Original Research

Influence of Vertical Barrier Surrounding Old Sanitary Landfill on Eliminating Transport of Pollutants on the Basis of Numerical Modeling and Monitoring Results

Eugeniusz Koda*

Department of Geotechnical Engineering, Warsaw University of Life Sciences – SGGW, Nowoursynowska 159, 02-776 Warszawa, Poland

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Abstract

This paper presents results of the numerical modeling of pollution transport and groundwater quality monitoring for an old sanitary landfill where an advanced protection system has been introduced. The protection system consists of a vertical bentonite barrier and peripheral leachate drainage. The 3-D FEMWATER numerical program has been used for the groundwater flow and transport simulation. The local monitoring program includes chemical analyses of surface and ground water leachate concentration as well as groundwater level observations. The modeling and monitoring results were aimed at the assessment of the vertical barrier effectiveness as a groundwater protection system in landfill surroundings. These analyses were performed for the Radiowo landfill located near Warsaw. This site was established in 1962, and the permission for its exploitation was extended to the end of 2010. The landfill remedial works have been conducted since 1998 and include: installation of the vertical bentonite barrier, the leachate drainage system, the leachate recirculation system, the mineral cover, the degassing system, and the regulation of water relations in surroundings. The influence of remedial works on groundwater quality on landfill surroundings also has been analyzed in the paper.

Keywords: sanitary landfill, remedial works, transport modeling, water monitoring, vertical bentonite barrier

Introduction

The sanitary landfill is a specific bioreactor in which wastes are decomposed under the influence of aerobic and anaerobic conditions and microorganisms in chemical, physical, and biological processes. Rainwater penetrates the waste and dissolves products in the biochemical processes and forms leachate. The significance of this issue and recent suggested solutions, was presented by such authors as Visudmedanukul et al. [1] and Joshi et al. [2]. Pollutants migration depends on geological conditions that can be favorable to the transport of water and the substances it carries (large thickness of permeable layers, high hydraulic gradients) or it can completely stop and keep the transport away from the landfill (impermeable layers, low gradients) [3, 4]. The leachate from sanitary landfills is ranked as strong sewage with considerable content, diversity, and concentration of pollution. Remediation works on old sanitary landfills, among other phases, need the solution for pollutants utilization. Particular attention must be paid

*e-mail: eugeniusz_koda@sggw.pl

to the protection against groundwater pollution by leachate. The protection of groundwater on surroundings can be achieved by the cut-off wall and peripheral drainage installation [5].

In Poland there is still a large number of sanitary landfills where environmental protection standards are not fulfilled. Therefore, on these areas, the remedial works aimed at protecting the environment against progressive degradation should be carried out immediately. The example of engineering solutions for groundwater protection (cut-off bentonite barrier and peripheral drainage for leachate collection) applied as a remediation of the large embankment sanitary landfill in Radiowo is presented in this paper. In the case of the analyzed landfill, the basic remedial problem is connected to protection against leachate migration and groundwater pollution [6]. The schemes of the old landfill before and after remedial works are presented in Fig. 1.

The assessment of remedial work efficiency was performed with the use of numerical transport modeling [7] and analysis of water quality monitoring in the landfill surroundings [8]. The FEMWATER numerical program has been used to define and predict groundwater flow and the pollutant transport direction. The example of similar analytical modeling was also presented by Chen et al. [9], VanGulck and Rowe [10], Zaradny [11], and Gutierrez-Neri et al. [12]. The research of the last author, however, was more related to the issue of core biodegradation in groundwater plumes.

The control tests of the vertical barrier material and subsoil were conducted directly in the field, which is one of the requirements of the observational method [13, 14] applied during the reclamation works at Radiowo. The tests were performed to determine permeability parameters for the numerical model. Further research on the bentonite material quality was also presented in [15, 16]. It is observed that, after closing the vertical barrier and constructing leachate drainage, the pollution concentration has been directed toward groundwater flow. The modeling and monitoring results allow estimating the effectiveness of remedial works that have been carried out at the landfill.

