfill, penetrating into the ground relining a storage site, and then getting into the aquifers.

From the perspective of the natural environment there is no a good location for a landfill. Location of landfills can cause significant deterioration of the natural conditions in the neighbourhood and make it difficult to use the land (Rosik-Dulewska 2008). The most important is to choose the location that will minimize the inevitable environmental effects, as well as the amount of expenditures incurred on construction of landfills so that its impact on the environment is as small as possible (Wiater 2011).

This paper aims to show how the location of landfills and soil and water conditions affect the quality of groundwater under landfills constructed without artificial sealing layers, using an example of small municipal waste landfills.

The location of landfills and groundwater conditions

Sealing of municipal and industrial waste landfills, applied to reduce the impact of waste on the environment, is the most important element in the construction of landfills. Sealing of landfills (Fig.1) is achieved through a system of independently operating protective barriers in the form of geological barriers, landfill liners and covers, and vertical barriers (Daniel 1997). The main objective of sealing the surface of the landfill is to protect its surface from the weather and biological impact, and also to preserve the surrounding environment from the collected waste (odours, dust). This seal reduces infiltration of precipitation into the mass of waste landfill and prevents the formation of an increased amount of leachate. The task of sealing the base and slopes is to create an impermeable barrier sealing, protecting the subsoil against draining of leachate and landfill gas to the lower layers of the ground and groundwater, and to channel the resulting leachate to effluent treatment system. The side sealing, in the form of vertical barriers, reaching impermeable subsoil, eliminates the horizontal migration of leachate beyond the landfill, and allows maintaining a lower level of ground water within a closed barrier (Zabielska-Adamska 2006).

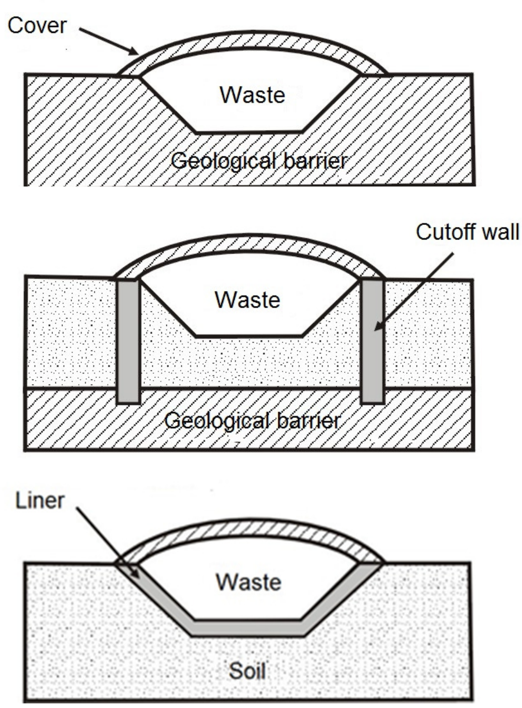

Fig. 1. Lining schemes for waste landfills using: a) natural soils, b) vertical cutoff walls, c) engineering liners (source: own elaboration based on Daniel 1997)

Selection and construction of the sealing depends mainly on the type of landfill, geological and hydrogeological structure of the ground and on the type of stored waste. The landfill is preferably best situated within its natural geological barrier sealing the base and side walls. According to the applicable Regulation of the Polish Minister of Environment of 30 April 2013 on the landfill of waste (Journal of Laws 2013, item 523) thickness of the natural geological barrier in municipal waste landfills should be no less than 1.0 m, and the value of the filtration coefficient of soil constituting a natural barrier should be $k \leq 1.0 \cdot 10^{-9}$ m/s. The barrier should have horizontal extent exceeding the area of the planned landfill. Expected piezometric highest groundwater level should be located at least 1 m below the planned bottom of the landfill. In the absence of geological barriers, artificial materials are applied to sealing layers.