Site Characteristics

The Radiowo landfill is located in the NW part of Warsaw. It started to operate in 1962 and no protection system was installed there at that time. Mixed municipal solid wastes were disposed there up to 1991. Since 1992 only non-composted wastes, i.e. glass, plastics, textiles, and scrap, have been stored there. It covers the area of approximately 16 ha and is almost 60 m high. Since 1998, the remedial works have been carried out on the landfill. They include, among others: shaping and planting of slopes, stability reinforcement techniques, mineral capping systems, cut-off wall and peripheral leachate drainage protecting groundwater, and leachate recirculation and degassing systems. It is expected that the landfill will be closed in 2012.

The landfill subsoil consists of sandy soils, 2-5 m thick, locally to a depth of 20 m. In the upper part they are represented by dense sands, in the deeper part – by well-graded sands. This layer forms the first groundwater level with the table at a depth of 0-2 m b.s.l. Water is supplied to this layer mainly by infiltration of precipitation and water inflow from the forest area located in the SE. Dewatering trenches from the NE and W parts, as well as the stream (from the N), compose a local drainage system for the first groundwater layer. The leachate from the landfill is pumped to the landfill surface (re-circulation system).

The vertical bentonite barrier of the landfill was constructed in 1999-2000. The 0.6 m wide cut-off wall was installed 2 m below the top of clayey soils, i.e. 3.5-22.0 m below the surface level. This aquitard layer consists of boulder and Tertiary clays. Closure of the bentonite barrier contributed to significant improvement in the quality of the first groundwater layer and the surface water in ditches. A large improvement in surface water quality is visible at the first sight – samples of the groundwater are colorless (in the past it was a brownish smelly liquid). Fig. 2 presents the generated model mesh and the assigned boundary conditions for the flow and the transport modeling. The analyzed technical solution for the model simulation consists of the protection

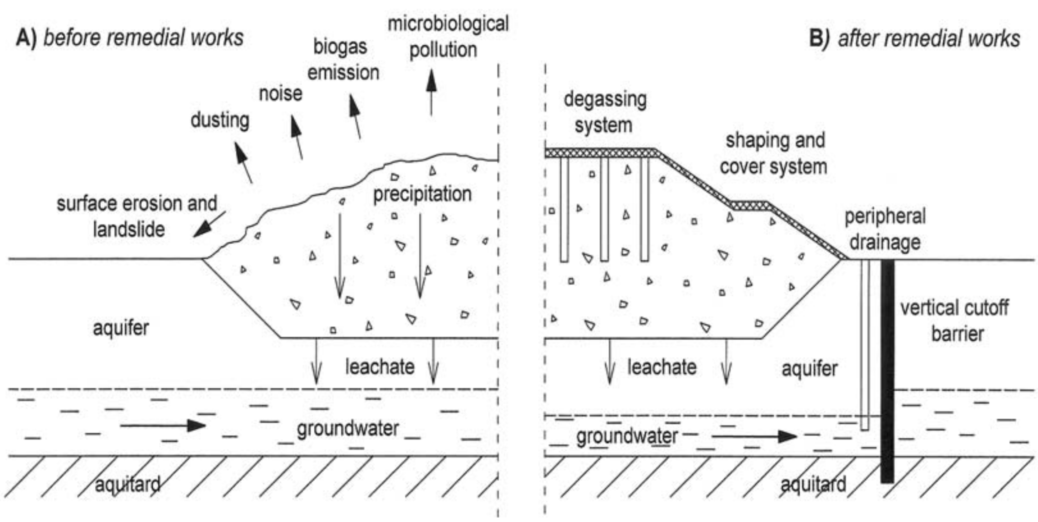

Fig. 1. The old landfill schemes before and after remedial work performance.

Table 1. The influence of the vertical barrier on groundwater quality in piezometer P-7A on the basis of values of select indicators.

Pollution indicator	Unit	Date/Concentration of pollutants				
		11.07.00		20.06.01	23.11.04	11.03.09
Color	-	Black	Closure of the vertical barrier. November 2000	Brown	Yellow	Natural
Electrical conductivity	µS/cm	10,830		8,370	4,400	996
BOD_5	mgO_2/dm^3	650		75	50	17.2
COD_{Cr}	mgO_2/dm^3	1,758		226	194	85.6
Ammonium nitrogen	$mgNNH_4/dm^3$	97.7		14.1	6.2	<0.04
Chlorides	$mgCl^-/dm^3$	2,374		1,595	530	37.4
Sulphates	$mgSO_4^{2-}/dm^3$	690		630	450	182
Copper	$mgCu/dm^3$	2.1		0.6	0.261	0.039
Lead	$mgPb/dm^3$	0.2		0.05	0.006	0.004

system including the vertical barrier stopping the leachate outflow from the landfill and application of the leachate recirculation. The model mesh consists of 8,903 elements and 5,289 nodes. The total area covered by the model is approximately 88 ha, including 16 ha of the landfill area.

Local Monitoring of Surface and Underground Water

The analysis of water quality in the Radiowo landfill neighborhood is conducted according to a local monitoring system that includes:

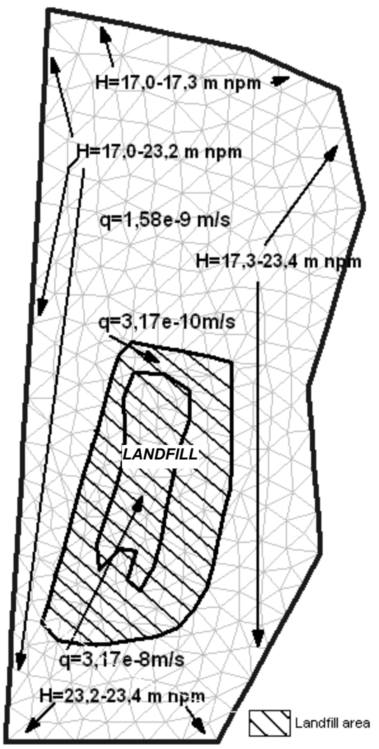

Fig. 2. Boundary conditions for the numerical model of Radiowo landfill.

1) 17 observation points (shallow piezometric wells) used to control the first groundwater table
2) 1 deep well used to control a second water-bearing layer
3) 6 sampling points situated at surface watercourses (ditches)
4) 4 sampling points of raw leachate (from leachate reservoirs)
5) 1 sampling point of rainwater from the compostory (from open reservoir)

This network of points enables appropriate control and estimation of the water quality in the vicinity of the landfill and compostory (Fig. 3). The analysis of the surface and underground water located in the surroundings of the landfill has been carried out since 1997, whereas chemical analysis of a "raw" leachate from the peripheral drainage situated at a dump has been made since 2000 [8]. Measurements of the water level in piezometric wells are conducted once a month and are used to define the groundwater flow directions, thereby migration directions of pollutants. The analysis of water quality is made twice a year.

Chemical and physical analysis of the underground water has been conducted since 1997 (the landfill owner is obliged to reclaim it). The results obtained show improvement of water quality in the landfill area. The analysis of data from Table 1 reveals that introduction of the vertical barrier has positively changed basic parameters of the first groundwater layer. This paper presents only basic parameters to characterize water quality. Detailed results of the monitoring research are presented in annual reports.

The Use of Transport Modeling for the Remedial Work Assessment

The numerical model of the groundwater flow was constructed with the use of GMS software [17]. The basis of the model is the 3-D simulation of groundwater flow and pollutant transport. Numerical modeling was focused on the assessment of the vertical barrier influence on hydrogeological conditions in the Radiowo landfill area.