Landfill's liner and cover are usually composed of single or double complex sealing. They consist of layers of specially embedded cohesive soils with permeability coefficient $k < 10^{-9}$ m/s, characterised by a long-term ability to bind and retain compounds present in the leachate from the landfill waste and gas, and synthetic geomembrane (Brandl 1992; Bouazza, Van Impe 1998; Rowe *et al.* 2004; Rowe 2005, 2011). GCL (*Geosynthetic Clay Liner*), which is a sealing geomat composed of industrial compound of geotextile and bentonite, may also be used instead of compacted cohesive soils. As the damage to the geomembrane results in unsealing of the entire structure, the leakage through a hole in geomembrane is minimized by placing a mineral sealing layer below the geomembrane. The flow rate of leachate through the complex type of sealing is significantly smaller than through the geomembrane or mineral layer, when applied separately. So it is in the case of the rate of migration of contaminants due to molecular diffusion. Materials most commonly used for the construction of layers of mineral sealing are clays and boulder clays, improved with bentonite, hydraulic binders or silica (Zabielska-Adamska 2006).

Authors' research on the effect of landfills on groundwater

Examination of landfills

The subjects of research were municipal landfills for non-hazardous and neutral waste, located in Podlaskie Province. These landfills have been closed due to failure to meet the requirements of the then Regulation of the Minister of Environment. The analysis covered three landfills, further referred to as: landfill A, landfill B, and landfill C. Landfill A was operated from 1989 to 2009, the landfill B from 1990 to 2011 and the landfill C from 2000 to 2011. Landfills A and B are under-over ground type (depositing of waste took place in the former excavation sites of sandy-gravelly soils), and the landfill C is in the form of a waste open dump. Each of these landfills covers an area of up to 1 hectare, with the amount of deposited waste under 10 tons/day. Waste, deposited in landfills, was mostly of unsorted, municipal origin, produced by households and transported from the municipal areas. Waste typically rural, with a predominance of inorganic waste, such as plastic packaging, glass, ceramics, ash and debris prevailed in the apparent mass of the collected waste.

Geological formation and hydrogeological conditions of the area underneath studied landfills

All the tested landfills: A, B and C lie in the region of residual quaternary cover reaching to a depth of approx. 150–180 m:

A. Subsurface formations occur here as sandy-gravelly soils with silty interbeds to a depth of approx. 12 m. In the floor there is a series of clay formations to a depth of approx. 25 m. In the depth zone from 25 m to approx. 67 m lie glaciolacustrine silt-clay formations, under which there is a saturated, useful aquifer associated with fluvio-glacial deposits of different granulation. Sandy-gravelly soils are associated with a subsurface aquifer with free water table forming at a depth of 7.3–7.6 m below ground level. This layer is not isolated from the area surface by cohesive soils. In terms of morphology, the landfill is located on the local elevation with a slope of land in the north-west, in the direction of a nearby watercourse, flowing at a distance of approx. 500 m west of the studied area. The watercourse functions as a local drainage base for subsurface water. The main useful subsurface aquifer occurs underneath glaciolacustrine deposits at a depth of approx. 67 m.

B. The first subsurface aquifer is connected with sandy and sandy-gravelly soils, with some clay content. This layer is partially covered with patches of clay deposits. The direction of water runoff in drilled subsurface aquifer was determined as NE, in line with the flow of a nearby river whose heads are localised approx. 1000 m to SE. Aquifer is in the form of both free and confined water table. The hydrostatic pressure is caused by the above-lying cohesive soils. The main useful aquifer used for local public water supply lies below a depth of 55 m and is isolated from the subsurface aquifer by low-permeability glacial till with a thickness of over 30 m.

C. Subsurface formations comprise sand and sandy-gravelly layers with a thickness of approx. 3 to approx. 15 m, with silty interbeds. The floor of these formations contains clay soils surging to a depth of approx. 50 m, under which there is a useful aquifer associated with fluvioglacial deposits, i.e. sands of different grain size. Non-cohesive surface sandy soils are connected with aquifer with a free-water table remaining at a depth of 0.8–1.2 m. The layer is not isolated from the area surface by any low-permeable formations. These waters are in hydraulic contact with the heads of a nearby river located approx. 90 m to the northeast, functioning as a local drainage base. In general, the direction of subsurface waters' runoff is positioned towards SE, i.e. in line with the decline in the area in the direction of the nearby river. The main useful aquifer, used for local public water supply, is below a depth of 50 meters and is covered with a layer of glacial till constituting a natural insulation for the water against potential contamination from the landfill.

Quality of groundwater below examined landfills

According to the Regulation of the Minister of Environment, level and chemical composition of groundwater in the vicinity of a landfill site is subject to examination: once, before commencement of waste storage (in order to understand the geochemical background); during the operation of the landfill every 3 months; after closure of the landfill, measurements should be performed every 6 months. Water samples for physico-chemical tests should be collected from special openings in a landfill, so-called piezometers.