The Richard's partial differential equation is used to describe groundwater flow:

$$\nabla\left[k_r k_s\left(\nabla h + \nabla z\right)\right] + q = F\frac{\partial h}{\partial t} \quad (1)$$

...where:
k_r – relative hydraulic conductivity
k_s – saturated hydraulic conductivity tensor
h – pressure head
q – source/sink discharge
t – time
$F=\partial\theta/\partial h$ – differential water capacity
θ – volume moisture content

Generally, it can be assumed that: F, θ, and k_r are functions depending on h. In the model, these relationships were defined as functions described by van Genuchten [18].

The governing equations used in the FEMWATER model for the transport are worked out based on the continuity of mass and flux laws. In the presented model, the transport process was respected as the advective-dispersive migration of a single dissolved indicator – chlorides (Cl^-). It can be described by the equations:

$$\theta\frac{\partial C}{\partial t} + V\cdot\nabla C - \nabla\cdot\left(\theta D\cdot\nabla C\right) = 0 \quad (2)$$

$$\theta D = \alpha_T\left|V\right|\delta + \left(\alpha_L - \alpha_T\right)\frac{VV}{\left|V\right|} \quad (3)$$

...where:
V – discharge velocity vector (in Darcy flux)
C – material concentration in aqueous phase
t – time
D – dispersion coefficient
α_T – transversal dispersivity
α_L – longitudinal dispersivity
δ – Kroneckers delta.

In the numerical model for Radiowo landfill, taking into account geological deposits in subsoil of landfill surroundings, four landfill subsoil materials were distinguished.

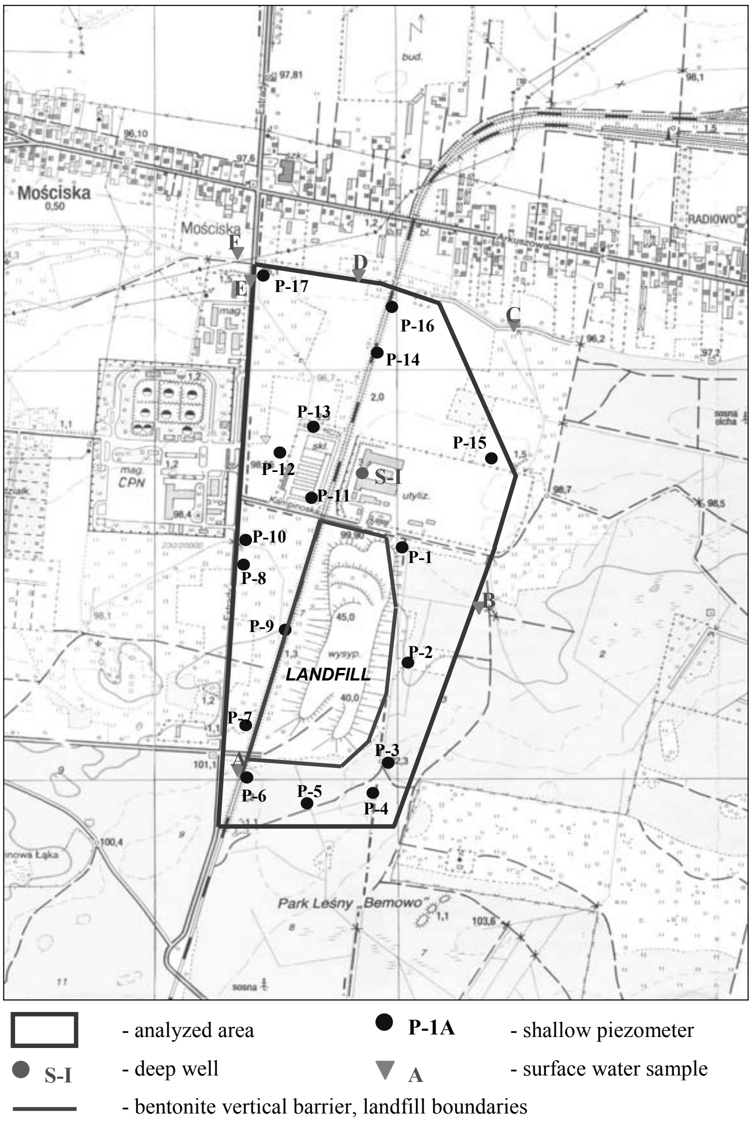

Fig. 3. Local water monitoring system of Radiowo landfill surroundings.