Monitoring tests have never been conducted at the investigated landfills before and during their operation. Piezometers were made just before the closure of landfills. At every site piezometer P-1 was located on the inflow of groundwater, whereas the openings P-2 and P-3 – on its outflow. Figure 2 shows the results of drilling in the form of geological profiles, including lithology and the retention of subsurface aquifers at individual landfills.

The analysis of groundwater quality in the area of landfills was based on monitoring studies. They included, in accordance with the Regulation of the Minister of Environment: measurement of pH, electrolytic specific conductance, and the content of total organic carbon (TOC), total polycyclic aromatic hydrocarbons (PAHs) and heavy metals, including: copper, zinc, lead, cadmium, chromium and mercury. In addition, as part of the study carried out by the author at landfills B and C, nitrate was designed as an indicator of water quality class, as shown in Table 1.

Results of water quality monitoring tests are presented in Table 2 and Figs. 3–5.

Table 1. Content of nitrates (mg/dm^3) tested immediately after installation of piezometers (source: own elaboration)

Landfill	P-1	P-2	P-3
B	18.1	34.9	45.6
C	8.5	19.3	45.6

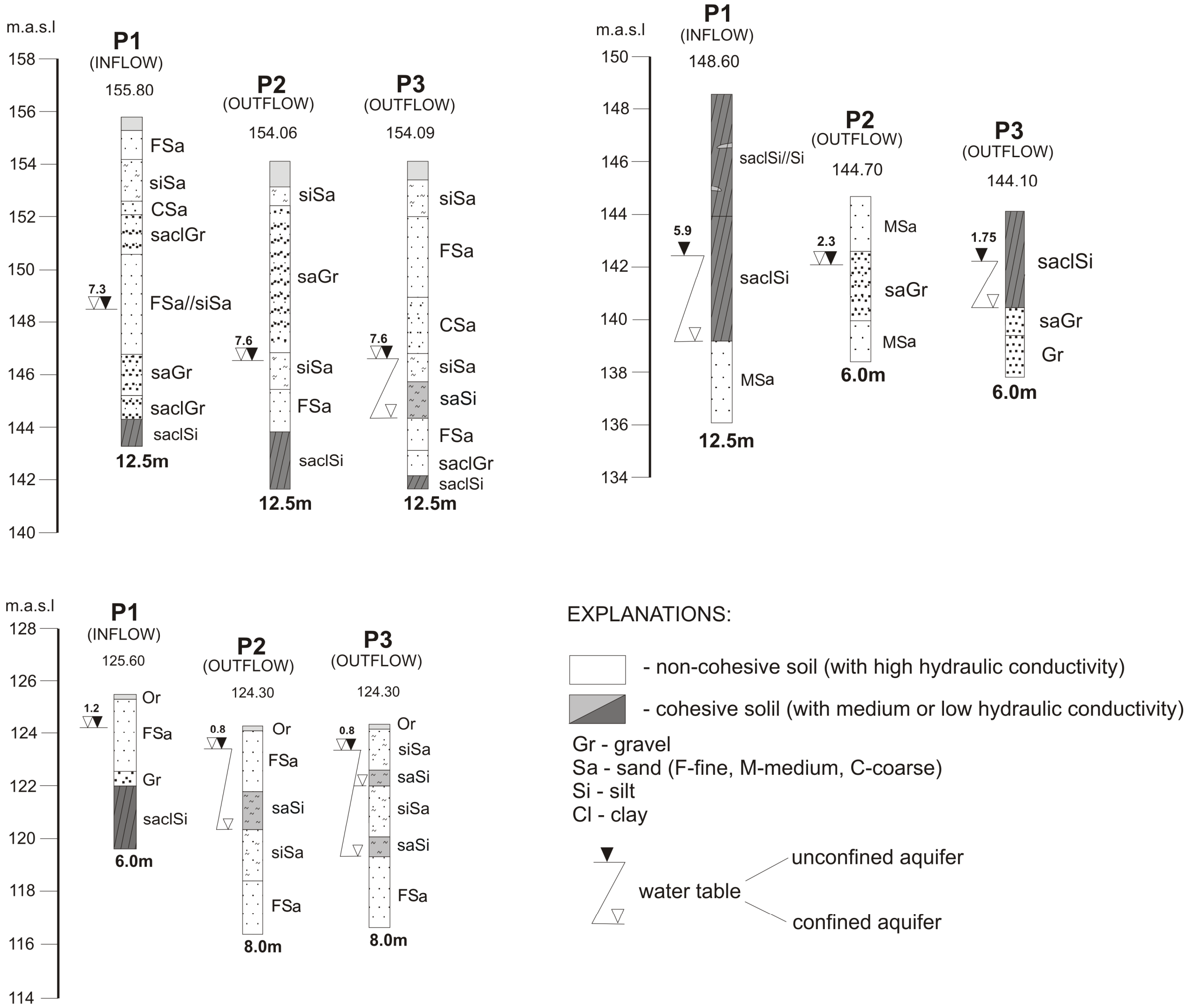

Fig. 2. Research holes (soil classification according to EN ISO 14688-2. 2004): a) landfill A, b) landfill B, c) landfill C (source: own elaboration)

Analysis of research results

Tested landfills were located directly on the sandy soils and sandy-gravelly soils with high coefficients of filtration. Below landfilled waste lies subsurface aquifer which is not insulated from pollution sources, i.e. stored waste, so the leachate from the landfill freely migrate to the waters of this layer and can be transmitted over long distances with their confluence. Only in the area of the landfill B low-permeability, small thickness formations can be observed on parts of the ground surface. Useful aquifers, used for public water supply in individual municipalities, are isolated from the ground by a few-dozen-metre overlay of poorly or practically impermeable formations. Waste landfilling without natural geological barriers and complex anthropogenic sealing lead to degradation of subsurface waters which, without doubt, are used by households (in the form of dug wells).