Starting from the older to younger (occurred directly below surface level), these are:

- tertiary clays, with the coefficient of hydraulic conductivity k_s=5·10^{-9} m/s
- sandy clays, with the coefficient of hydraulic conductivity k_s=1·10^{-7} m/s
- non-uniformly grained sands, with the hydraulic conductivity coefficient k_s=5·10^{-4} m/s
- dense sands, with the coefficient of hydraulic conductivity k_s=5·10^{-5} m/s

The parameter values of unsaturated zone, demanded in the numerical model, for sands were accepted on the basis of the literature data [19]. They were, as follows:

- differential water capacity, F=0.0725
- volume water capacity θ, reached from θ=0.045 for h=-4 m to θ=0.36 for h=0
- relative conductivity, reached from k_r=0 for h=-4 m to k_r=1 for h=0

The water quality monitoring system, including 17 piezometers, 1 deep well, 5 points of leachate sampling and 6 points on local dikes, enables appropriate control and estimation of water quality [20]. The plan of monitoring point locations on the Radiowo landfill surroundings is illustrated in Fig. 3. Chemical analysis for underground water has been conducted since 1997. The analysis of water quality results reveals that the introduction of the vertical barrier has positively changed the principal parameters of the first groundwater layer. The results of water monitoring were used for a numerical model verification.

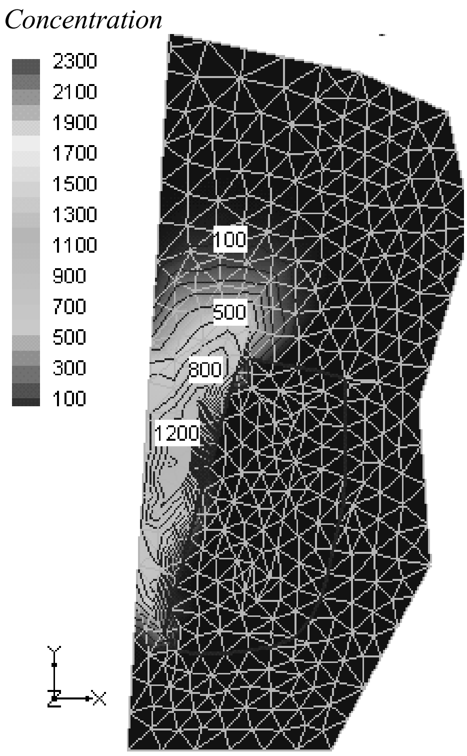

Fig. 4. Chloride concentrations (mg Cl/dm^3) at the first groundwater layer before the vertical barrier construction.

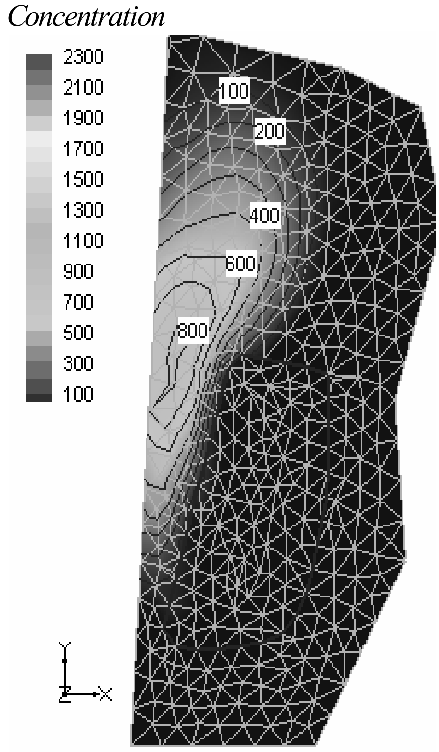

Fig. 5. Chloride concentrations (mg Cl/dm^3) at the first groundwater layer 5 years after vertical barrier constriction.