Nitrogen content, at the time immediately after installation of piezometers (still during the operation of the landfill) in water from piezometers located at outflows is respectively: 1.9–2.5 and 2.3–5.4 times higher, compared to the water from piezometers at the upstream of landfills B and C (Table 1). During exploitation of landfill the principal pollutants in leachate are organics and ammonia. As the age of landfill increased, it was observed that organics concentration in leachate decreased, whereas ammonia nitrogen concentration increased (Kulikowska, Klimiuk 2008). This explains the lower content of nitrates in water from piezometer P-1 at landfill C, as being a newer landfill.

The analysis of results for water collected from piezometers at landfill A (Fig. 3) shows that the water samples from the observation opening P-3, located in groundwater downstream are in the worst quality. Also, higher electrolytic conductivity and the content of total organic carbon (TOC), in relation to the piezometer P-1 and P-2 were recorded. In water samples collected during the operation of the landfill, higher content of lead and zinc was noted, as compared to subsequent years. Also, worthy of note is growing quite intensively over time (2007–2013) content of polycyclic aromatic hydrocarbons (PAHs), which in 2007 was in the range of <1–6 μg/dm³, and in 2013 in the range of 82.16–106.7 μg/dm³. After 2013, the contents of PAHs significantly decreased.

Analysis of the water from the landfill B area showed that the parameters of water samples collected from the opening P-3, located in groundwater downstream (Fig. 4) are significantly inferior, and the water samples from the piezometer P-2 slightly inferior than the water taken from the piezometer P-1. This is particularly evident in the first study, still conducted during operation of the landfill, immediately after drilling openings. The main observation related to increased conductivity and a higher content of total organic carbon (TOC) and copper, as well as enhanced levels of nitrates. It should also be noted that once the landfill was closed and recultivated, contents of TOC and conductivity decreased, whereas copper content in the water is still rising.

Analysis of monitoring data of landfill C (Fig. 5) points primarily to increased content of total organic carbon (TOC) and higher electrolytic conductivity of water collected from piezometer P-3 at the outflow of water from the landfill area. The values of these indicators are rising over time. Water samples taken from piezometers P-1 and P-2, even during the operation of the landfill have higher conductivity and TOC than in the years following the closure of the landfill.