Discussion of Results of Water Monitoring and Transport Modeling

The technical works conducted according to the reclamation project, including those introduced in 2000 in the vertical bentonite barrier (it was closed at the end of November 2000) and drainage system separating leachates from the landfill, helped to obtain significant improvement in the quality of the groundwater and the surface water in the vicinity of the landfill. Table 1 shows the influence of the above-mentioned reclamation operations, especially the influence of the vertical barrier on the quality of groundwater during 2000-09. The results show that construction of the barrier significantly improved water quality. The presented results have been obtained from piezometer No. 7A, when the vertical barrier was closed.

The numerical modeling of pollutant migration in the first groundwater layer is shown in Fig. 4 as a map of chloride concentrations before the closure of the vertical bentonite barrier, while the situation 5 years later is presented in Fig. 5.

In Fig. 5 the movement of a pollution-slick toward groundwater flow direction is observed. The maximum chloride concentrations in the slick have been reduced significantly as a result of dilution. It is predicted that the chloride concentrations will be reduced by 2-3 times during the next 15 years, while total elimination of chloride pollution will take place after ca 30 years from the closure of the bentonite barrier.

The verification of the modeling results has been done based on water monitoring in the landfill surroundings. Figs. 6 and 7 present spatial distribution of the chlorides for two periods: before and 5 years after the closure of the vertical bentonite barrier.

Comparing the maps of chloride distribution received from the numerical modeling and monitoring, one can observe the confinement of a polluted zone and decrease in a maximum value of chloride concentrations. Pollution movements can significantly affect water quality in the outflow direction. After 5 years from the vertical barrier closure, the maximum concentration was moved from the zone of piezometer No. 7A to the zone of piezometer No. 11A (Fig. 8). The remedial works carried out at the Radiowo landfill are preceded in an appropriate direction and should be brought to an end. After closing the vertical bentonite barrier, the water quality on surroundings has improved.

Conclusions

The remedial works carried out on the Radiowo landfill proceed in the right direction and should be brought to the end soon. After closing the vertical barrier, the quality of groundwater (first layer) has improved. Simultaneously, after closing the vertical barrier, the main pollution concentration has been moving toward groundwater flow direction.

Numerical transport modeling is useful for the assessment of vertical barrier influence on groundwater flow and on the improvement of water quality. The results of numerical modeling for the Radiowo landfill, presented and analyzed in the paper, proved the containment role of the ver-