Table 2. Basic statistic of analysed water (source: own elaboration from monitoring data)

Landfill	A			B			C			Standard limits*
Piezometer	P-1	P-2	P-3	P-1	P-2	P-3	P-1	P-2	P-3	
ph (-)										
N	14	14	14	9	9	9	4	4	4	6.5–9.5**
Mean	6.6	6.9	6.8	7.13	6.96	6.76	6.8	6.2	6.6	
Median	6.7	7	6.7	7.12	7.08	6.8	6.8	6.2	6.4	
Min	6.1	6.3	6.4	6.90	6.70	6.57	6.5	6.0	6.2	
Max	7.0	7.2	7.2	7.30	7.13	6.90	7.0	6.6	7.2	
St. deviat.	0.3	0.3	0.2	0.12	0.17	0.11	0.2	0.2	0.4	
Electrolytic conductivity (μS/cm)										
N	14	14	14	9	8	9	4	4	4	2500
Mean	844	643	1731	574.6	621.8	1341.4	420.5	364	1187.4	
Median	818.5	595.5	1655	590.8	583.1	1241	346.5	152.5	1173	
Min	268	367	1097	427.8	252.4	414.9	284.0	121.0	917.5	
Max	1831	1591	2993	749.0	1384.0	3276.0	705.0	1030.0	1486.0	
St. deviat.	523.3	285.2	486.8	106.1	397.6	783.1	193.7	444.7	236.7	
Total organic carbon (mg/dm³)										
N	14	14	14	9	9	9	4	4	4	5.0**
Mean	6.20	4.38	8.30	2.98	4.49	5.96	4.425	5.2	12	
Median	2.65	2	8.58	3	3.67	3.07	4.5	4.4	11.65	
Min	1.50	1.14	2.00	1.00	3.00	2.45	3.30	3.30	11.00	
Max	23.80	13.10	22.30	5.59	9.09	29.30	5.40	8.70	13.70	
St. deviat.	6.76	4.01	5.03	1.40	2.20	8.76	0.90	2.39	1.18	
Polycyclic aromatic hydrocarbons (ng/dm³)										
N	13	13	13	8	8	9	3	3	4	100.0
Mean	32.16	24.37	28.40	26.25	28.75	29.04	43	43	32.75	
Median	11.02	10	10	30	30	30	36	36	36	
Min	1.25	1.00	1.06	20.00	20.00	20.00	36.00	36.00	2.00	
Max	106.70	91.13	82.16	30.00	40.00	51.38	57.00	57.00	57.00	
St. deviat.	35.39	27.84	27.90	5.18	6.41	9.68	12.12	12.12	22.77	

*Explanation: values for potable water according Regulation of the Polish Minister of Health (Journal of Laws 2015, item 1989); **values applicable before 2010 (Journal of Laws 2007, item 417).

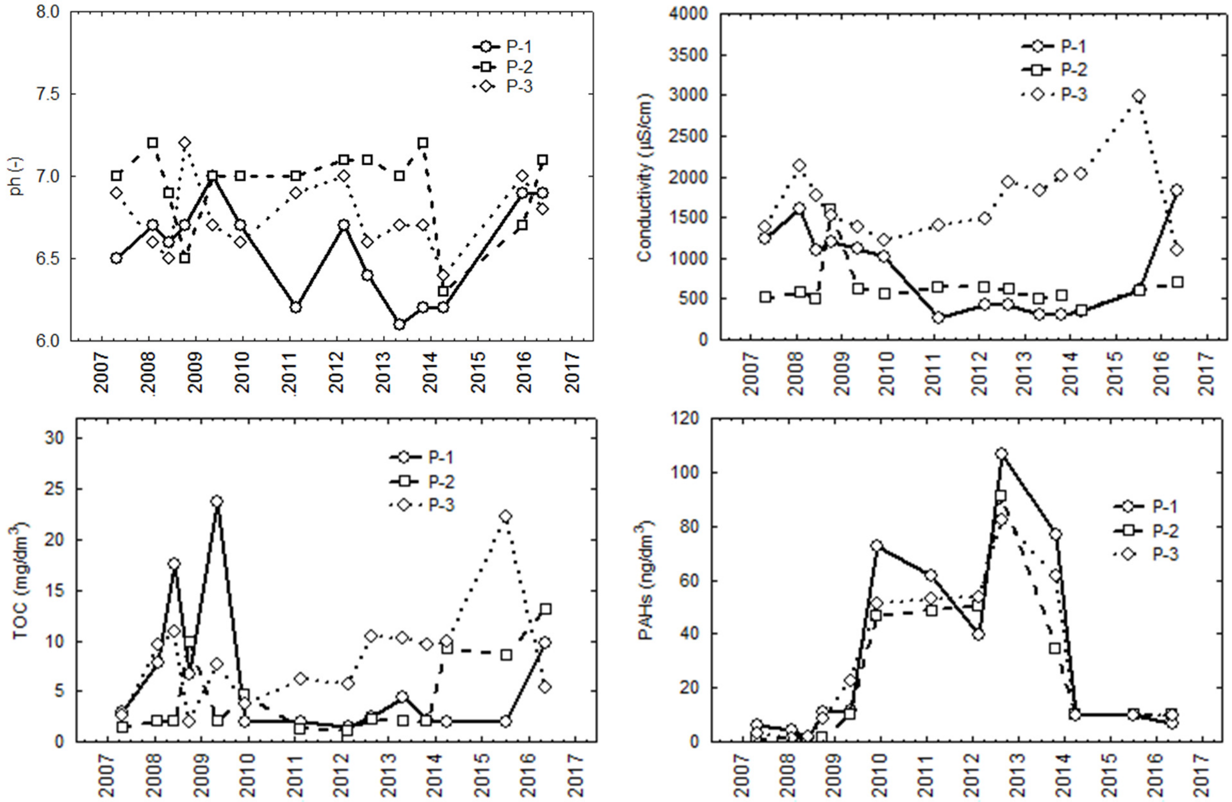

Fig. 3. Results of groundwater quality tests at the landfill A (source: own elaboration from monitoring data)

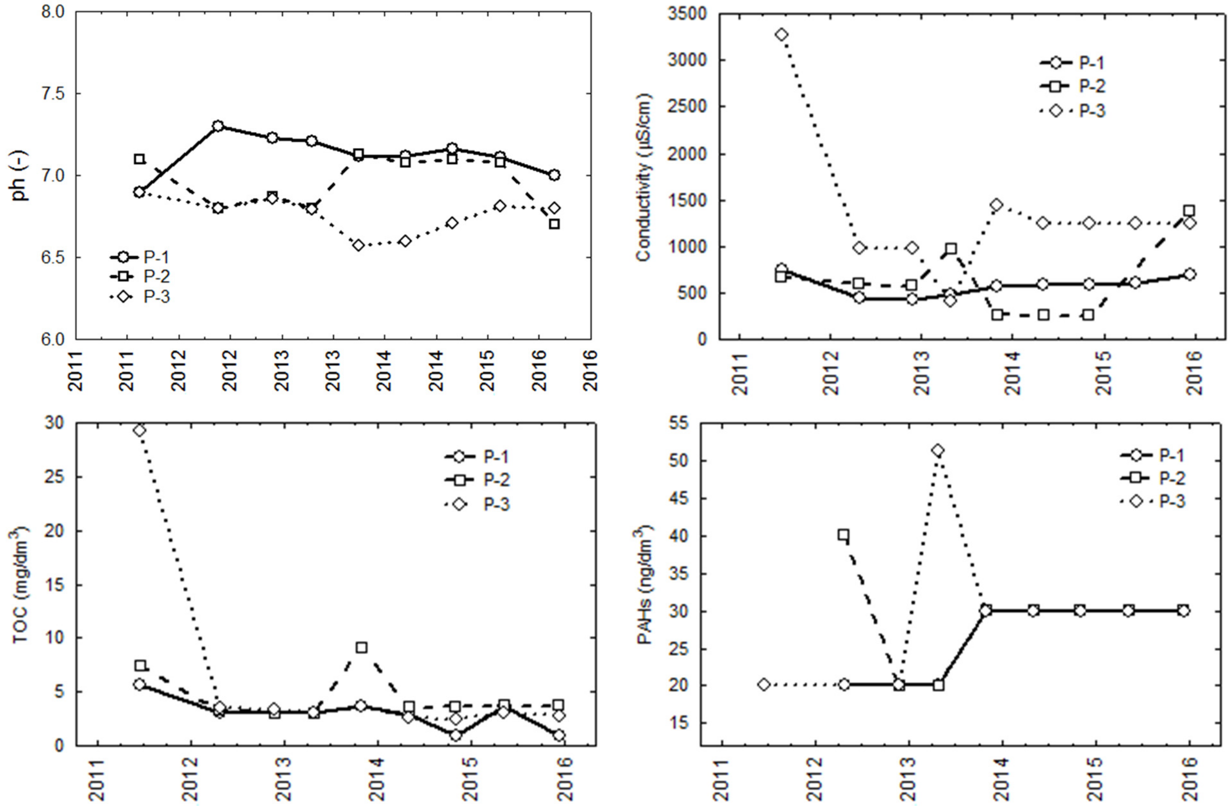

Fig. 4. Results of groundwater quality tests at the landfill B (source: own elaboration from monitoring data)