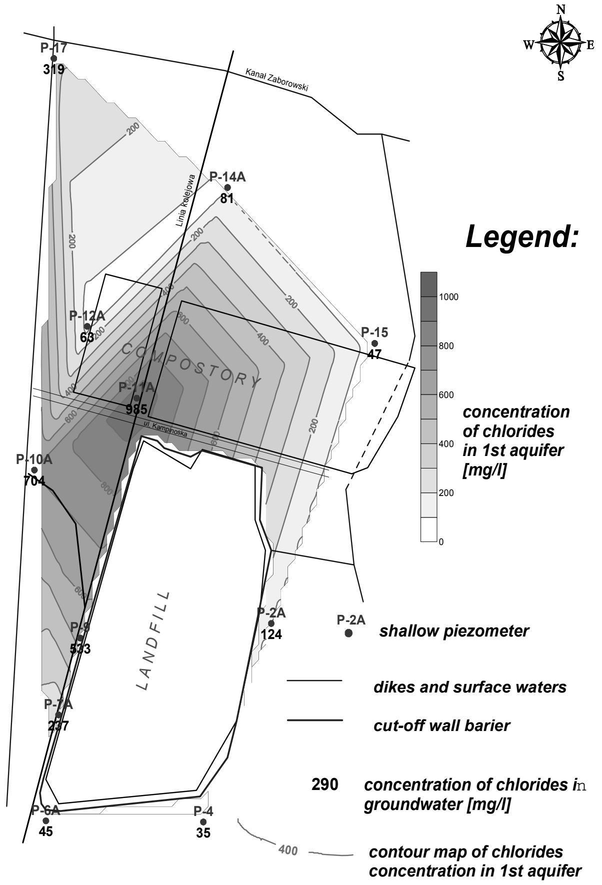

Fig. 7. Chloride concentrations (mg Cl/dm³) at the first groundwater layer 5 years after the barrier construction, according to monitoring results.

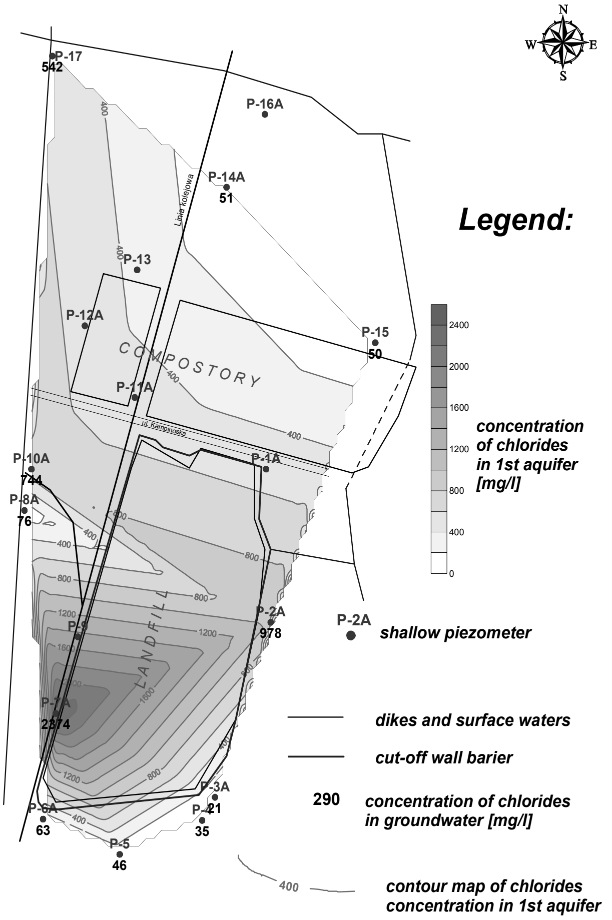

Fig. 6. Chloride concentrations (mg Cl/dm³) at the first groundwater layer before the vertical barrier construction, according to monitoring results.

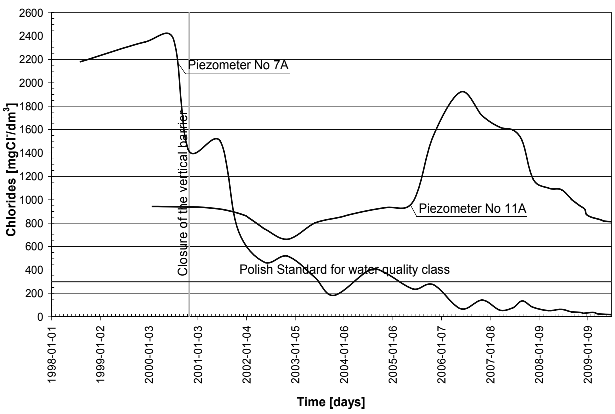

Fig. 8. Movement of the maximum chloride concentrations (in mg Cl/dm³) toward flow in the first groundwater layer from piezometer No. 7A to piezometer No. 11A.

tical bentonite barrier. The transport modeling results correspond to the monitoring measurements.

Due to the vertical bentonite barrier, construction and introduction of the recirculation system of polluted water on the landfill surface, the groundwater (leachate) table level in the landfill area (surrounded by vertical barrier) has also changed, i.e. a decrease or increase in the leachate level appeared, depending on the landfill zone.

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