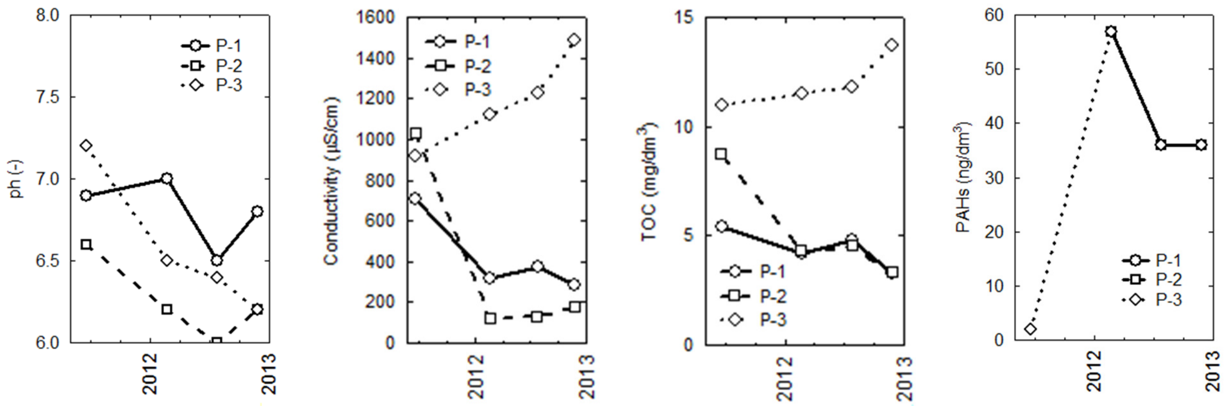

Fig. 5. Results of groundwater quality tests at the landfill C (source: own elaboration from monitoring data)

The high values of electrolytic specific conductance in water from piezometers P-3 at the outflow of all examined landfills (Table 2) indicate presence of direct hydraulic contact between sampled groundwater and stored waste (Rzepa *et al.* 2006). Electrolytic conductivity, as an indicator of the overall mineralization of the water, proves to be a very good indicator of pollution of groundwater in the area of the landfill. TOC value, apart from the initial measurements taken during the operation of the landfill, generally does not exceed the range allowed for groundwater, which is influenced by the decreasing amount of organic matter content in the leachate with progressing age of the landfill (Kulikowska, Klimiuk 2008). The content of PAHs, common on old landfills due to deposited here ash and slag from home furnaces, remained at an acceptable level, and with the exception of landfill A, tended to decrease from the beginning of measurement operation. PH value in landfills without seals steadily decreases, exceeding the lower limit for drinking water set before 2010 (Journal of Laws 2007, item 417).

The worst water quality of samples taken from piezometers P-3 is explained by the position of the boreholes. On the basis of maps prepared for groundwater level contour lines (hydroizohypses), it can be concluded that the strongest groundwater flow occurs in the direction of the boreholes P-3. There was no distinguished seasonal variability of tested water parameters over time.

Conclusions

1. Examined landfills have been approved for use without natural geological barriers and complex artificial seals. The leachate generated in the landfill freely migrates to a non-insulated subsurface aquifer and can be transferred over longer distances. Only in the area of the landfill B there are low-permeability formations of small thickness.
2. Water samples collected from piezometers located at the outflow of water from the landfill area are characterised by a worse qualitative composition than water from the piezometers located at the inflow of groundwater. Particularly noticeable is increased content of total organic carbon and higher electrolytic conductivity.
3. It has been observed that within the landfill B, whose construction is characterised by the presence of clay formations partially covering the aquifer, water quality has improved even with incomplete insulation after the cessation of disposing of waste, what confirms retention of contaminants by these formations. Landfills A and C, where the ground is built exclusively of non-cohesive formations with high coefficients of filtration, have steadily deteriorating water quality.
4. Electrolytic specific conductance, as an indicator of the overall mineralization of the water is a very good indicator of pollution of groundwater in the area of the landfill.
5. Subsurface aquifer is a kind of "indicator" delivering information about the harmful impact of landfills and the need to take remedial actions to restore the good condition of the water, to prevent the penetration of pollutants into the deep-seated useful aquifer.

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Disclosure statement

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